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Additive Manufacturing Essentials

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SENIOR CONTRIBUTING AUTHORS

TIMOTHY E. SIMPSON, PENNSYLVANIA STATE UNIVERSITY

JOHN E. BARNES, THE BARNES GLOBAL ADVISORS

openstax™

OpenStax
Rice University
6100 Main Street MS-375
Houston, Texas 77005

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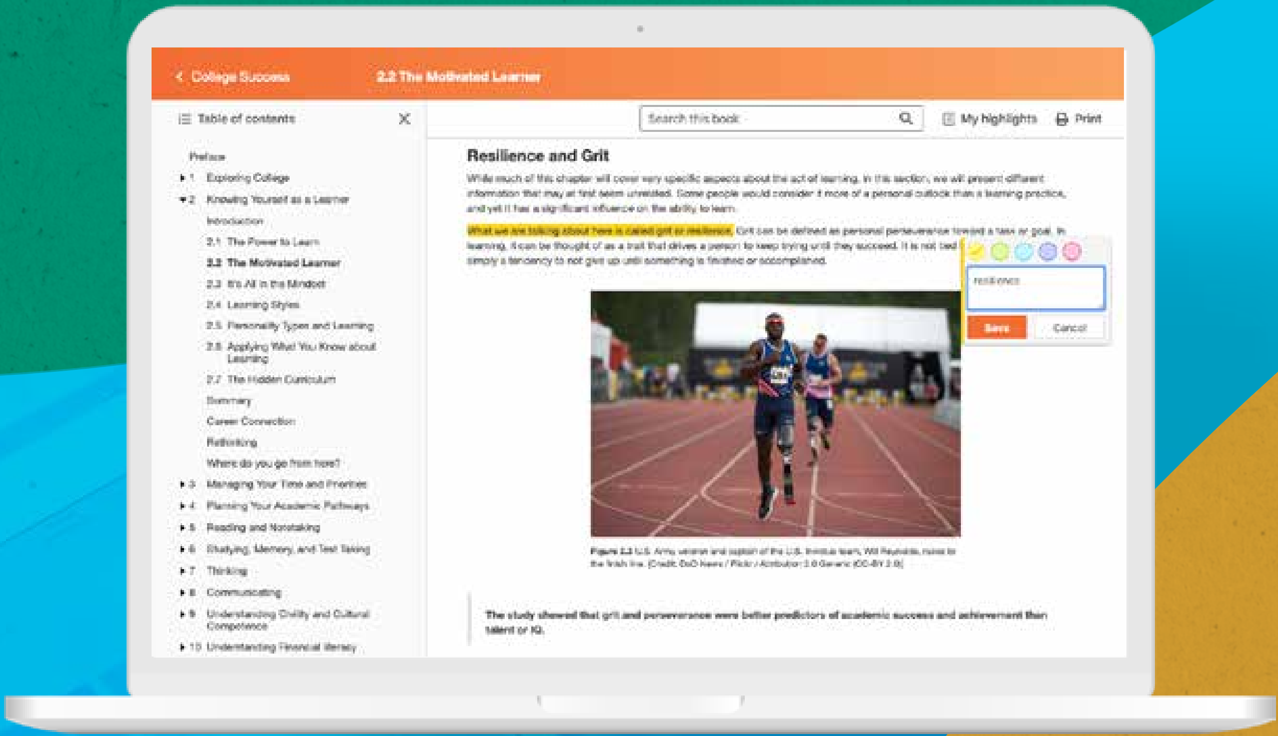
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About *Additive Manufacturing Essentials*

Additive Manufacturing Essentials provides a clear, effective introduction to the core principles, technologies, and methods in the field of additive manufacturing. Rooted in industry practice and innovation, the material presents examples and approaches from an array of additive manufacturing companies, equipment producers, and software developers. *Additive Manufacturing Essentials* provides new entrants to the field with a working knowledge of the concepts and key applications of this critically important domain. Whether readers are engineers, scientists, fabricators, production/operations managers, entrepreneurs, educators, or career-changers, additive manufacturing can play a significant role in their studies and future careers. This offering is designed to help those students and professionals grow conversant in additive manufacturing, so that they can use their knowledge in further studies and organizational decision making.

Coverage and Scope

Additive Manufacturing Essentials begins with an overall introduction to the key characteristics, applications, and industrial-organizational uses AM. The first chapter also introduces the AM maturity model, developed by The Barnes Global Advisors, which serves as a theme throughout the course. The book then presents various AM methods, including illustrated discussions of the main manufacturing approaches and 3D printing types. Subsequent chapters explore materials, design, certification, qualification, and the digital thread. The book concludes with the business of AM, which aims to help readers apply what they've learned to their own organizations and workflows.

Answers to questions in the book

The answers to the end-of-chapter questions are intended for homework and assignments, and are therefore provided to instructors as instructor resources.

About the authors

Senior Contributing Authors

Timothy E. Simpson, Pennsylvania State University
John E. Barnes, The Barnes Global Advisors

Contributing Authors

Jennifer Coyne, The Barnes Global Advisors
Chelsea Cummings, The Barnes Global Advisors
David Dietrich, PADT, inc. Laura Ely, The Barnes Global Advisors
Michael Hickner, Ph.D., Michigan State University and The Barnes Global Advisors
Kirk Rogers, Ph.D., The Barnes Global Advisors
Kevin Slattery, D.Sc., The Barnes Global Advisors

1 FUNDAMENTALS OF ADDITIVE MANUFACTURING

Figure 1.1 Additive manufacturing can take place in many types of spaces, using machines of almost any size. (credit: Modification of “Maker Space Post-Finishing an Additive Manufacturing Part Made with a Formlabs Form 2 SLA 3D Printer V2” by Formlabs/Flickr, CC-BY 2.0)

Chapter Outline

Introduction

Humans are quite good at subtractive manufacturing. For millennia, we have been removing material to make things, such shaping tools by striking stones together or carving pieces of wood to form a useful or artistic object. We developed these techniques through trial and error, and passed knowledge first from generation to generation and eventually across cultures. Later, humans learned how to isolate metal from rock, how to form it and combine it into alloys to meet increasingly advanced needs. As you likely know, the history of humanity is often described in terms of these materials and knowledge – the Stone Age, the Bronze Age, the Iron Age. Most of the items you see and use every day – from pens to keyboards to cooking pots to contact lenses – are created based on techniques that, even if highly complex, are considered to be “legacy” manufacturing. As humans have many times in our history, we have developed a new series of techniques, known as advanced manufacturing. Additive Manufacturing is one of those forms of advanced manufacturing, distinguished by the process of building an object one layer at a time.

1.1 The Components and Processes of of Additive Manufacturing

Learning Objectives

By the end of this section, students will be able to:

- Define commonly used terms.
- Understand the building blocks of additive manufacturing.
- Understand the digital workflow required for 3d printing a part.
- Describe the STL file format

Additive manufacturing is often referred to as “3D printing,” which is an important component of the domain, but does not describe the entire process. 3D Printing is the act of making a 3-dimensional shape via a “printer,” while additive manufacturing is everything needed to make that shape into a “part.” Parts have requirements where form, fit and function are critical.

To make a shape, the 3D printer adds the material where it is needed, most likely in a thin, essentially 2-dimensional layer. The printer only concerns itself with a 2D layer at any point in time. It creates a stack of these layers, incorporating spaces and other details to build a 3-dimensional shape that can have complexity, internal details, and doesn’t typically require additional tooling to be considered complete. 3D printing is that *additive* approach, which is a major shift in innovation from legacy manufacturing. But as the box below demonstrates, 3D printing is only one aspect of additive manufacturing.

The Four Building Blocks of AM

Four building blocks are necessary for success in the world of AM: Machines, Materials, Digital, and People.

Machines are the easiest to focus on, specifically the 3D printers, but our definition expands beyond the printers to include the machinery required to meet the part requirements.

Materials
The building block of materials includes material science, metallurgy, polymers, ceramics, welding, powder, wire manufacture, finishing steps, and possibly heat treatment. How we manufacture the materials and the changes they will undergo both as a feedstock and subsequently as a printed object are very important.

Digital
Within the building block of Digital, we encompass design, simulation, sensing, and essentially any data input or output.

People
The management and organization of people is an essential skill to be successful in AM due to the multidisciplinary and complex nature of AM. Skilling to include AM thinking alongside traditional design for manufacture has to be recognized and permeating those skills throughout a company is a challenge.

Additive manufacturing has diverse process technologies. This diversity creates unique design spaces for shapes, sizes, materials, mechanical performance, etc. When we couple the mechanical operations with design, business, and qualification guidance, we need to seek a more overall comprehensive appreciation. For example, for a part to be qualified, we must first understand the requirements for that part. These requirements likely include both technical and commercial considerations. These requirements will eliminate some of the manufacturing processes as candidates. We then may need to consider what material is appropriate and the properties of that material in the manufacturing process. Now we get into the design of the part and the design of the build which will critically determine the cost of the part as well as the strength. And while design for manufacturing (DFM) is not a new topic, designing for additive manufacturing can be quite counterintuitive to those versed in legacy manufacturing. In this book, we weave together important topics to gain a strong, holistic understanding of additive manufacturing – which we’ll often abbreviate as AM – including how it is done and where it can be used.

Process Steps: Concept to Part

The best place to start thinking about using AM is at the concept stage. Often, this is not a luxury afforded to an engineer working on a part, because they need to replace a part that is already designed. However, the concept stage is the most fertile because we are still conceiving the product requirements and because AM enables complexity. The concept is the first opportunity to design to the requirements before we have a constraint of a specific manufacturing method.

The AM journey requires a 3D file and follows a similar digital workflow regardless of the AM process employed. The source for the future 3D object can originate from Computer Aided Design (CAD) or from a 3D scanning source such as structured light, Magnetic Resonance Imaging (MRI), or Computed Tomography (CT). Once available in a 3D file, the source data will be turned into an STL file.

The STL file format originally hails from stereolithography and can only describe the surface geometry of a three-dimensional object. It does not relay any other information, including color, material, or texture. The STL file describes an unstructured, triangulated surface by unit, and vertices of the triangles use a three-dimensional Cartesian coordinate system. STL files contain no scale information and have arbitrary units. There are many efforts afoot to replace the STL file because, while simple, it contains little real information making the task of tracking and documenting changes difficult. One approach is to stay in the native CAD format which has the advantage that, if changes are made to the file for printing, they could be traced back to the design file.

The build file is the next step in the workflow. The build file can be just a single part or part number but could also be multiple parts, part numbers, test coupons, etc. It is very important to remember that the original engineering design may or may not specify items like orientation during the build, but this a requirement for the build file. The build file is very important to ensure consistent results, expected results, economic results and compliance. The build file should be treated like a released engineering or manufacturing drawing. It is akin to a forging die that is employed to manufacture parts over and over.

From here our build file will be sliced into finite 2D layers. Recall that the computers in 3D printing typically only concern themselves with a layer at a time, so each slice represents a build layer. Once sliced, a tool path is generated, and the shape can be printed.

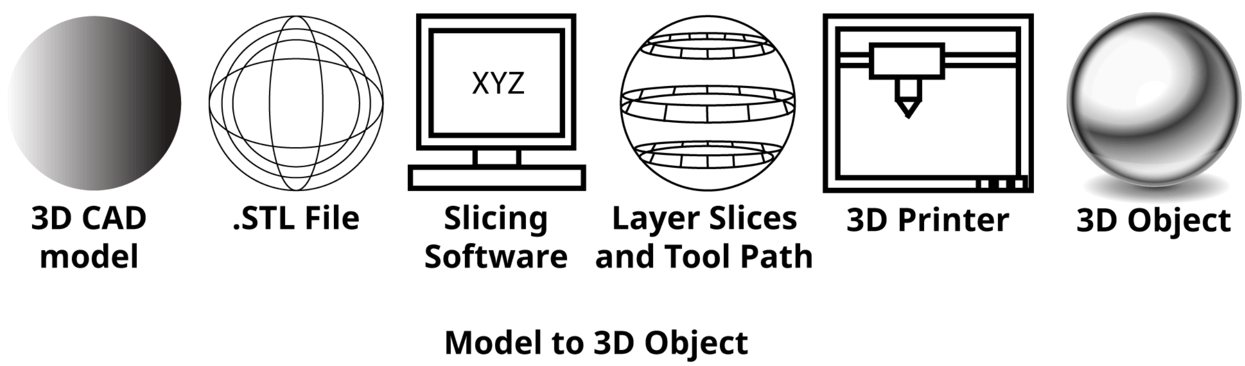


Figure 1.2 From CAD to part. The 3D CAD model is saved as an STL file, which is processed by the slicing software. The layer slices and tool path are next, followed by the actual printing via a 3D printer to produce the final, physical 3D object.

Post-processing is the name given to a host of manufacturing processes employed after the 3D printing step. These processes serve to finish an AM part by improving the appearance or material properties after it has been printed. These processes could be, but are not limited to, material removal, thermal processing, and surface treatments. The printed shape can be dimensionally measured to ensure consistency to the original drawing or source file.

What Does STL Stand For?

Similar to JPEG or GIF, the STL file name (or extension) is regularly used without much consideration to what it means. In the case of STL, this is helpful because there are several accepted terms associated with it. The abbreviation initially stood for stereolithography, a common additive manufacturing technique. But since STL files are used for other processes within additive manufacturing, it has been re-associated with two other terms. “Standard triangle language” refers to the surface of an object being broken into a series of triangles. And “standard tesselation language” refers to the surface being made up of a series of shapes (or tiles) that do not overlap. None of these perfectly describe all of the potential use cases of the STL file, so most people in the field simply use the abbreviation – just like other file extensions.

1.2 Additive Manufacturing Processes

Learning Objectives

By the end of this section, students will be able to:

- Define seven standard AM processes.
- Describe the similarities and differences between the seven processes.

Additive manufacturing has matured into a diverse set of technologies all of which share an adding, or layer by layer, approach. While AM can be segmented into seven broad categories, innovation is occurring so rapidly that hybrids and combinations of AM processes are frequently being brought to market.

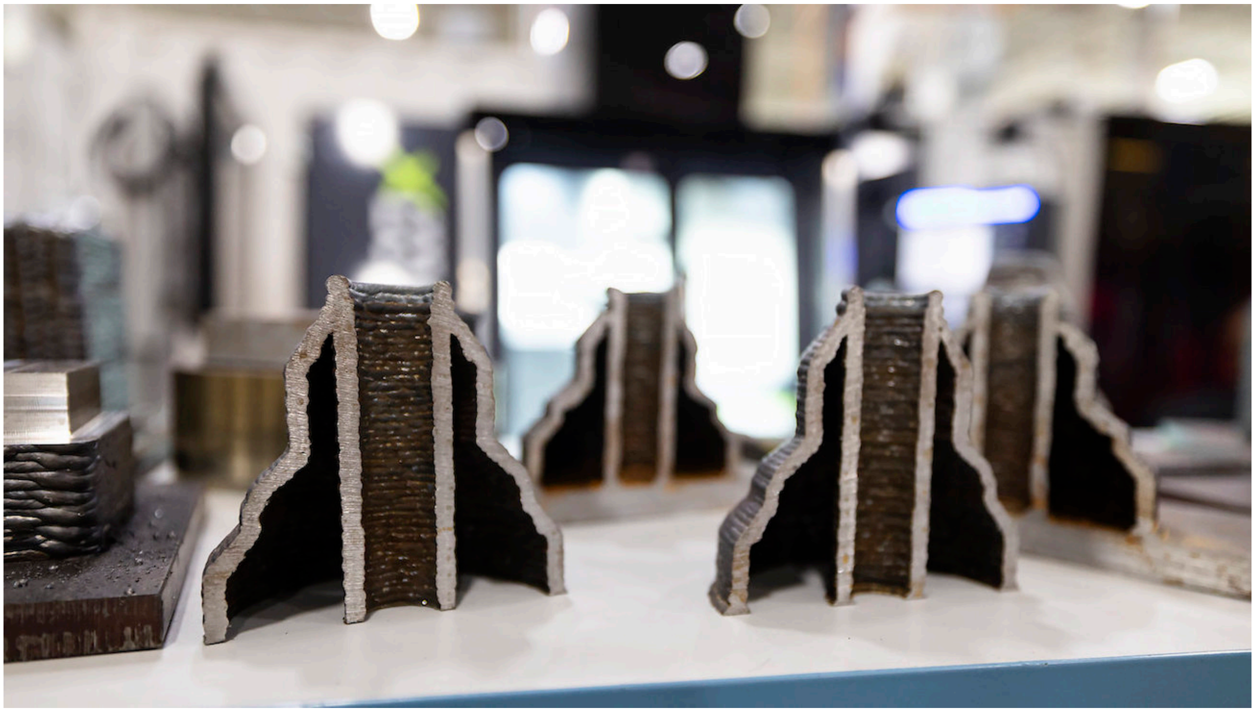


Figure 1.3 Selecting the AM process depends on the requirements of the part and the ability to answer three core questions: How is the layer created? How is the energy applied? How is the material applied? (credit: Modification of "3D Printed Objects" by Oak Ridge National Laboratory/Flickr, CC-BY 2.0)

Any AM process can be described with just three questions: How is the layer created? How is the energy applied? How is the material applied? If you can describe the process with this simplified view of AM, you can easily move to the next layer of detail.

With the simplified view in mind, the seven broad methods employed in AM are:

Binder Jetting – A manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.

Layer – The layer is made by spreading powder across a bed and stepwise lowering the bed defined by the slice thickness.

Energy – Two forms of energy are used: print ejectant which is deployed through a print head and contains a polymer adhesive to bind the particles together. Thermal energy is used to cure the adhesive in subsequent steps. In metals, a sintering or infiltration step is required.

Material – The materials used must be in powder form but may be metal, ceramic or polymer.

Directed Energy Deposition – A family of processes in which focused energy is used to fuse materials as they are being deposited.

Layer – The layer is made by depositing one or more beads onto a substrate, which could be an existing part, with new deposits building either beside or on top of the previous beads.

Energy – Two forms of energy are used: Thermal energy is used to melt the material in a fusion DED process akin to traditional welding. In a solid state DED process, kinetic energy accelerates powder particles to a high velocity splatting them into the previous layer, creating a solid state metallurgical bond.

Material – The materials used may be in powder or wire form and are predominantly metal.

Material Extrusion – A process in which material is heated and delivered precisely through a nozzle or an orifice.

Layer – The layer is made by layering new deposits over the previous.

Energy – Two forms of energy can be used: Heat is applied to cause the material to flow through the nozzle. This is true for all materials. For metals, a sintering step is required for bound particles but not for friction-based processes.

Material – The materials used can be polymer and/or metal where the polymer is a filament and the metal is a particulate bound in the filament. The metal may also be a wire or particulate in the friction-based version.

Material Jetting – A process that selectively deposits droplets of build material through a print head.

Layer – The layer is made by selectively and precisely depositing the material in a desired location in an X-Y manner and then stepping is defined by the slice thickness.

Energy – Two forms of energy are used. Print ejectant is deployed through a print head and contains a fluid to deliver the target material. Thermal energy is used to cure the deposit. In metals, a sintering step is also required.

Material – The materials used can be polymer, metal or ceramic in solution with a liquid delivery agent.

Powder Bed Fusion – A process in which thermal energy selectively fuses regions of a bed or build area made of powder particles.

Layer – The layer is made by spreading powder across a bed and stepwise lowering the bed as defined by the slice thickness.

Energy – A beam of energy is used to fuse the particles together which could be a laser or an electron beam.

Material – The materials used must be in powder form but may be metal, ceramic or polymer.

Sheet lamination - An additive manufacturing process in which sheets of material are bonded to form an object

Layer – The layer is created by joining sheets of a material.

Energy – Flexible: ranges from a bonding agent to welding techniques like ultrasonics.

Material – Sheets of polymer, metal, paper & fibers

Vat Photopolymerization - An additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization

Layer – The layer is created where the energy intersects the material to create the shape in a step wise fashion.

Energy – Focused energy in the form of a laser or focused light.

Material – Polymers, composites, and metals in photo curable polymers

1.3 The TBGA AM Maturity Model

Learning Objectives

By the end of this section, students will be able to:

- Describe a maturity model for AM adoption.
- Understand the technological and people requirements for AM adoption.

The AM Maturity Model, used throughout the book, is a way to approach marrying the product requirements to the skills and knowledge of AM. The Barnes Global Advisors (TBGA) pioneered the use of a maturity model to describe an approach to adopting AM throughout a product or design lifecycle. The scenarios on the Y axis describe increasing product or design complexity and therefore increasing product requirements. The X axis contemplates the necessary learning to be able to deploy, make, or manufacture a part to meet the requirements.

It is normal for one to see the culmination of an organization's efforts in AM and want to replicate that success. Often, this success was built on years of development and trial and error. Jumping straight into making complex parts (e.g. Level 4) requires the highest level of skill and training. This is analogous to running a marathon. A runner trains extensively to be prepared to finish a marathon race. Without training, you introduce a high risk which could include injury or worse.

The AM Maturity Model contemplates both direct and indirect use of AM. At the lower levels, the indirect methods include prototypes (Level 0) and tooling (Level 1). In these efforts, AM is being deployed to support some other goal, but the AM part is not the part to be put in service. Prototyping and tooling are great places to begin an organization's journey in AM because of the reduced requirements.

In the direct use of AM, the part made by AM is intended to go into service. This begins with replacing a legacy part with a part made by AM (Level 2) and is typically very restrictive from a design flexibility standpoint. Progressing to Level 3, the ability for AM to integrate complexity comes into play as several parts are unitized into a single assembly or part. At Level 4, the organization's design, materials, people, and equipment knowledge is so extensive they can make a part with unrivaled performance that is not only complex and unitized but also is multi-functional. Perhaps it is a structural part that carries a load but also serves to exchange heat or employ a sensor.

Level 0

Prototypes for product development or system testing describes parts made at this level. We may be interested in form, fit or function but not all three. Making pieces for product development assist us in visualizing how the product could be used, for example. In other scenarios, AM pieces are made as stand ins for limited duration testing. Level 0 is a great place to gain experience initially, because the requirements are often not as tough, the risk is lower, and the learning opportunity is greater. At this level, it is expected you will start to explore the types of AM equipment and materials but neither may be critical to success.

Level 1

As we continue the path of indirect parts, Level 1 use of AM is oriented at making tools or fixtures which are assistive in manufacturing or assembly of the final system. Making tooling has been a successful path for many organizations to reduce the cost of manufacturing for legacy processes that can have expensive or lengthy lead times for tooling, such as casting or reinforced polymer composites. The exploration of the machine type and mode narrows, and materials selection is more critical. In addition, traceability and/or configuration control increase in importance. You will also find that other entities like supply chain players become stakeholders in the outcome. Lastly, design thinking and AM thinking is starting to mature, as there is now more experience manufacturing components and using different types of machines.

Level 2

Now we begin the journey into direct application of AM, as these parts will enter service. At Level 2, the parts look very much like they did with legacy manufacturing methods. This could be due to many reasons such as AM being used to support spare parts, obsolescence or a very restrictive design space where the ability to make changes are minimal. There could be larger objectives to achieve, such as simply reducing risk by employing a new manufacturing method and seeing different materials performance. Whatever the reason, Level 2 presents a significant challenge, because the designer has little room to maneuver and the design was likely optimized for a different process. Later, we will describe the restrictive and opportunistic design space with modify for AM (MfAM) and design for AM (DfAM), but at Level 2, MfAM skills are more dominant than DfAM.

The broader organization will become more involved in Level 2 as you will have to build a strategy for AM adoption and assess things like the supply chain as you are using a new technology, likely with new vendors, and/or new suppliers of materials or feedstock. Inspection, material specifications, process specifications and design allowables may also be important considerations to support manufacturing. The supply chain implications are discussed in more depth in Chapter 8 The Business of Additive Manufacturing.

Level 3

At this level, the AM skills are becoming more critical. As parts are being consolidated and joints or interfaces are being eliminated, likely a structural efficiency benefit is being sought. This efficiency will give rise to weight savings or better performance and endurance.

Financially, the AM part will likely have fewer manufacturing steps and decreased assembly time, thus collapsing the Bill of Material (BOM), drawing count, vendors and touch labor to assemble.

DfAM skills are now quite high, and you will understand that you may now have to start making design considerations for the additive manufacturing process. For example, if you redesign the part and make it too light, other considerations will come into play.

The organization will continue to lean in to support the design and manufacture; computers and algorithms can mathematically design and optimize, but they have no consideration for practical aspects, such as a part's surrounding environment. MfAM is still very relevant when it comes time to print the part successfully or meet the final part dimensional requirements by adding stock during printing, for example, to be able to machine to final tolerances.

Level 4

At this Level, a part can only be made economically through use of AM. There are less examples of Level 4 parts today due to the merging of the need for world class DfAM, supply chain support, marketing awareness and general management support to acknowledge the need to integrate organizational awareness. The Level 4 part will have unrivaled performance and will likely impact the system it sits within, thus driving the need for organization wide AM awareness. There will be a need to fully appreciate the system level tradeoffs in design for additive manufacturing.

1.4 Reasons for Using AM

Learning Objectives

By the end of this section, students will be able to:

- Enumerate common reasons for using additive manufacturing.
- Describe the requirements for choosing an AM process.
- Enumerate industries where AM is in common use.

There are numerous reasons that people and organizations employ AM. Typically, we refer to the Project Management Triple Constraint of Schedule, Scope (or Performance) and Cost as the fundamental considerations. Digging further into the trinity, there are many sub-elements to consider.

Schedule – Reducing production time or working inventory, compressing test or product development cycles, printing tools versus legacy means.
Scope – Improving system and/or part performance through complexity or part count reduction, added functionality, improving durability, reducing CO2 emissions.
Cost – Reducing cost of parts by improving assembly time and/or repeatability, reducing and/or expediting tooling time, design for AM improvements in part cost, reducing the number of parts that need to be produced, reducing the touch labor and processes in assembly, reducing cost to produce generally, and increasing revenue through enhanced performance.

To expand the Triple Constraints further, let's explore some additional characteristics of AM design:

Speed	Cost Savings	Performance Improvement	Complexity	Design	Durability	Lightweight	What Else?
no tooling net shape reduced machining	multiple PCs fewer resources	precise features eliminate leak points	optimized internal fluid/air passages	organic designs geometric flexibility	design for stress	value added material only	supply chain eco-friendly

Table 1.1 Why Use Additive Manufacturing? Additive manufacturing fulfills many business, product, and project goals.

Speed

Additive manufacturing improves time to market. AM provides a fast track from concept to production where complex objects can be manufactured in a single process step. Innovations are designed, developed and tested more rapidly, eliminating the need for expensive and time-consuming prototype fabrication.

Cost

Inevitably, designers and engineers learn that taking weight out of a part leads to faster printing or faster build times. With traditional machining, more time on the mill often means lighter parts, but it costs more because of the time it takes to produce the part. With additive manufacturing, as we are adding material in a layer wise fashion, we think about weight and cost differently.

Complexity

This simply means that, with AM, parts can be designed with more complexity than before. As with all things, however, there are limitations. These parts can more closely follow a load path and, therefore, be lighter or more efficient in carrying load or stiffness.

Design

Sometimes this means adding design details in the form of functional features like cooling channels for tooling. Complex passages can be utilized, because there is no drilling required; therefore, you can manage the critical things like turbulent flow and pressure drops. This can lead to performance advantages when truly optimized. Other performance advantages allow the designer to include features that would otherwise have to be added in a secondary operation.

Durability

The durability of parts can be enhanced primarily through elimination of mating parts or surfaces. Elimination of weldments, brazes, fasteners, etc. create structural inefficiency. Unitization, or the combination of multiple parts via AM, is more efficient and therefore more durable. Increasing durability is also possible through local or bulk additions of new material. Repairing, locally supporting, or adding material has the benefit of making parts that may come in contact with other parts more durable. In some cases, the ability to add material to a specific location efficiently will improve the longevity of the part.

Light Weighting

The ability to make parts lighter than their legacy designs is one of the most exciting elements for engineers when first introduced to AM. Because we are adding material layer by layer, we can achieve lightweight structures. Conventional manufacturing is largely subtractive, meaning it continues to add cost the more we remove material. In AM, you don't pay for material that you don't add.

Social

AM has benefits to society and the environment. Using less material and fewer operations reduces energy consumption, transportation, and logistics costs which have a direct benefit on the environment primarily through the reduction of CO2 emissions.

AM Process Selection

How does an individual or an organization decide on which AM process or processes to use? It will always be a question of commercial and technical requirements. Commercially, we are interested in things like the annual demand or throughput of parts, cost versus the legacy manufacturing method, lead time, supply chain maturity and risk. Technically, the overall size of the part, the detail resolution, the material, part performance, inspection needs, and surface finish factor into which AM process is suitable.

The combination of technical and commercial requirements creates a picture of what has to be true to deploy AM as a method. In one instance it may be as simple as we need a specific material and there are only one or two methods that use that material. In others, the overall size of the part will dictate the process selection. It could be that manufacturing speed and delivery of parts is a key driver as AM processes today still seem quite slow compared to their legacy manufacturing counterparts.

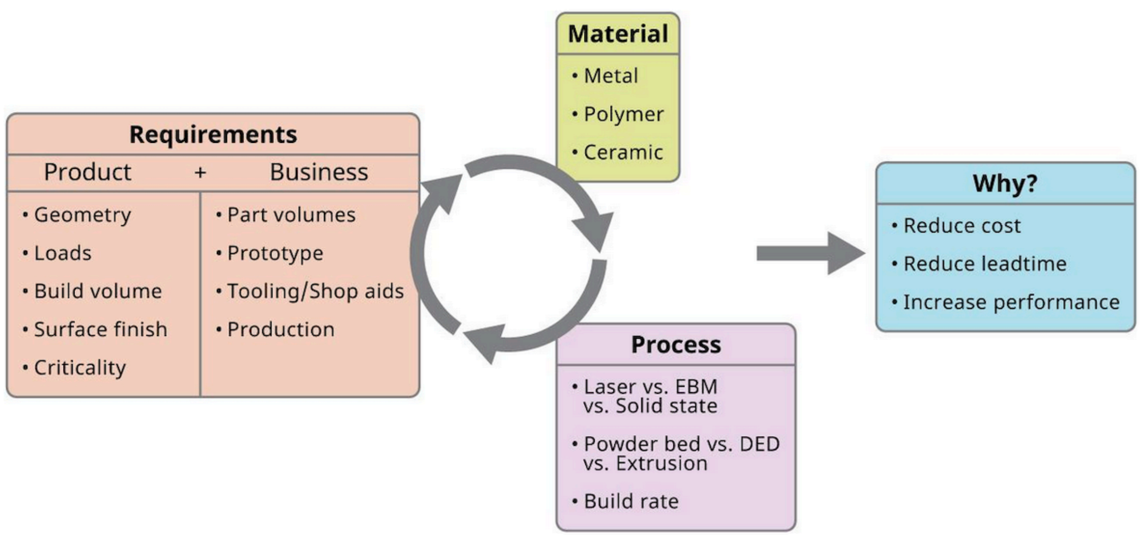


Figure 1.4 Choosing an AM process involves assessing the product and business requirements. Choices of materials and processes lead to the directed outcome, answering the question "why this process?"

AM is Interdisciplinary

Just as AM process selection requires input from multiple groups within an organization, it is imperative that an AM project is also staffed with an appropriate skills mix. AM encompasses multiple fields of materials ranging from polymers to metals and ceramics. Manufacturing specialists will be interested in feedstock and process sensitivities. Design engineers have a newfound sense of freedom to design for complexity, but they need to consider which AM process is going to be used and the associated tradeoffs.

The technical community needs to be engaged early and working with manufacturing, supply chain, and program management which ultimately calls on the leadership to create an environment where the organization can be successful with AM. If all the parties mentioned are not present at some point, the risk of the AM project becomes higher. In Chapter 8 The Business of Additive Manufacturing, we further reflect on the organizational knowledge required for successful AM adoption.

AM in Use Today

AM found early adopters in the Aerospace, Medical and Defense industries. These sectors are distinct as they have a high mix and low volume of parts, meaning they make a low number of a lot of different parts. Tooling is particularly un-economical for this scenario because the tooling amortization becomes a significant component of the per part cost, but often hard to avoid.

The luxury goods and jewelry sectors learned that personalization brought with it a price premium and so have taken AM into the mainstream. Similarly, dental applications are small and bespoke creating a natural fit. Energy sectors have been researching AM for years as they share some similar characteristics to aerospace and in some cases even similar materials. High value, low part quantities drive the Energy sector to avoid tooling solutions when possible.

Figure 1.5 Industries using additive manufacturing can be considered markets for the technology as well as for equipment makers and for fabricators, designers, and other professionals.

Most recently, automotive and heavy transportation have found successful uses. In automotive several factors are converging and driving intense interest in AM:

1. Material substitution has matured and further light weighting now relies on re-design versus simply changing to aluminum from steel, for example.
2. Electrification of cars needs lighter structures due to the mass of the batteries and electric motors.
3. Performance and customization have shown to be a profitable segment using AM to make specialized components for higher end cars, like Formula 1.

All these industries are exploring the ability to create digital warehouses wherever possible to avoid keeping and paying for inventories of costly spare parts some of which may also be facing issues with obsolescence.

Summary

AM is akin to a family of children where each child is a different age and they are not all maturing at the same rate but eventually, they will become strong contributors to society. It is important to keep this kinetic mindset as you progress through the different chapters of the book. Here are four Ds to remember to prepare you for all the new AM technologies and improvements.

- Disruptive – AM doesn't work like previous methods of manufacturing. It is additive by inception which requires different conceptual thinking and design rules.
- Diverse – AM is a family of technologies but if you learn the Simplified View of AM: Layer, Energy and Material, you can likely describe any process.
- Deployed – How an organization deploys AM is important. The TBGA AM Maturity Model provides a conceptual roadmap to build skills and grow the organizational knowledge to successfully adopt AM.
- Developing – Along with the how you deploy AM, the 4 Building Blocks create a successful construct to reduce risk and friction within an organization as AM is inherently interdisciplinary.

Review Questions

1. The Four Building Blocks of AM are:
   a. Layer formation, Energy, Materials and Printers
   b. Machines, Materials, Digital, People
   c. Machines, Materials, DfAM, Innovation
   d. 3D printers, materials, design, people

2. When referring to Machines within the Four Building Blocks, we refer to the 3D printers
   a. True
   b. False

3. AM thinking is a key element of which Building Block?
   a. Machines
   b. Materials
   c. Digital
   d. People

4. True or False, polymers have been used in AM longer than metals and are more mature
   a. True
   b. False

5. Which statement is most correct?
   a. All of the AM processes that can be invented, have been
   b. AM is limited to non critical applications and consumer goods
   c. Management and the organization of people is essential to be successful in AM
   d. DfAM is another term for lattice structures and designs that cannot be made conventionally

6. The best time to start thinking about using AM is
   a. At the concept stage
   b. To make spare parts
   c. When all other good options have been exhausted
   d. With a big budget

7. The 3 dimensional data to make a 3D printed part comes from
   a. Computer Aided Design (CAD) files
   b. 3D scanner
   c. MRI or CT scans
   d. All of the above

8. Which of these statements is most true about the STL file format?
   a. It can only describe the surface geometry of a 3 dimensional object
   b. It is in metric units

c. It is used by the designer to designate features like color and material
d. It is interchangeable with CAD

9. Which of these statements is applicable to the build file?
a. It can be a single part or multiple parts
b. Controlling the build file is important to ensure consistent results
c. It is similar to a manufacturing drawing
d. All of these statements are applicable

10. Which is not a component of the Digital Workflow?
a. 3D model
b. Copy/Paste of CAD for management briefings
c. DfAM
d. The Build file

11. Which is the least commonality of all AM processes?
a. A layer by layer approach
b. Use of powders
c. They can be described with describing the layer, energy and material
d. Starting at the design concept phase

12. Which is not a question used to define any AM process?
a. How is the layer created?
b. How is the energy applied?
c. How is the DfAM applied?
d. How is the material applied?

13. The material in Binder Jetting is applied by which statement?
a. As a glue via the print head
b. As a powder in a bed
c. As a wire or filament
d. As a sheet

14. The material in Directed Energy Deposition is applied by which statement?
a. As a sheet
b. As a powder in a bed
c. As a wire or filament
d. As a powder or filament

15. This statement is true of which AM process? The layer is created by spreading a layer of powder in a bed.
a. Powder Bed Fusion
b. Binder Jetting
c. Material Jetting
d. A and B

16. Which AM process is least compatible with metals?
a. Vat Photopolymerization
b. Material Extrusion
c. Binder Jetting
d. Material Jetting

17. The AM Maturity Model describes an approach to match product requirements and the skills needed to meet them in what way?
a. Go for the biggest return on investment
b. Print any part, any time, anywhere
c. A risk adjusted path to spend money
d. A risk adjusted path for learning as product requirements get tougher

18. In which of the following processes would you expect to find a high-energy laser?
  a. A Directed Energy Deposition system using 100% titanium wire
  b. A Binder Jet system with 98% steel powder and 2% plastic
  c. A Material Extrusion system with 60% steel powder and 40% plastic

19. Which of the following is an example of a Level 2 design?
  a. A clip made via Material Extrusion to test a new design of a prosthetic leg
  b. Spare parts for a railroad car that are out of production
  c. A fully designed for AM hydraulic manifold that has a reduced part count
  d. A rocket nozzle that has internal passages to cool and reduced part count which improve performance

20. Which statement is most true when considering the TBGA AM Maturity Model?
  a. Contemplating the use of both directly manufactured parts as well as tooling to make parts
  b. Mimicking a current part is a good example of a Level 4 design
  c. Level 4 is where the most value is and the where efforts should begin
  d. It is methodology for an organization to match its product requirements to its competitors

21. The Project Management Triple Constraint is
  a. Schedule, Scope and Labor
  b. Cost, Scope and Value
  c. Schedule, Scope and Cost
  d. Performance, Schedule and Budget

22. Which was not discussed as a use case for employing AM?
  a. Speed – AM improves time to market
  b. Complexity – Design freedoms allow for complex designs
  c. Durability – Consolidating parts eliminates joints
  d. Cost – Use AM to apply pressure on current vendors

23. True or False: When choosing an AM process, only technical requirements are used.
  a. True
  b. False

24. Which of the following is not a good example as an important consideration on how to choose an AM process?
  a. The surface finish attainable
  b. The part must be made from Ti 6Al4V
  c. The company owns a Powder Bed Fusion machine
  d. The annual demand is 865 parts a year

25. Of the AM process types discussed, which of the following is the best list of those that use powder in any way as a feedstock?
  a. Powder Bed Fusion, Binder Jet Processing, Directed Energy Deposition, Material Extrusion, Material Jetting
  b. Powder Bed Fusion, Binder Jet Processing, Directed Energy Deposition, Material Extrusion, Vat Photopolymerization
  c. Powder Bed Fusion, Binder Jet Processing, Directed Energy Deposition
  d. Powder Bed Fusion, Binder Jet Processing, Directed Energy Deposition, Material Extrusion, Vat Photopolymerization, Material Jetting, Sheet Lamination

26. Materials Engineers are important team players in AM because they can contribute to which of the following?
  a. Assessing the impact of property anisotropy, or if printed parts will exhibit different properties in the build or vertical direction
  b. Applying materials science as to whether a polymer material can be used in Material Extrusion
  c. Assessing the necessity of post build processing to meet requirements
  d. All of the above

27. Design Engineers are an important AM team player as they contribute to which of the following?
  a. Cost through minimizing print time with efficient designs
  b. Cost by taking into account post processing up front

c. Cost and performance by optimizing build file
d. All of the above

28. What differentiates Material Extrusion from the other AM processes?
a. Can be plastic or metallic
b. The material is deposited through layers in the X and Y direction
c. The material is extruded through a nozzle, die, or orifice
d. All of the above

29. Which is a true statement?
a. All AM processes are about the same level of maturity
b. There is one AM process that will ultimately be chosen as the best
c. AM is dynamic and growing rapidly
d. AM will replace most of manufacturing in the next 20 years

Discussion Questions

30. What is the primary distinction between 3D printing and Additive Manufacturing?

Key Terms

1.1 The Components and Processes of of Additive Manufacturing

STL

1.2 Additive Manufacturing Processes

Binder Jetting, Material Extrusion, Directed Energy Deposition, Material Jetting, Powder Bed Fusion, Sheet Lamination, Vat Photopolymerization

2 CORE AM TECHNOLOGIES AND SUPPORTING PROCESSES

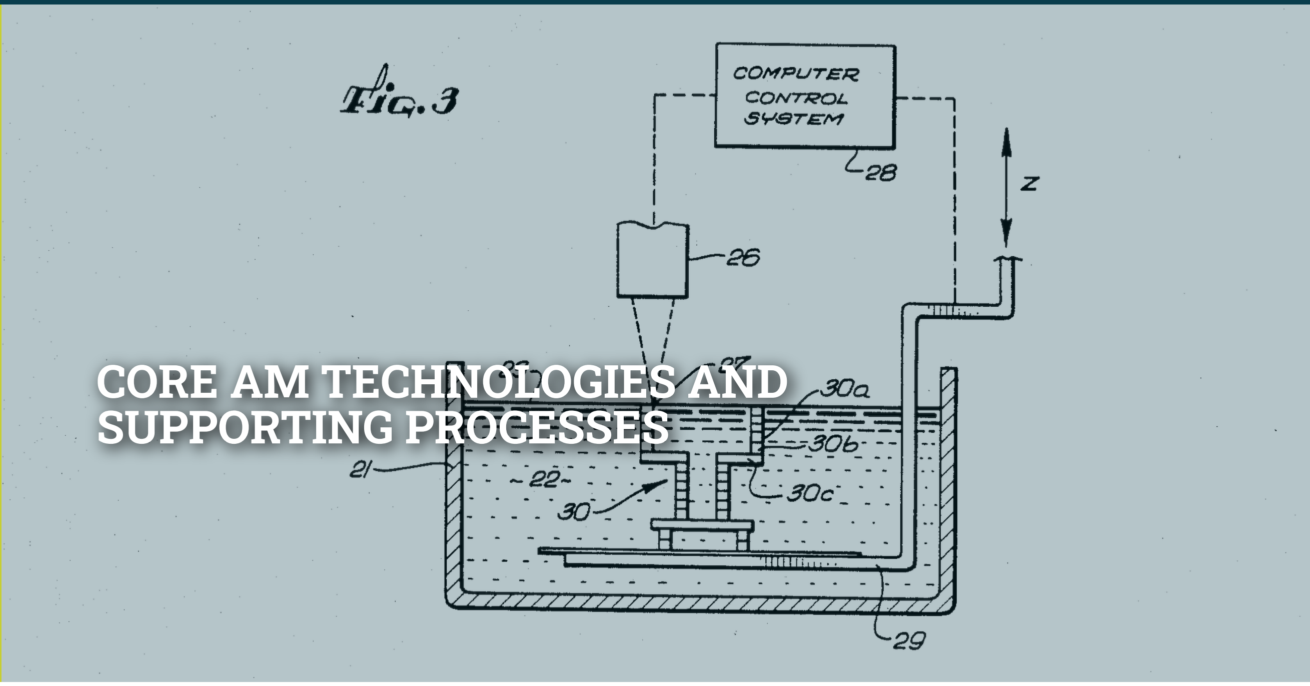


Figure 2.1 The Patent that ignited an industry. Chuck Hull's patent titled, "Apparatus for production of three-dimensional objects by stereolithography" became the first commercial patent associated with a new technology known as stereolithography. Stereolithography, as a process, was the beginning of modern additive manufacturing and is still largely used today for prototyping and other applications in thousands of factories, schools, and other environments. (Credit: Charles A Hull, Patent US4575330, retrieved from https://patents.google.com/patent/US4575330A/en)

Chapter Outline

Introduction

Within this chapter, we will walk through the various technologies and supporting processes used in additive manufacturing. These will include additive polymer, metallic and ceramic processes. In addition, we will present supporting technologies that transform AM from initially fabricated object to the completed part.

2.1 Processes and Process Organization

Learning Objectives

By the end of this section, students will be able to:

- Describe the basic categorization of AM technologies originally developed by ASTM.
- Describe the limitations of ASTM definitions.
- Apply the AM subfunctions.

During the early 2000s, engineers were continually inventing new AM machines and technologies. With each new development, they brought forth a new process with specific advantages and disadvantages in relation to others that already existed. These new AM technologies required different types of energy sources, feedstocks, and material types, and it soon became confusing for people – even those with deep expertise and experience – to understand exactly what type of AM was being discussed.

To solve this confusion, in 2012, the American Society for Testing and Materials **(ASTM) F42** committee defined seven categories of AM processes, as follows:

- **VAT Photopolymerization** - process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization
- **Material Jetting** - process in which droplets of build material are selectively deposited
- **Binder Jetting** - process in which a liquid bonding agent is selectively deposited to join powder materials
- **Material Extrusion** - process in which material is selectively dispensed through a nozzle or orifice
- **Powder Bed Fusion** - process in which thermal energy selectively fuses regions of a powder bed
- **Sheet Lamination** - process in which sheets of material are bonded to form a part
- **Direct Energy Deposition** - process in which focused thermal energy is used to fuse materials by melting as they are being deposited

By grouping AM technologies into seven different types, it became easier for people to understand exactly what type of AM technology was being described. However, the development of process variants and hybrid AM processes began to accelerate at an unprecedented pace. By 2019, processes were being created that did not fit neatly into the seven categories.

To maintain the classification method and develop a more logical way to differentiate between the technologies, experts began looking at the AM process itself in combination with the subfunctions are used to create a part. Specifically, how each **Layer** is created, where or how the **Material** feedstock is added to the layer and what **Energy** source is used during the process.

Additional post-processing and, sometime, *Densification* steps, described below, may also be required for some processes. Table 2.1 defines the options for each of these technologies and how often they are required.

	Remove Supports or Substrate	Subtractive process for Dimensions	Process for Surface Finish	Process for Material Density	Heat Treat/Cure for Material Performance
Vat Photopolymerization	Very often	Rare	Sometimes	Rare	Sometimes
Material Extrusion	Very often	Sometimes	Sometimes	Rare	Rare
Power Bed Fusion	Very often	Sometimes	Sometimes	Rare	Very often
Directed Energy Deposition	Sometimes	Sometimes	Sometimes	Rare	Very often
Material Jetting	Very often	Rare	Sometimes	Sometimes	Rare
Binder Jetting	Rare	Sometimes	Sometimes	Sometimes	Very often
Sheet Lamination	Very often	Sometimes	Rare	Rare	Rare

Table 2.1 Overview of downstream processing requirements for each AM process (Original data compiled by TBGT).

For example, the Material Extrusion process is characterized by: a) wire material feedstock commonly known as filament, b) mechanical fusion from a nozzle, using c) liquification as the means to push the feedstock through the nozzle, resulting in a d) fully dense part. By deconstructing AM processes into three distinct subfunctions of material, layers, and energy sources, and an optional fourth, densification when required, an unlimited number of AM processes can be mapped that stretch beyond the limits of the limited ASTM process definitions.

Energy Source

The **energy source** subfunction describes how the AM process initiates to create a chain of events that produces AM hardware. Using thermal energy and/or pressure overcomes the material flow stress to change the physical characteristics of the material feedstock. This can be accomplished using a number of different technologies, these include:

- **Laser**, which is a device that emits a special type of light that can be focused in a tight spot.
    - Nd:YVO_4 (aka UV): Used in commercial SLA machines to generate ultraviolet laser energy
    - Nd:YAG: Used in some metal powder bed fusion machines. Typically, older machines CO_2: Used in SLS polymer machines
    - Yb-fiber: Used in most metal powder bed fusion machines and DED blown powder or wire fed machines
- **Plasma**: Similar to conventionally manufacturing process known as plasma arc welding (PAW), AM machines have been outfitted with PAW deposition heads to build up freeform structure
- **Fluid Flow**: Spouts a liquid that is made up of nanoparticles of ceramic or metallic material to freeform build a part. This category may include low pressure and temperature deposition process that deposits a variety of materials through an inkjet printing head system. Materials could be conductive for circuitry or polymer based.
- **High Pressure Gas**: A gas is compressed at a high pressure to act as a catalyst to the remaining process.
- **Electrical Resistance**: An energy source that opposes the flow of electrical current in a circuit, thereby converting electrical energy to thermal energy
- **Compression**: The phase transformation of a solid material to a liquid typically through a compression and/or material sheering in a heated process.
- **Electron Beam**: A discharging of a stream of electrons generated by magnetic and electric fields

Material Feedstock

Material feedstock is defined as the raw material form factor that is used at the beginning of the AM process, that is ultimately, physically transformed by the energy source. These may be in the forms of the following:

- **Liquid**
    - Epoxy based photopolymer
    - Nano particle slurry
- **Powder** Either metallic or polymeric
    - Stationary before the energy source is applied
    - Dynamically moving when the energy source is applied
- **Wire** Typically, in the form of conventional welding wire that is ordered in spools
- **Polymer filament** A polymer monofilament feedstock that comes in spools
- **Pellets of polymer** Similar to injection molding feedstock. Resin pellets created specifically for engineering plastic applications
- **Sheets** Sheets or foil made from metal, plastic, paper or other fibrous material

Figure 2.2 Additive manufacturing process materials come in many forms, including powder and liquid. (credit: Modification of "Additive manufacturing process material" by Oak Ridge National Laboratory/Flickr, CC BY 2.0)

Layer Creation

Once the raw material is physically transformed into the AM processing material form factor, new layers are created during the AM process fabrication. As such, the layer is created with the energy and material coming together at a focused point. The following are ways that AM layers are formed:

- **Curing**: A change in physical state of transformation within a material. The material is hardened by a cross linking of polymer chains typically from a liquid solution to a solid.
- **Welding**: Joining of additive layers using high thermal energy to melt the feedstock together thereby creating a fusion of metallic or polymer layers into a homogenous structure
- **Mechanical fusion from nozzle**: Joining liquified polymer material together by welding a heated bead of material to an already cooled region of polymer material
- **Kinetic energy**: The successive buildup of layers by impacting new material on top of previously impacted material to form a thick coating or structure
- **Ultrasonic energy**: The bonding of materials using an ultra-high frequency sound waves that is vibrates material thereby merging feedstock together to form a mechanical layered bond
- **Friction**: The use of a tool or rotating body to locally increase temperature of a mater to allow solid state bonding.

For some of the layer creation method, a material other than the feedstock can be applied. For example, a low-melting polymer powder used to fuse sheet materials together, an agent that increases the feedstock's ability to absorb energy and fuse, or that prevents fusion for control of features.

Full Densification

Though not a strict definition, full densification is an aggregate of each layer creating hardware that results in a structure which is greater than 99.5% dense directly from the machine without post-processing steps being necessary. These post-processing steps would include other non-AM related processes such as sintering, ultraviolet curing, etc. In the densification sub function, it is a binary decision. Will the part that is removed from the AM machine exhibit 99.5% microstructural density or not?

2.2 Vat-based Processes

Learning Objectives

By the end of this section, students will be able to:

- Provide a baseline description of vat-based AM processes.
- Differentiate based on the nuances of SLA, DLP and LCD technologies.

Stereolithography (SLA) is the most common vat-based process. It has traditionally held the title of being one of the oldest 3D printing technologies still on the market and continued to be used daily throughout medical, industry and educational sectors. The SLA vat size ranges from $100mm^3$ to 2100 x 700 x 800 mm.

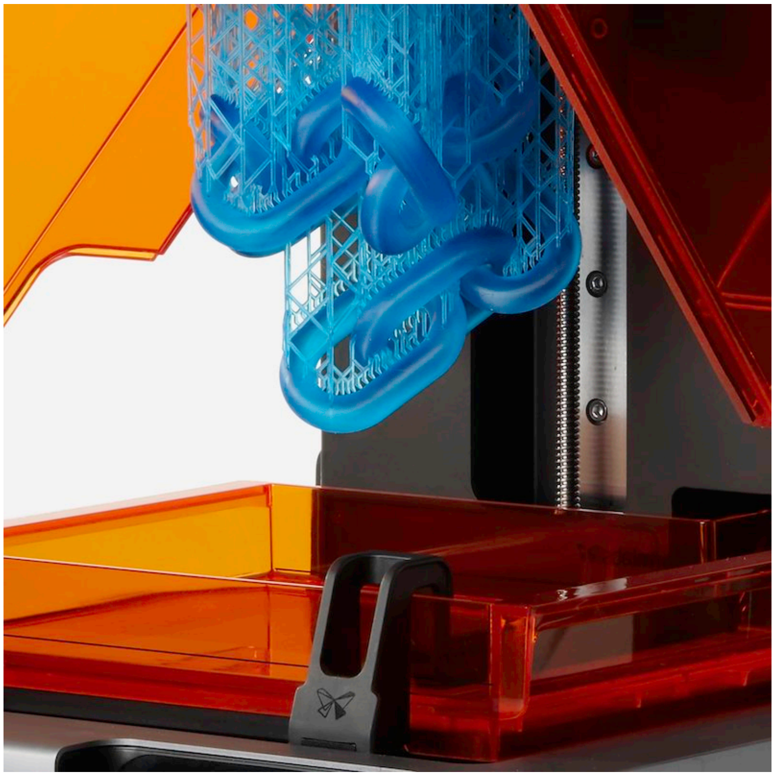


Figure 2.3 SLA parts with supports SLA parts constructed with support material. The thicker oval chain links are the parts being created ,and the thinner lattice structures above the chain links are the support materials. (credit: Modification of “A Functional Chain Printed on a Formlabs Form 2 SLA 3D Printer” by Formlabs/Flickr, CC-BY 2.0)

Derivative technologies to SLA include Digital Light Projection (DLP) and Liquid Crystal Display (LCD) masking systems. **DLP** is an AM process where a projector screen is used to cure photopolymer resin by projecting pixels of light using a digital micromirror device. **LCD**, also known as *masked SLA*, uses a liquid crystal display to mask projects one full layer at a time using UV light emitting diodes as a light source. Resolution on the XY axis depends on the LCD screen pixel size. We will highlight each of the major characteristics of each 3D printing subsystem to distinguish the difference among the processes (SLA, DLP, LCD).

Material Feedstock

Generally, SLA, DLP, and LCD use similar materials: ultraviolet-sensitive photo curable liquid resins. The UV sensitive liquid material is filled in a tank, or vat, which holds the material. The type of liquid resin depends on the size of the machine and the machine’s UV laser wavelength energy. For example, the small desktop SLA systems have a laser wavelength of approximately 395 nm.

Material options include:

- ABS-like
- Polypropylene-like
- Epoxy
- Polyurethane
- Silicone

- Cyanate Ester
- Urethane Methacrylate

Once the laser discharges into the material feedstock, a solid structure is formed layer upon layer. The resultant part is considered a "green part," whereas it is not at full material strength. Green parts are removed from the vat and post-processed in a UV light chamber to reach full material strength.

DLP energy systems use a wavelength ranging from 400 nm up to 680 nm. Due to the differences in wavelengths, the UV sensitive liquid that is held in the vat must be compatible with the DLP system.

Similarly, LCD energy systems use a wavelength from 405 nm for UV-based versions and royal blue 450 nm for daylight versions.

In summary, SLA, DLP and LCD all use a vat-based material feedstock system with similar material types, however, the feedstock itself must be compatible with the light wavelength for each respective technology to produce optimal parts.

Energy Sources

SLA: As discussed in the material section, for SLA systems, the energy source is a UV laser. The energy from the laser partially cures the liquid material, and the specific wattage varies from the large industrial SLA machines that can have up to 800mW to the small desktop machines of 400mW. The laser spot size governs how small of features one may be able to print and is steered in the X-Y plane by a set of galvanometer mirrors

DLP: The DLP systems cure resin with a much different approach than the laser SLA systems. The digital light projector flashes images of layers onto the vat. A digital micromirror device (DMD) selectively directs the light. DLP printers produce layers made up of "voxels" the 3D equivalent of pixels"

LCD: LCD technology is similar to DLP, with the light flashing images with LEDs. In this case, a screen reveals only the pixels necessary for the current layer. The screen eliminates the need for a special device to direct the light.

Process Architecture

SLA: The platform lowers by a layer thickness and a vacuum pumping smooths out any disturbances in the surface of the liquid material using a metal re-coater blade. There are two distinct approaches to the build plate. Some SLA technologies have a platform dropping, top-down laser approach, other SLA technologies have a platform lifting, bottom-up projection. For clarity regarding the distinction, reference the images below.

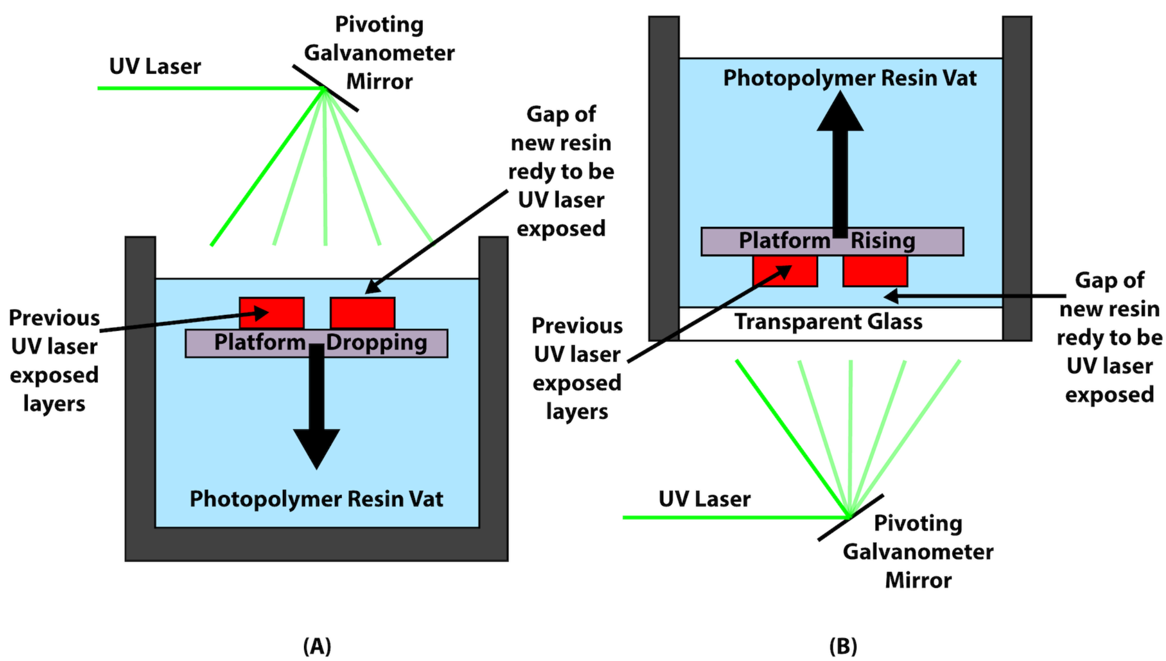


Figure 2.4 (a) SLA platform dropping approach (b) SLA platform raising approach

No matter if the build platform raises up during fabrication or lowers, the basic machine anatomy is made up of:

- Laser/Light Source
- Mirror/Scanning Galvanometers

- Build Platform and Motion System
- Vat (Liquid Resin)
- Computer / HMI

The laser beam is columnated through a series of optics and steered directionally into the vat of liquid resin using scanning galvanometers as shown. The liquid resin is temporarily cured using a process known as photopolymerization.

DLP and LCD: DLP and LCD processes exhibit the same processing architecture as SLA machines and may also be platform dropping or platform raising. However, the major difference between SLA and DLP/LCD is the energy source, which is less expensive to manufacture for DLP and even less expensive for LCD. As highlighted in the DLP energy sources subsection, DLP technology uses tiny mirrors to project an image, while the LCD machines project LED based light energy.

Part removal

SLA, DLP and LCD: All SLA based processes may require sacrificial support material to be designed into the part to support features of a part. This supporting material will be in either tension for platform lifting machines or in compression for platform dropping machines. In either condition, extreme care must be taken to gently remove the support material after curing.

The actual parts fabricated during the SLA, DLP or LCD process may go through a rinsing system after fabrication to remove all loose resin from the part before being placed in a UV light booth for final curing.

2.3 Powder Bed Processes

Learning Objectives

By the end of this section, students will be able to:

- Understand the foundation of:
  - Powder Bed Electron Beam.
  - Powder Bed Fusion Laser Metal.
  - Selective Laser Sintering Polymer.
  - Binder jet.

Powder Bed Fusion Laser Metal System Architecture

For metallic powder bed systems, the basic machine architecture consists of the following:

- Powder Distribution System
  - Powder Feed Tank or Hopper
  - Roller, Rake or Knife
- Heat Source and Control System
  - Laser with Optics
  - Electron Beam with Magnetic Coil
- Build Platform and Motion System
- Build Plate
- Gas System or Vacuum Chamber
- Computer / HMI

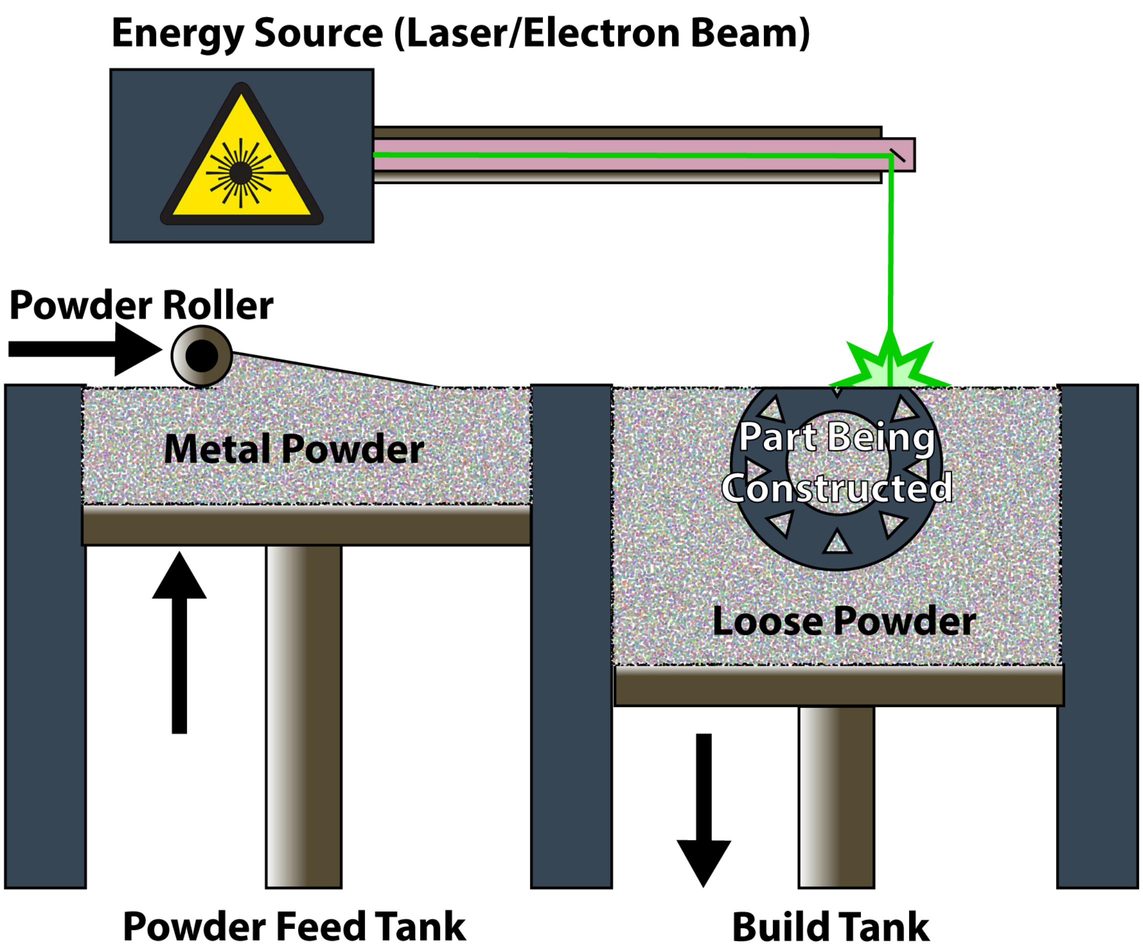


Figure 2.5 Basic architecture of a metal powder bed fusion machine

Recoating systems

The recoating system is a critical aspect of powder-based AM processes. It ensures that the layer is uniform and even, and it controls the thickness of the layer. Recoating, then, influences the structure, shape, and function of the part. Common recoating systems are described below.

- **Roller** - The roller system, offered in a few powder bed fusion laser metal systems, affords the ability for consistent powder spreading without risk of catching on previously melted features that may have heaved out of the powder during fabrication. In some systems the roller additionally provides a downforce that compacts the powder bed, which is useful in materials systems that have some degree of compressibility.
- **Hard knife blade** – While not as forgiving as the roller, this system is found in most powder bed fusion laser metal systems and electron beam melting systems and is made of a blade that spreads the powder evenly. This offers superior powder spreading consistency over the roller method. Blades can be made of several different materials from hardened steels, to erosion resistant cobalt alloys such as stellite to ceramics.
- **Soft gasket wiper blade** - Offered as an option on many powder bed fusion laser metal systems. This type of system acts as a hybrid approach to powder spreading by allowing for superior powder spreading, while at the same time, remaining flexible enough to accommodate the occasional feature heaving from the powder bed during fabrication.
- **Dosing wheel systems** – This system is designed to dose, or drop a measured amount of feedstock material over the bed as the recoating system traverses the print bed. Dosing is coordinated with the motion of the recoating mechanism so each area of the bed receives a uniform dose. Dosing wheel systems are often followed by a soft gasket-style wiper blade to ensure uniformity. As designed today, dosing wheel systems can require feedstocks with high flowability requirements than the other recoating system styles.

Energy sources

- Laser: The **Yb-fiber laser** is by far the most common laser found in commercial metal powder bed fusion machines. Depending on the relative scale of the machine, this laser can be specified from 100W to 1000W. Other lasers for

specific applications, like green for printing copper are available.
- Electron Beam: The **electron beam gun** is used in powder bed electron beam machines. This gun is capable of over 3000W of electron energy for metallic fusion, and consists of a filament used to generate electrons, and a strong magnet used to accelerate them towards the build layer.

Material Feedstock

Typically, the powdered material used to date for both laser and EBM systems are different in terms of the powder particle size distribution range. Most Laser Powder Bed Fusion users specify finer PSDs, such as 15-45 microns, whereas EBM powder lots are typically specified at larger PSD ranges, such as 45-105 microns. This is because the EBM process runs at an elevated temperature, and fine powders have a higher driving force for sintering which results in powder cake that is difficult to exhume parts from.

Common materials used in metal powder bed fusion laser machines include Aluminum, Tool Steel, Cobalt Chrome, Copper, Nickel Alloys, Tungsten, Stainless Steel, and Titanium.

Common materials used in metal powder bed electron beam machines include Titanium, Cobalt Chrome, Niobium, Pure Copper, and Nickel Alloys.

Selective Laser Sintering – Polymer System Architecture

For Selective Laser Sintering – Polymer Systems, the basic machine architecture consists of the following:

- Powder Distribution System
  - Powder Feed Tank or Hopper
  - Roller or Hard Blade
- Heat Source and Control System
  - Laser with Optics
- Build Platform and Motion System
- Build Plate
- Gas System
- Computer / HMI

Recoating systems

- Roller - The roller system, used in SLS systems, affords the ability for consistent powder spreading without risk of catching on previously melted features that may have heaved out of the powder during fabrication.
- Hard knife blade – While not as forgiving as the roller, this system is found in EOS SLS systems and is made of a hardened steel blade that spreads the powder evenly. This approach offers superior powder spreading and layer thickness consistency over the roller method.

Energy sources

The energy source for the polymer SLS systems is a CO2 laser. In CO2 lasers, the gas CO2, fills a tube electrified using a DC or AC current to induce the lasing. 10.6 µm is the most widely used wavelength for SLS polymers.

The laser wattage specified for polymer SLS machines can vary depending on the specific polymer being fused, but a range between 20-50W will typically cover most of the polymer powders commercially available.

Material Feedstock

Though not as stable in wattage as fiber lasers, the wavelength of the CO2 laser offers compatibility with the semi-crystalline polymers used in SLS. Therefore, the commercially available materials used in the SLS process are the following semi-crystalline polymers:

- Semicrystalline
  - Polyamide
  - Polypropylene
  - Polyaryletherketones

There are also limited cases of amorphous polymers being printed in SLS. These include:

- Amorphous
  - Elastomers
  - Polystyrene (used for indirect tooling patterns)

Binder Jet Technology System Architecture

ASTM defines **binder jet technology** as an additive manufacturing process in which liquid bonding catalyst is selectively deposited to join powder materials. Once joined, the parts are fired in a sintering oven to melt out of the bonding catalyst and form a dense part. For binder jet machines, which range from machine size from 100mm3 to 10m3. The basic machine architecture consists of the following:

- Powder Distribution System – Powder Feed and Leveling Roller
- Binder Printhead
- Build Platform and Motion System
- Build Plate
- Computer / HMI

Recoating system

- Roller - The roller system, typically used in direct manufacturing systems, affords the ability for consistent powder spreading from the feed bin.
- Blade – Blade based systems are common in the sand and aggregate printing used in the foundry industry. These systems typically consist of a moving hopper containing the aggregate. The hopper deposits the aggregate on the powder bed, and connected hard recoater blade that ensures good layer uniformity. Vibration and/or rotary distribution systems are used to uniformly fill the moving hopper.

One of the biggest advantages to using binder jet technology is that no sacrificial supports need to be produced with the parts. The powder itself self supports part made from the process.

Energy source

The energy source used for binder jet printing is the ink jetting process itself. The ink jet deposition from the print head flows droplets of a catalyst material that acts like a glue to 'bind' the catalyst material to the raw material loaded in the powder bed.

Material Feedstock

As the binder jet process requires no heated physical transformation, a number of different materials are available for printing. The following list of materials are commercially available for binder jetting:

- Ceramics
    - Silicon Carbide
    - Alumina
    - Zirconia
    - Boron Carbide
    - Silica
    - Sand
- Metals
    - Titanium
    - Tool steel
    - Stainless steel
    - Inconel
    - Tungsten
    - Tungsten Carbide

Curing

In many binder jet processes, the printed part contains binder that is partially cured during the print process. This is known as the brown stage. In order to develop sufficient binder strength to be able to handle the parts, the entire build box is thermally cured in an oven at moderate temperature (between 100 and 300 C). After curing the parts are in the green stage, and can be removed from the build box.

De-powdering

De-powdering is the act of removing unfused powder from fused powder and is typically accomplished by vacuuming of the unbound material out of the print bed, followed by layerwise removal of the printed objects.

Debinding, Infiltration and Sintering

For direct manufacturing operations, after printing is complete, the parts are placed in a high temperature furnace for either the process of infiltration or sintering. Because the binder content is typically less that 5% by weight, a separate de-binding step is rarely used in BJP processes. Once parts are in the furnace, the binder is melted out burned or vaporized from the part early in the thermal cycle, and separated from the raw material powder, leaving voided areas. This is what is known as **debinding**. At this point in the process, the part exhibits between 50%-75% porosity, depending on the density of the powder bed, and initial binder content.

- **Infiltration** - In infiltration another material is introduced, such as bronze, that wicks into the part void areas, resulting in lower porosity. The infiltrated material has typical mechanical properties between the base material and the infiltrate so is used for prototyping, art pieces and consumer products like jewelry.
- **Sintering** - Alternatively, the part is placed in an even higher temperature furnace directly after de-powdering to go through a sintering process. During early stages in this process, the raw material powder is fused together, and as temperature increases begins the process of densification. Densification can be thought of as a process whereby the individual powder particle centers move towards each other, resulting in a shrinkage of the part. As the part densifies, the porosity present after printing curing and de-binding is eliminated, resulting in a solid piece of the printed material.

During these secondary processes, it is important to note that significant shrinkage of the part will occur. Shrinkage may be as much as 20%-30% by volume if sintering process is used, whereas if the infiltration process is used, shrinkage may only be 1- 3% of the part volume.

Hewlett Packard has commercialized a binder jet technology known as Multi Jet Fusion (MJF). MJF is similar to traditional binder jet processes, however, with two notable differences. 1) the materials used in MJF are nylon polymers instead of metal and ceramic 2) the parts are heated at each layer of fusion, therefore eliminating any post-processing step.

Like all binder jet processes, MJF affords the ability to rapidly produce a large quantity of plastic parts, nested in all three dimensions within the build chamber, without the need for sacrificial support structures. As such, this technology is meant to compete more with the injection molding industry, but with the notable difference of being able to print complex parts that may be difficult to injection mold.

2.4 Liquid-Addition Processes

Learning Objectives

By the end of this section, students will be able to:

- Understand material jetting.
- Comprehend slurry-based AM systems.
- Grasp the concept of direct ink write systems.

Material Jetting System Architecture

Material jetting is an AM process in which droplets of specialized materials sometimes referred to as ink are selectively applied to a build surface. The layer is typically cured using UV light, and the process repeats itself to construct the 3D object. The size limits of the machines can range from 500mm3 to 1200mm3. The basic machine architecture consists of the following:

- Jetting Head
- UV Lamp
- Build Platform and Motion System
- Build Plate
- Roller
- Computer / HMI

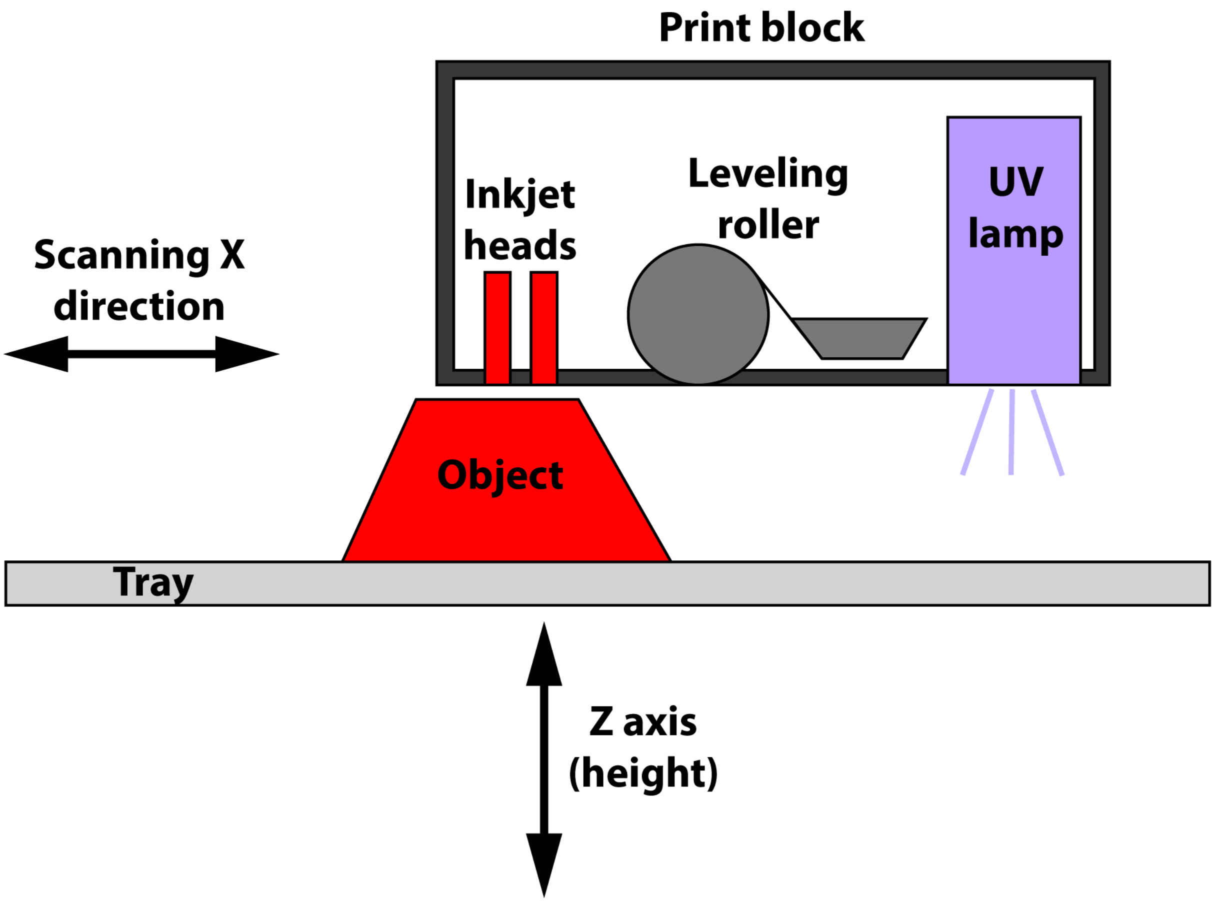


Figure 2.6 Material jetting system architecture

Material Feedstock

- Polypropylene
- ABS
- Acrylic thermoset photopolymers
- Nano ceramics
- Electrically conductive nano metal particles

Slurry based system architecture

The sustainable and affordable housing industry has adopted **slurry-based AM** as a way to make quick housing on the worksite using cement deposited on a very large gantry system. Cement is fed as a slurry into a deposition head that is suspended from a gantry to additively construct housing.

By fabricating homes at the worksite, may pre-fabricated labor and shipping steps are eliminated, thereby making the homes more affordable.

Figure 2.7 AM structures can be created by a deposition head suspended from a gantry system. The system prints the cement or other material layer by layer from the ground up, with the gantry lifting the system as the layers are deposited. (credit: Modification of "The Tecla as of 2021," by Alfredo Milano/Wikimedia Commons, CC-BY 2.5)

Direct ink-writing system architecture

Direct ink writing, also known as aerosol jetting or robocasting, is a process that allows for the additive manufacturing of functional electronics. In this process, a conducting ink made from silver or copper sprays 1 to 5 micron droplets onto a surface using an atomizer to create an aerosol mist that moves to the deposition head. In many cases, the machines capable of doing this work also operate on a 5 axis platform. This allows for direct writing of circuitry on conformal surfaces. This aerosol spray can apply the conductive ink to a variety of substrates. Features can be from 10 microns to a few millimeters in scale. Individual layer thicknesses can range from 10nm to greater than 10 microns. The basic machine architecture consists of the following:

- Deposition Head
- Atomizer
- Sheath Gas
- Build Plate
- Ink Material Feed
- Computer / HMI

2.5 Molten Material-Addition Processes

Learning Objectives

By the end of this section, students will be able to:

- Understand EBM wire technology.
- Comprehend DED blown powder technology.
- Grasp the concept of DED wire fed technology.
- Realize both large and small scale polymer material extrusion.

EBM wire process architecture

The **Electron Beam Melting wire process** is used to melt metal wire feedstock with an EBM gun that discharges directly in the melt weld pool. This entire process takes place inside of a vacuum chamber. The resultant weld pool is approximately 3/8" wide and must be machined after being fabricating. Gross deposition rates range from 7 to 25 lbs. of metal per hour depending on the specific metal selected. The EBM wire process machines are quite large, existing machines scaling to 19ft x 4ft x 4ft, and the process is not size constrained. After feature deposition on the build plate substrate, the resulting structure is stress relieved and machined to the final shape.

Relative to traditional hog-out machined parts, the advantage of using EBM wire to construct parts includes:

- Less material wasted during fabrication
- Less processing time incurred during fabrication

The typical machine architecture consists of the following:

- Wire Feed
- Electron Beam Gun

- 3 Axis Gantry
- Vacuum Chamber
- Build Plate Substrate
- Melt Pool Closed Loop Control Optical Feedback System
- Computer / HMI

Material Delivery System

The material delivery system consists of a mechanism that feeds common welding wire feedstock through a feeding system. Similar to traditional welding systems, the feed system is installed at an angle to provide the optimum material fusion upon electron beam welding

Energy Source

An electron beam gun is used to provide the energy to the workpiece. The electron beam gun used in this process uses a high powered laser, ranging up to 42kW. Coupled with the feedstock, this energy creates a weld pool on the surface of the workpiece.

Metal Wire Feedstock

Example wire materials that are used in this process include:

- Titanium
- Inconel
- Tantalum
- Tungsten
- Stainless Steel
- 4340 Steel
- Aluminum
- Zircalloy

DED blown powder process architecture

DED blown powder process architecture is defined as an additive manufacturing process in which a laser source, attached to a gantry, melts a weld pool from a feedstock of free-flowing powder typically being discharged from a coaxial deposition head. In addition to constructing freeform geometry, DED blown powder is often used as a weld repair cladding process to efficiently laser weld cracked surfaces on various metallic structures. This entire process takes place inside of an Argon filled low pressure chamber. The resultant weld pool can range from .065” - .100” wide and exhibits a rough surface similar to a casting. The DED blown powder process machines can range in scale and capability. Some of the larger machines commercially available displays a build volume of up to 5ft x 5ft x 7ft. Hybrid DED blown powder machines are also commercially available. These machines have the ability to build layer by layer similar to a traditional AM machine, but also include the ability to stop between deposition and machine away the previously deposited surface, thereby leaving a very smooth surface finish.

The basic machine architecture consists of the following:

- Powder Feed Mechanism
- Deposition Head
- Laser
- 3 Axis or 5 Axis Gantry System with Articulating Table
- Argon chamber
- Baseplate Substrate
- Optional Mill Cutting System for Hybrid Machines
- Computer / HMI

Material Delivery System

Metallic powder is pressurized through a series of tubes to a coaxial deposition head, where a stream of powder is evenly distributed onto the surface of the workpiece. Only about 25% of the feedstock is melted during the deposition process, with the remaining 75% of material being recycled.

A unique aspect of the DED blown powder process is the ability to include multiple powder feedstocks at different rates into the deposition head, thereby creating a functionally gradient weld system within a part.

Energy Source

DED blown powder processes use a solid state IPG laser system. Smaller systems contain 2-3kW lasers, where some of the larger machines can showcase up to 4kW laser systems. The DED blown powder process are easily capable to scaling to much larger sizes and laser wattages will scale in relation to the machine sizing.

Metal Powder Feedstock

Like all powder based additive manufacturing technologies, the particle size distribution, morphology and flowability are key variables in maintaining a quality powder. Compared to laser powder bed material and EBM, the optimum particle size distribution range for DED blown powder is much coarser and is typically between 20-200µm.

Typical materials used in DED blown powder machines include:

- Nickel Alloys
- Cobalt Chrome
- Stainless Steel
- Titanium

DED wire fed process architecture

DED wire fed process architecture is defined as an additive manufacturing process in which a plasma arc discharging from a deposition head is attached to a gantry. This melts a weld pool from a feedstock of welding wire typically being fed from the side of the deposition head. This entire process takes place inside of an argon filled low pressure chamber or alternatively, shielded gas provides the appropriate environment to retard oxidization. The resultant weld pool can range from .125”-.250” wide and exhibits a rough surface similar to the EBM wire fed process. The DED wire fed process machines can range in scale and capability. Some of the larger machines commercially available exhibit a build volume of up to 6ft x 1.25ft x 2ft.

The basic machine architecture consists of the following:

- Wire Feed Mechanism
- Deposition Head
- Optional Pre-heat head
- 3 Axis or Gantry System
- Argon chamber or gas shielded deposition head
- Baseplate Substrate
- Optional Mill Cutting System for Hybrid Machines
- Computer / HMI

Material Delivery System

Metallic welding wire is fed through a series of pinch rollers to a deposition head, where a plasma arc flows the molten metal onto the surface of the workpiece. As with all AM systems, layers of newly deposited material are placed on top of previously deposited layers, thereby building up structure.

Energy Source

Similar to traditional welding, DED wire fed processes use a plasma arc energy source to deposit the material. Specifications for each plasma deposition head may vary between 50 to 350 amps and voltage from 27 to 31 volts. On some systems two multiple plasma arc heads are used. One head for preheating the baseplate substrate, while the other head is used for material deposition. This approach limits the amount of distortion of the baseplate during part fabrication. Similar to DED blown powder, the DED wire fed process is easily capable to scaling to much larger sizes and the amount of plasma arc heads will scale in relation to the machine sizing.

Metal Welding Wire Feedstock

Much more cost effective than powder based additive manufacturing technologies, the welding wire used in DED wire fed processes reduces production costs substantially. Commercial grade off the shelf welding wire may be used which can vary in diameter from .025”-.120” and price based on the material type.

Typical materials used in DED wire fed machines include:

- Steel
- Titanium

Small scale polymer material extrusion process architecture

One of the most common desktop AM technologies, **small scale polymer material extrusion** machines are available in very small scale for hobbyists (4” x 4” x 6”), and larger scale (39” x 39” x 39”) for industrial applications, and a range of sizes in between. Also known as Fused Deposition Modeling (FDM), this technology uses amorphous polymer filament as a feedstock. The feedstock is liquified in a deposition head which moves in the x-y plane, depositing the polymer material. The part is built upon a table that moves in a z direction. Variant machines also exist that allow for the build plate to move in y axis and the deposition head to move in the x and z axis.

The basic machine architecture consists of the following:

- Material Feeder
- Heated Head/Nozzle
- Build Platform and Motion System
- Build Plate
- Computer / HMI

Delivery Systems

Polymer filament is pulled from a spool of material through a series of pinch rollers and pushed into a liquefier head, where it is melted. Material oozes out of the tip of the head and belted stepper motors drive a linear x-y motion, thereby depositing a small contour of material in a selective manner.

Energy Sources

Electrical resistance in heating elements provide the energy to melt the polymer filament. The heating elements are embedded in the deposition head around the liquification tip. Before the process begins, the deposition tip must warm to a temperature just above the melting temperature of the filament, but not too high that it burns the filament leaving behind carbon buildup deposits.

Material

A wide variety of polymers are available to be processed using small scale polymer extrusion. Typically, because of the relatively large melt range, amorphous polymers tend to be more compatible with small scale polymer extrusion than semi-crystalline. Though semi-crystalline Nylon and PEKK materials have started to become available recently. The following list provides an idea of the type of polymers compatible with small scale extrusion technology:

- PLA
- ABS
- PC
- PEI
- PPSF
- PEKK
- PA

Large scale polymer material extrusion process architecture

Large scale polymer material extrusion machines are available exclusively for industrial applications. Also known as big area additive manufacturing, these machines represent a very scaled up version of the small-scale polymer extrusion machines. These are enormous systems had originally been designed for laser/plasma cutting applications and retrofitted with a deposition head to create large AM machines. This technology uses polymer injection molding pellets as a feedstock as it is less expensive to scale to larger sizes relative to filament. The feedstock is liquified by a heated screw in a deposition head which moves in the x-y plane, depositing the polymer material. The part is built upon a table that moves in a z direction. Deposition rates of 80 pounds of material per hour are attained on a build workpieces as large as 240” x 90” x 72”.

Delivery Systems

Polymer pellets are stored in an air dryer system to ensure little humidity effect on the pelletized polymers. The pellets are sourced from injection molding polymer suppliers. Once dried to a desired relative humidity level, the pelletized resin is transferred through air handler lines to the injection screw. Material oozes out of the tip of the screw head and linear motors drive the large gantry up and down the part build area, thereby depositing a large contour of material in a selective manner. Various extrusion die nozzle diameters are available from .200”, .300” and .400” to adjust to specific part application feature sizes.

Energy Sources

The **screw head** is heated and spins to create a compressive shearing effect on the pelletized polymer resin which liquifies the material for deposition. The spin rate, shape and pitch of the screw threads are adjusted depending on the material being extruded. For example, it is not uncommon to have an optimized screw for use with ABS and a different screw shape for PPS.

Material

Most common injection molding materials are used for large scale polymer extrusion. These would include:

- PEI
- PPS
- PC
- PLA
- ABS
- Carbon filled ABS
- TPU

2.6 Solid Material-Addition Processes

Learning Objectives

By the end of this section, students will be able to:

- Understand sheet lamination processes.
- Comprehend cold spray technology.

Sheet Lamination Process Architecture

Sheet lamination process architecture is defined as an additive manufacturing process in which an ultrasonic transducer attached to a 3-axis gantry fuses feedstock of thin metallic foil that is coiled approximately .5" wide with a thickness similar to aluminum foil used in everyday household needs. After a few layers of ultrasonic bonding of the foil feedstock, a mill cutter is introduced into the process and material is machined away to provide the feature definition needed to fabricate the part. After the part is completed, the part exhibits a smooth machined surface. This process is known as **ultrasonic consolidation**.

Due to the relatively low temperature solid state bonding process, ultrasonic consolidation has unique benefits compared to other AM processes. These include:

- The ability to embed temperature sensitive objects into the part during fabrication. Some examples include strain gage wires, sensors, fiber optics, printed circuits, etc.
- Being able to bond very dissimilar metals together that would typically be difficult to bond using a high heat fusion process.

It is worth noting that there exists an alternative sheet lamination process that involves adhesive backed paper rolls that are layered. At each layer, the paper is cut to the desired profile with a laser cutter on a gantry system. The resultant wooden part is mainly used for basic prototyping. This type of AM technology is known as Laminated Object Manufacturing (**LOM**) or Selective Laminated Deposition (**SLD**) and is very niche with limited application space. For the sake of brevity, it will be excluded from the sheet lamination discussion with a sole focus on ultrasonic consolidation.

Commercially available ultrasonic consolidation machines are capable of a build volume of up to 6ft x 6ft x 3ft. The fundamental systems that make up an ultrasonic consolidation system includes:

- Foil Feed Mechanism
- Transducer
- Horn
- Booster
- 3 Axis Gantry System
- Baseplate Substrate
- Mill Cutting System
- Computer / HMI

Delivery Systems

The transducer and horn fusion head are directly mounted to a X-Y gantry system. The gantry system moves the horn to the desired location for fusion. The **foil feedstock** is fed into the work area. A specified amount of force is applied from the horn onto the foil to hold it in place while the ultrasonic vibration motion takes place. After a few layers are deposited, a CNC programmed mill cuts away undesired material from the consolidated metal part profile. Water soluble material may be used as a support structure if needed for overhanging features.

Energy Sources

Ultrasonic consolidation occurs primarily through the energy transfer of the transducer which generates ultrasonic vibrations at 20 kHz. The frequency is a static value whereas the amplitude value may be varied depending on the type of metal being fused. The **sonotrode**, which is a disc shaped horn, transmits the ultrasonic vibrations to the foil feedstock that are being fused together.

Materials

There are a wide variety of metals available for the ultrasonic consolidation process, some of which may be bonded together to create functionally gradient metal. Some examples have been demonstrated include, steel-nickel, tantalum-steel, aluminum-titanium, aluminum-copper. For single metal bonding, the typical materials used in the ultrasonic consolidation process include:

- Aluminum alloys
- Copper alloys
- Low alloy steel
- Titanium

Cold Spray Process Architecture

Cold spray technology is commonly used as a coating process; however, it has been demonstrated to be effective for freeform AM. Despite being named ‘cold’ spray, the process is heated just below the melting temperature of the metal being deposited and is anything but ‘cold’.**Cold spray** is an impaction process where metal powder is discharged from a gas nozzle jet at extremely high velocities. These metal powder particles impact onto a surface and buildup material based on force. Care must be taken to tune process parameters to ensure part integrity and avoid delamination and porosity in the resulting built up structure. Once the bulk geometry is deposited, the structure is transported to a 5-axis mill for final machining.

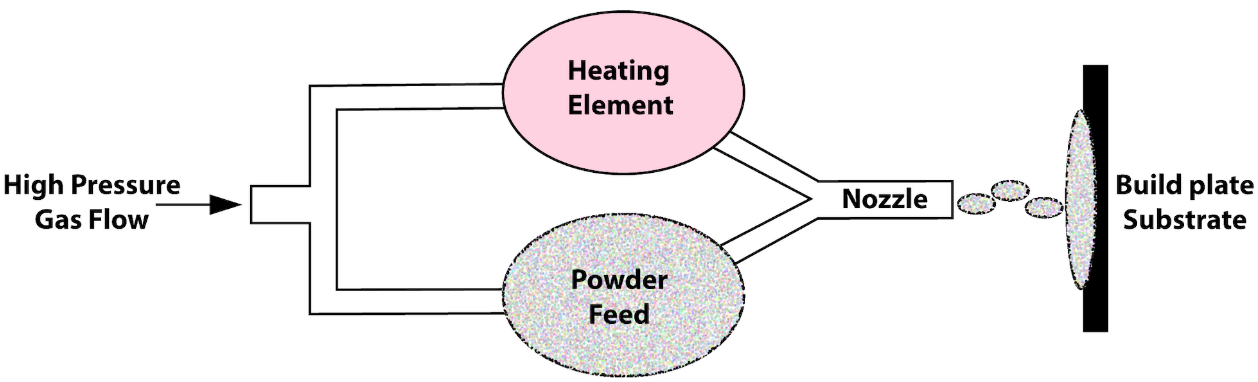


Figure 2.8 Functional diagram of cold spray system

Delivery Systems

There are a number of variations to the delivery systems for cold spray. The first includes a gas nozzle jet moving in a linear motion spraying material on feedstock on a lathe producing a gradual buildup. Second, the nozzle jet may remain stationary below a tilt table shooting material vertically while a 5-axis tilt table receives the material from the nozzle creating a 3D freeform structure (shown in F02_19). A third approach includes a substrate plate mounted vertically in a stationary format while a nozzle delivers material horizontally against the build up baseplate.

Energy Sources

The originating source of energy for cold spray technology is highly compressed heated gas. The heated gas acts as a supersonic velocity carrier to transfer the metallic powder to a substrate to be impacted on the surface up to 4000 feet/sec. The kinetic energy of the particles is transferred to plastic deformation energy in the bonding process. The gas composition is typically either helium, nitrogen, or compressed air above 15 bar resulting in a flow rate of more than 71 ft3/min. The power required for the heating the gas. can range from 3-5kW.

Material

Similar to other AM powder based systems, cold spray is sensitive to powder particle size variation. Ceramics and metal powders can all be used for cold spray. Some of these include:

- Aluminum
- Copper
- Nickel

- Titanium
- Zinc
- Tantalum
- Niobium
- Tungsten
- Zirconium
- Steel
- Copper-Tungsten
- Al-SiC

2.7 Supporting Processes

Learning Objectives

By the end of this section, students will be able to:

- Understand all of the post-processing requirements relative to each AM technology.
- Grasp the concepts of:
  - Powder removal.
  - Support removal.
  - Curing.
  - Sintering and densification.
  - Thermal post-processing (stress relief, heat treatment, HIP).
  - Machining surface and surface preparation.

Once an AM part has been processed using any of the aforementioned processes, the part will most likely endure subsequent processing steps on its journey to become a quality part. These additional steps are what is known as **post-processing**. The specific post-processing steps will vary significantly depending on which AM process is being considered. Reference Table 2.1 on which specific AM technology requires which specific post-processing type.

Powder/Support Removal

Once a part is removed from the build chamber of SLS Polymer, Binder Jet machines, the resulting volume of powder, also known as a **build cake**, is removed from the build chamber and de-powdered. Parts are dug out of a build cake of powder to expose the parts fabricated.

Next, for powder bed electron beam and laser metal systems, part build cakes are removed from the machine and de-powdered. In addition to de-powdering, since these processes require supporting structure, sacrificial support structures are removed from the parts. This is accomplished by a technician using conventional hand tools to chisel, pry and machine off the support structure from the parts.

Finally, large scale polymer material extrusion, stereolithography and liquid deposition requires a physical removal of support structure after fabrication. Small scale polymer material extrusion may also require a physical removal of support structures, however, water soluble support material has been developed that allows for support structure to be dissolved easily from the part.

Some AM processes require curing, or the introduction of additional heat to strengthen the part after the part is built. For example, stereolithography and liquid deposition processes require a subsequent UV curing process that occurs after parts are temporarily cured in the AM machine because they are UV photopolymer based.

For binder jet technology, a binder catalyst temporarily 'cures' a structure into a green part during the fabrication process so that it can be moved to a sintering and densification step.

Curing of the binder is necessary to develop sufficient mechanical strength in the bound metal part for handling, in most of the binder jet processes. Curing is typically done as a batch process where the entire build box is fit into an oven and heated to 150-260°C (300-500°F) for a couple of hours.The temperature allows the polymer in the binder to crosslink, increasing its strength and therefore the strength of the printed part.

Sintering and Densification

Once binder jet technology is partially cured, it is sintered to bake out the binder material and then subjected to a densification process to reduce internal porosity.

There are several important subtopics to sintering: Setters and Trays, Furnace Environment and Control, De-Binding and Sintering. Table 2.2 highlights just a few of the topics and impacts.

	Setters and Trays	Furnace Environment and Control	De-Binding	Sintering
Consideration	Temperature and sintering process dependent	Atmosphere, temperature ramp control	Chemical interactions and thermal control	Final de-bind and densification
Impact	Slumping, part distortion or material interaction	Excessive time in the furnace to achieve density or de-bind	Trapped binder could be a defect	Failure to achieve density requirements or excessive sintering time

Table 2.2 Sintering Steps and Impacts

Choice of atmosphere in the furnace and thermal control is closely related to the binder employed and the material being processed. There is no one single solution to sintering. The atmosphere in the furnace could be a reducing gas, flowing hydrogen, or a vacuum. Control of the furnace thermal profile is important to achieve good results given variable ramp up and hold schemes to “burn out” the binder.

In addition to the temperature and environment, the part will be necessarily shrinking to densify. This shrinkage is influenced by gravity, so some tooling may be required to control slumping. It is also necessary to consider that great care was taken to put the binder in the right place and cured. The binder is removed as the particles transition from being held together by the binder, to being held together by powder particle to powder particle bonding.

Sintering is fairly simple in concept. Where two particles contact, atoms can begin to move from one to the other, and, with time, multiple particles coalesce in 3 stages: 1) Neck growth, 2) Intermediate sintering and 3) Final sintering. Table 2.3 shows the main considerations, and Figure 2.9 Stages of Sintering shows the stages conceptually.

	Stage 1: Neck Growth	Stage 2: Intermediate	Stage 3: Final
Consideration	Packing density / disruption by the binder impact	Packing density and part densification	Gas egress from part
Impact	Particle contact initiates sintering	Higher density speeds sintering, part densification leads to shrinkage	Decrease in part density

Table 2.3 Three Stages of Sintering

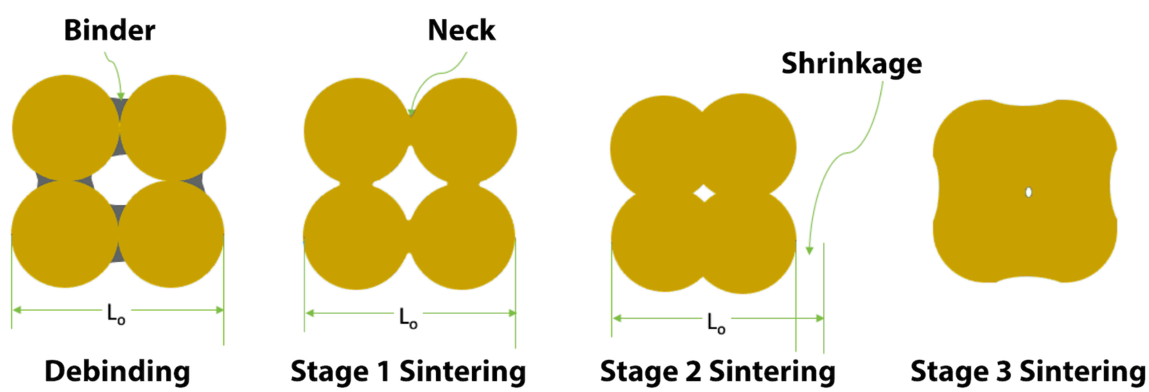


Figure 2.9 Stages of Sintering: 2-dimensional view of debinding and sintering from a particle perspective.

All sintering stages are important, but the packing density of powders in the printed part is important in Stage 3 as a higher density produces more rapid sintering. The powder bed density can be impacted by the binder impacting the surface. The bulk of densification occurs during this stage which drives the entire body to shrink up to 15-20% by volume. This shrinkage results in distortion of the part, because thick features shrink more than thin features. Abrupt changes in section thickness can result in surface cracks due to the differences in shrinkage.

Large openings and overhangs can distort due to gravity during this stage of sintering, and the drag of the shrinking part on the tray can cause the bottom of the part to shrink less than the top.

A typical debind and sintering cycle for an Iron-based alloy is shown in Figure 2.8_Typical Debind and Sinter Cycle. Debinding occurs at the first hold at 300C, and finishes at the 2nd hold at 600c. This temperature is chosen such that stage 1 sintering begins at about the same temperature. Sintering completes stage 3 in this example cycle during the hold at 1400C.

With the exception of sheet lamination, all metallic AM processes typically require one or more processes of stress relief, heat treatment and hot isostatic pressing to achieve full mechanical density.

Machining/Surface Preparation

All metallic AM processes require some form of post-process machining. Some powder based metallic processes may simply require wire EDM or bandsaw removal of parts from the build plate. Complex parts with threaded holes and features that fit up into assemblies will at least need mating surfaces machined, and many tight tolerance features will also need machining or finishing.

However, all metallic wire fed, sheet lamination and cold spray processes will require subsequent machining to reach final feature definition. Also, large scale polymer material extrusion will need full machining. This is due to the fact that these processes produce parts that are near net shape preforms.

SLS polymer and small-scale polymer material extrusion may also require surface treatment of sanding, painting and seal coating to provide a smooth surface. The need for these additional steps will depend on the customer requirements.

Which post processing steps are required for binder jet technology?

Summary

Choices for AM technology are extensive and distinct, with each option offering unique benefits and extensive processes. The most common processes are vat-based processes, powder processes, liquid addition processes, molten material processes, and solid material processes. Each requires expertise and equipment to bring to bear the proper materials and energy source. Within each AM technology there may be dedicated steps that are highly specific to that application, such as recoating in a powder-process. Supporting processes include curing, polishing, and sintering.

Review Questions

1. What are the original ASTM categories of AM, and how were they grouped?
2. Describe the different ways that layers are formed in AM processes. Can one way be more effective than another?
3. What are the different types of feedstocks available for AM processes?
4. Describe the differences and similarities between SLA, DLP and LCD stereolithography.
5. How are parts cured after being fabricated used vat-based processes?
6. Which UV wavelength is compatible with DLP?
7. Which process is more similar to injection molding?
8. Which recoating process is the most forgiving for part failure during the build process?
9. Which is a more powerful energy source for metallic powder bed, laser or electron beam?
10. Which liquid addition process can be used to fabricate homes?
11. Which liquid addition process can be used to fabricate circuit boards?
12. What is the resolution size limitation of direct ink write technology?
13. Which polymer addition process can be used to fabricate full size car chassis?
14. What is the most significant advantage of using welding wire as a feedstock over metallic powder?
15. What is the most significant advantage of using a screw over filament for polymer processes?
16. Which process has a unique ability of making functionally gradient parts, and why?
17. What are some advantages of using the sheet lamination process called ultrasonic consolidation?
18. What types of items can be embedded within ultrasonically consolidated parts?
19. Which post processing steps are required for DED blown powder?
20. Which post processing steps are required for powder bed fusion laser metal?

Discussion Questions

21. Of the different types of energy sources, which do you believe is the most powerful for AM processing?
22. As more AM processes become available, how would you categorize AM technologies?
23. Of the different types of Vat based processes, which process would be best for a hobbyist or student?
24. Describe in your own words the definition of a green part.
25. From a process standpoint, in what significant way is a binder jet part similar to SLA?
26. Why does binder jet technology require infiltration or sintering where EBM does not?
27. Describe how a slurry-based process can be used to fabricate homes.
28. Provide your thoughts on what the future may hold for slurry-based AM.
29. Why is there a limit to geometric design freedom for wire fed EBM systems compared to powder bed processes?
30. Why is blown powder DED used for crack repair in parts?
31. In your own words describe the process of cold spray.
32. Why is cold spray typically a coating process?

33. Why is sintering and densification needed for binder jet technology, but not for SLA?

34. Why is an UV curing process needed for SLA, but not for SLS polymer powder?

Case Questions

35. Print out the process mapping image. Search online for 3 different additive manufacturing technologies of your choice and learn all aspects of the technology. Follow the flow lines on the process map of each of your identified technologies to ensure the process map's accuracy. Is it correct? Did you find errors? Will the technology change in the future thereby making the process map obsolete?

36. Read the following case study (https://openstax.org/l/AMMammoth) and answer the following questions.
a. Why did it take so long to print the mammoth skeleton?
b. With the file size of 21 GB of data representing the mammoth, what problems could this cause with processing AM files?

37. Read the case studies (https://openstax.org/AMEOS) and answer the following questions.
a. Why was AM used for these systems?
b. Which case study is your favorite example of AM powder bed processes, and why?

38. Read the case study (https://openstax/org/l/AMGuestHouses) and answer the following questions.
a. What are the advantages and disadvantages of these homes?
b. Could this technology be used beyond earth?

39. Read the case study (https://openstax.org/l/AMOptoMec) and answer the following questions.
a. What are the advantages and disadvantages of direct ink write technology?
b. What applications exist for this technology?

40. Watch the case study videos regarding large scale polymer material extrusion technology known as BAAM (https://openstax.org/l/AMBAAM) and answer the following questions.
a. What are some other applications you could think of that could be made with this system?
b. Which demonstrated application could have broader industrial implications?

41. Read the case study (https://openstax.org/l/AMRockets) and answer the following questions.
a. Given the scale of DED blown powder technology, what other uses do you see for this technology?
b. What is a main advantage of using DED blown powder for this application?

42. Watch the video regarding ultrasonic consolidation (https://openstax.org/l/AMUC) and answer the following question.
What are some other applications you could think of that could be made with this system?

43. Watch the video on cold spray of a copper rocket nozzle (https://openstax.org/l/AMspee3d) and answer the following questions.
a. Given the scale of cold spray, what other uses do you see for this technology?
b. What would be the limitation of this technology relative to feature detail of metal powder bed fusion or binder jet?

44. Read the article on post processing costs (https://openstax.org/l/AMPostCosts) and answer the following questions.
a. How much extra cost would you incur beyond printing your part with post processing in mind?
b. Though the article doesn't mention a time frame for each post processing step, take a guess on how much extra time may be involved to post process sheet lamination ultrasonic consolidated parts versus powder bed fusion laser metal.

Key Terms

2.1 Processes and Process Organization

ASTM F42, Binder jetting, Densification, Directed energy deposition, Energy Source, Material extrusion, Material jetting, Powder bed fusion, Sheet lamination, Vat photopolymerization, Laser, Plasma, High Pressure Gas, Electrical Resistance, Compression, Electron Beam, Feedstock, Curing, Welding, Mechanical Fusion , Kinetic Energy, Ultrasonic Energy

2.2 Vat-based Processes

LCD, DLP, SLA

2.3 Powder Bed Processes

Roller System, Hard Knife Blade, Soft Gasket Wiper Blade, Yb-Fiber Laser, Electron Beam Gun, Infiltration, Sintering, De-powdering, Debinding

2.4 Liquid-Addition Processes

Direct Ink Writing, Slurry-based AM, Material Jetting

2.5 Molten Material-Addition Processes

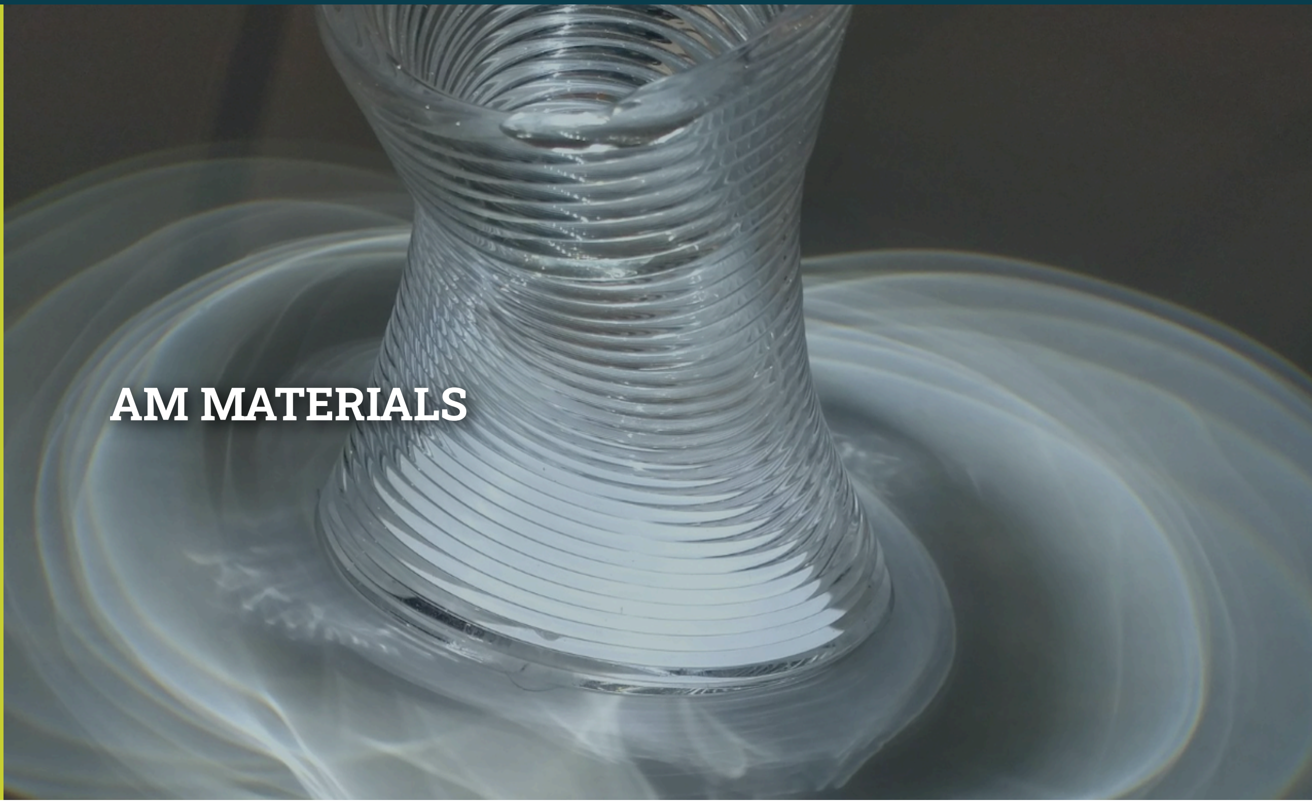
Powder Bed EBM, DED blown powder process, Small Scale Polymer Material Extrusion, Large Scale Polymer Material Extrusion, Polymer Filament, Polymer Pellets, Screw Head, Metallic Welding Wire

2.6 Solid Material-Addition Processes

Sheet Lamination, Ultrasonic Consolidation, LOM, SLD, Foil Feedstock, Sonotrode, Cold Spray

2.7 Supporting Processes

Post-processing, Build cake



3 AM MATERIALS

Figure 3.1 This 3D printed glass structure, one of several by innovative designer and architect Neri Oxman on display at the Cooper Hewitt Smithsonian Design Museum, required precise control and materials to maintain structure and produce the texture, strength, and light effects. (credit: modification of “3d printed glass” by walknboston/Flickr, CC BY 2.0)

Chapter Outline

Introduction

As AM technology has matured over the last 30 years, a wide range of materials including those with engineering properties are now available. While there are fewer choices than for conventional manufacturing processes, almost all classes of polymers, metals, and ceramics are available such that a product team does not have to rule out the use of AM due to a lack of suitable materials. However, achieving suitable properties is still not guaranteed. In this chapter, we will discuss the primary engineering materials classes: polymers, metals, composites, and ceramics, as well as other materials.

3.1 Polymer Materials

Learning Objectives

By the end of this section, students will be able to:

- Understand the range of engineered polymer materials and their characteristics that are available for AM.
- Differentiate the feedstocks of those materials, and how they relate to the different AM processes.
- Describe the relationships between polymer properties, feedstocks, AM processing, AM post-processing, and the resultant AM part.

Polymers have been widely available in AM since the beginning of rapid prototyping resins. However, many of the early polymeric materials for AM were only suitable for models and fit testing as the physical properties of early AM polymers, including toughness and strength, were poor. Polymers are still the first choice for rapid prototyping of AM models and demonstration test parts due to the proliferation of desktop and prosumer printers, but there are now a number of polymer feedstock products on the market with sufficient engineering properties to achieve the desired performance in a range of applications from biomedical to aerospace industries. Additionally, as AM process technology and use cases have flourished, companies with deeper experience in designing customized raw materials have entered the market to supply the AM industry with new feedstocks. Generally, for AM applications, polymers are classified into two types:

1. **Thermoplastics**, or heat-processible, heat-formable materials can be shaped using a variety heating schemes from thermal radiation to conduction. These materials can be heated and formed multiple times during reprocessing, often without major degradation in properties under the right conditions. Common means of AM processing thermoplastics include thermal material extrusion AM and powder bed fusion.
2. **Thermosets**, or materials that crosslink and change from a liquid to a solid state and cannot easily be reprocessed once solidified. The crosslinking process can be induced by photo or thermal means, generally, but photocrosslinking is most often used for AM due to the rapid solidification reaction required. The mainstream AM processes that incorporate thermosetting-type polymers are vat photopolymerization and material jetting, although post-processing crosslinking is sometimes used to stabilize initially thermoplastic, heat formed materials.

These two general processing characteristics of polymers drive the choice of AM processes where polymeric materials are deployed across a huge number of applications. In fact, in ASTM classification of polymer feedstock AM processes, all techniques fall under thermal bonding (mainly used for thermoplastics) or chemical reaction bonding (mainly used with thermosets). Within thermoplastics and thermosets, polymers have a range of processing conditions. There are low-temperature polymers that are easy to melt process and have low **viscosities** under flow at 80 °C, and there are high-temperature polymers and composites that push the limits of thermal processing conditions and degradation in excess of 400 °C. Similarly, thermosets can cure at room temperature or at elevated temperatures, up to 250 °C or higher. Table 3.1 lists a range of polymers across thermoplastic and thermoset materials that are widely used in AM. At first glance, there seem to be many more thermoplastics available than thermosets for AM. Thermoplastic properties are dictated by the backbone type. If a different set of properties is desired, then a different polymer must be chosen. However, the properties of thermosets can be varied by changing the ratios of resin components such as crosslinker, monomer diluent, or other additive – giving a huge range of possible formulations. The thermosetting photopolymer function is preserved in the precursor materials but the resin "recipe" can be optimized without too much of a change in the overall chemical formulation. Thus, there are different materials "knobs" to turn depending on the characteristics of the feedstock. This unique formulation flexibility of thermosetting resins for vat polymerization or material jetting AM provides many possibilities for customizing unique materials in these AM processes, even though the underlying crosslinking chemistry does not have to change much.

Processing Class	Polymer Name	Common Uses in AM
Thermoplastics	PLA – poly(lactide), poly(lactic acid)	Prototyping, hobbyist printing, degradable packaging
	PET – poly(ethylene terephthalate)	Clamshell packaging, composites in automotive applications
	ABS – acrylonitrile-butadiene-styrene	Tough plastics, cases, consumer goods
	PE/PP – poly(ethylene) and poly(propylene)	Low-strength parts, disposable components
	PC – poly(carbonate)	Transparent panels, tough components, composites
	PA – poly(amide), Nylon	Automotive and engineering parts
	PSU/PSf – poly(sulfone)	Medical, consumer, industrial, and automotive components

Table 3.1

Processing Class	Polymer Name	Common Uses in AM
	PPS – poly(phenylene sulfide)	Automotive and aerospace applications
	PEI – poly(ether imide)	Aerospace applications
	PEEK – poly(ether etherketone)	Medical and aerospace applications
	TPU – thermoplastic poly(urethane)	Elastomeric components, bumpers, energy adsorption, soft touch components
	TPE – thermoplastic elastomer	Elastomeric components, consumer goods, energy adsorption, soft touch components
Thermosets	Crosslinked acrylate photopolymers	Vat photopolymerization, material jetting
	PDMS – poly(dimethyl siloxane), silicone rubber	Elastomer applications, medical components
	PU – crosslinked poly(urethane)	Elastomer applications
	Epoxies	Adhesives, composite matrix phase

Table 3.1

Polymers and their precursor feedstocks for AM are all derived from product streams of the petrochemical industry, although there are a few AM polymers derived from bioplastics, such as PLA. Polymers and chemical feedstocks used for AM are generally widely available since polymers are such heavily used materials with robust distribution networks and a large number of suppliers. In the last 10 years with the increase in AM technology, a number of important polymer feedstocks have been adapted to AM processes. As AM has matured, the plastics and chemical industry has produced different grades of materials that are customized for AM including samples with tuned **melt flow index**, which is an indication of mass of polymer extruded in a given time, for ME, new grades of powder for BPF processes, and customized photo curable materials and composite resins. However, from the 1,000s of products available from the petrochemical industry for polymeric materials, AM consumes a small fraction of the possible accessible formulations. Consequently, there is a long way to go and a tremendous toolbox to access for customizing polymeric materials and composites for the AM industry.

Also noted here is that many of the polymers discussed above can be compounded with fillers to make composite feedstocks. Very few polymers are used in their pure form for commercial applications. Often the base polymer is mixed with colorant, filler, antioxidants, and other functional components (or inexpensive fillers to decrease the cost of the material) and hen shaped into the desired form. While the discussion of polymers in this chapter will emphasize the polymer portion of a composite, there are many types of polymer-based composite AM feedstocks available from carbon-filled elastomers to ceramic photopolymer resins.

Key characteristic of AM polymers and base monomers/chemistries

The key characteristic that must be considered for the polymers used in AM is the method by which they are shaped and under what conditions can the AM process yield the required resolution and properties required for a given material and application. For example, the only way to process a polyamide (Nylon) is by thermal shaping, as this material cannot be photopolymerized. Therefore, if polyamides are the desired end-use material, thermal AM processes, such as ME and PBF are the main pathways for production of these parts. Similarly, if a thermosetting **acrylate** is required, the only way to access this polymer composition is through vat photopolymerization. Using these conventional pathways for deploying polymers in AM, processes can be paired with the requisite materials, or vice-versa. From there, dimensional tolerances, surface finish, and post-processing schemes can be considered. However, new research breakthroughs are occurring in hybrid polymer processing where the shaping technology is complemented by a post-processing scheme to facilitate post-shaping chemistry or conversion of the material. Materials including crosslinked **polyurethanes**, **cyanate**

ester thermosets, and **liquid silicone rubber** are all being deployed in multistage processes to access both the advantages of AM shaping technology and robust engineering properties of these materials.

Polymer Feedstock Types and Processes

Based on the two general classes of polymers, thermoplastics and thermosets, there are two basic types of polymer feedstocks and printing processes that form the basis for understanding the constellation of polymer materials for AM. For thermoplastics printing, Material Extrusion AM, is ubiquitous. This type of printing employs a filament or pellet feedstock that is thermally extruded through a simple orifice to build a component from roads. Readers versed in the art will know the ever-present MakerBot and similar printers as a Material Extrusion AM thermal process. While ME is still the predominant technology for hobbyists and desktop printing, it has been adapted successfully to a number of commercial systems including units by Stratasys and Cincinnati Incorporated. ME is inexpensive in concept and can be successfully used to process a wide variety of thermoplastics at many different size scales.

Powder bed fusion of thermoplastics, while laser driven, is a thermal process. Long wavelength (1-10 μm) fiber or diode lasers are used to heat thermoplastic powder that is often darkened with carbon black or other additives to increase the heating of the powder for rapid fusion. This technology is deployed industrially for a few different types of polymers, namely PA11/12 and PEEK. The polymer PBF equipment setup is similar to that used for metals, however, the physics of fusion is much different between the liquid melt pool needed for metals and the fusion of viscous polymer powders above their melting temperature. Polymers have two thermal transitions, the Tg, or **glass transition temperature**, and the Tm, or **crystalline melting temperature** (Figure 3.2). The Tg, where a polymer turns from a glassy solid into a rubbery solid, can be observed for nearly all polymers and is defined as the temperature at which chains can diffuse past one another and the material can undergo flow when exposed to shear. At the Tg, the viscosity of the material drops in the transition from a glass to a rubber. To achieve reasonable flow, amorphous polymers must generally be processed 50 °C or more above their Tg. The Tm only exists for semi-crystalline polymers that have a mixture of amorphous and crystalline regions in their solid-state structure. Polymers with a Tm must be processed 20-50 °C above Tm to induce rapid flow and fusion. Still, even above Tm, polymers are viscoelastic and do not easily undergo rapid fusion. Thus, only a small number of polymers have been employed widely in PBF processes.

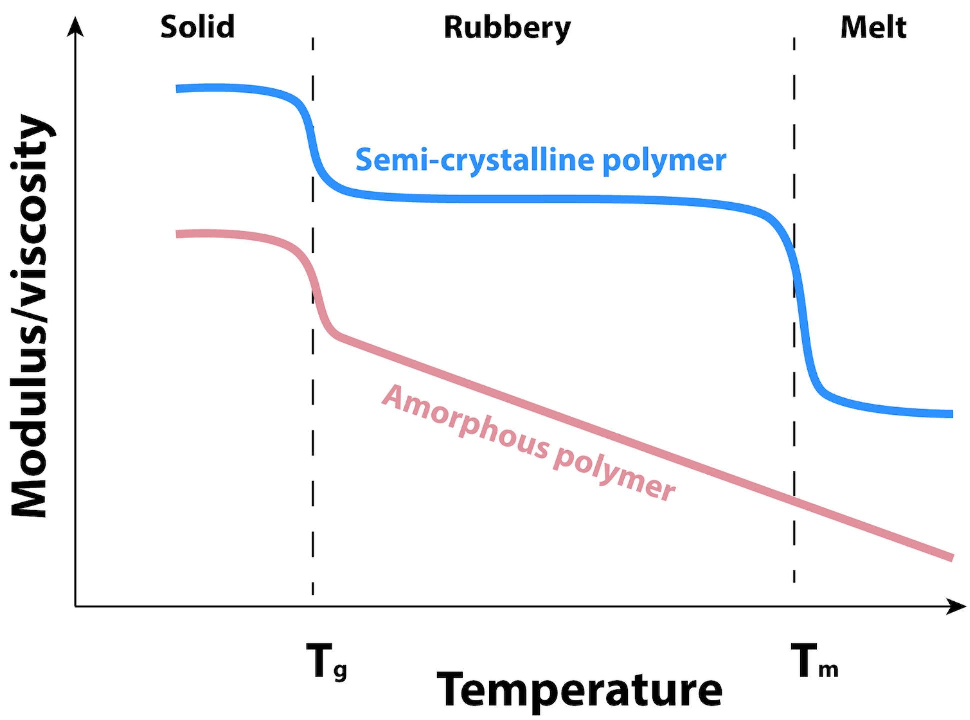


Figure 3.2 Viscosity/Modulus of thermoplastic polymers as a function of temperature

PBF generally requires a polymer to have a Tm and a rapid viscosity drop above Tm to achieve the temperature spike, flow, fusion, and solidification of the material. While some success has been achieved in the PBF of amorphous thermoplastics, the transient temperature spikes and rapid processing times of PBF are not compatible with a highly viscous polymer above Tg. Thus, material introductions to PBF are generally slow and the limited availability of development machines and suitable polymers has held back the widespread adoption of this technology outside of specialized applications. Additionally, polymer powders are highly explosive and pose a serious environmental safety and health risk due to their low density and ability to circulate in the air for extended periods.

For thermosets, light-driven vat photopolymerization including the variations of SLA, DLP, CLIP, (as described in Ch 2) etc. are employed. The feedstocks for these processes are all UV-cured photopolymers where the rapid liquid to solid curing kinetics are leveraged for component fabrication using high-intensity photopolymer curing methods such as UV DMD chips and diode lasers. While some heat is liberated from photocuring reactions, the primary mechanism of the liquid to solid transition is photochemical, although heat must be managed during rapid curing. Material jetting of UV curable polymers is widely employed to obtain highly detailed models with resolution rivalling the best VP systems.

Material preparation for polymers in AM is relatively straightforward in the industry, although production of well-dimensioned filaments, polymer powder, and shelf-stable liquid polymer resins is challenging for non-specialists. These materials can be prepared for processing under mild conditions which lends itself to widespread adoption and experimentation across the community.

Photopolymers

Photopolymers or light-cured materials are the feedstocks used in vat photopolymerization and MJ processes, among other light-driven AM processes. Photopolymers are a wide class of materials, but industrially, photopolymerization or photocrosslinking (a technique that uses light to create bonds) of liquid precursors to crosslinked solids is usually achieved through UV curing of acrylates. This photopolymer crosslinking chemistry is fast, inexpensive, and easy to deploy for a wide range of polymers to yield a tremendous variety of materials. In fact, nearly all commercially sold vat photopolymerization and ME resins are the same crosslinking chemistry.

The different properties derived from light-cured acrylate resins are due to the chemical composition of the groups between acrylate crosslinking sites, the crosslinking density, and other additives, such as monomer **diluents**. Using photopolymerization, elastomers, tough engineering plastics, and even highly filled ceramic resins can be accessed. Many feedstocks for vat photopolymerization are sold with descriptors such as "polyethylene like" or "polycarbonate like" properties. In fact, these materials may not contain any of the noted polymers in their descriptions, but the resin formulations are tuned to display thermal and mechanical properties that mimic more familiar thermoplastic polymeric materials. This approach is typified in Table 3.2. Many of these resins contain 20-30 components including UV absorbers and stabilizers and are not usually formulated by the manufacturer listed on the label, these materials are generally formulated by specialty chemical suppliers for private label reselling. Generally, the formulation of these materials is confidential. This type of feedstock formulation is still in the art phase although advanced experimental design and data analytics can be used to optimize these materials.

Manufacturer	Product Name	Properties Similar To
Formlabs	Tough 2000 Resin	ABS
	Flexible 80A	TPU
Stratasys (for Polyjet)	Digital ABS	ABS
	Tango	Rubber
	Rigur	Poly(ethylene)
Envisiontec	E-Rigidform	Acrylic, Nylon-6, polycarbonate
	ABS Hi-Impact	ABS
	E-EA90	Rubber

Table 3.2 Photopolymer resins marketed with thermoplastic-like properties.

The advent of advanced vat polymerization processes and chemistries that complement this rapid production of engineering-grade parts has ushered in a new approach of rapid light shaping and dual cure mechanisms. Companies like Carbon have leveraged new chemical approaches to VP feedstocks and post-processing schemes to achieve properties in photopolymerization materials that have not been possible previously. The resolution and surface finish of VP makes it alluring for direct production of consumer and industrial grade parts and new materials, coupled with improvements in printing technology, have brought a number of successful products forward.

Thermosets

Thermosets tend to refer to any crosslinked polymer system, including photopolymers (or perhaps photosets). Familiar thermosetting materials include epoxies, crosslinked polyurethanes, and thermally cured or room temperature vulcanizate (RTV) silicones, as examples. Thermoset usually implies thermal curing at temperatures greater than room temperature, but this does not have to be the case. Superglue is a thermoset, along with bathroom caulk. Once hardened, thermosets cannot be reprocessed due to the crosslinking of polymer chains and their inability to flow. By far, the largest use of thermosets in AM is in vat photopolymerization that leverages the liquid to solid transition that occurs due to the rapid increase in molecular weight and crosslinking of polymer chains during acrylate photopolymerization. As described above, these acrylate crosslinking systems can achieve a wide range of properties that are dependent on the polymer characteristics between acrylate groups. In addition to vat photpolymerization, MJ printing leverages thermosetting liquid acrylate resins for building voxel-based designs.

Thermosetting polymers such as two-part epoxies or thermally cured silicones can be deposited using direct ink writing, which is a form of material extrusion AM. In many cases, these thermally cured thermosets are post-processed to achieve the desired properties. For instance, many long pot life silicones and epoxies tend to cure at temperatures above 100 °C. These materials also have **Bingham plastic** behavior where they can support a finite stress at zero shear. This unique property of these highly viscous thermosetting precursors can be used to stabilize liquid direct ink writing printing before thermal post-curing.

Thermoplastics

Thermoplastics are ubiquitous in ME and PBF and there are at least 20 different types of thermoplastics used routinely in AM processes that can be sourced from any of the major manufacturers and polymer distribution houses. Thermoplastic polymers are characterized by their ability to be shaped under high temperatures (between 150-400 °C) and moderate pressures. All of the common AM polymers are thermoplastics, aside from those that are used in vat photopolymerization and liquid resin-based printing. These include Nylons (polyamides), PE, PP, PLA, ABS, PET, PC, and PEEK, among others, see Table 3.3. All of the thermoplastics available for AM are sourced from the plastics processing industry where extrusion and molding are the mass-production technologies of choice. Thermoplastics are generally used for inexpensive, moderately demanding applications. Composites of thermoplastics are widely used in consumer and automotive components and are the result of mass-production from injection molding. However, injection molding is prohibitively expensive for small part counts and machining of many plastics can be challenging. Therefore, AM of thermoplastics has filled an important gap in prototyping of plastic parts. These materials can also be ground and reprocessed, although degradation in performance usually results from repeated recycling.

Thermoplastic	Young's Modulus (GPa)	Elongation to break (%)	Upper use temperature (°C)
PE – poly(ethylene)	0.5-1	100-700	130
PP – poly(propylene)	1-1.5	100-600	80
PLA - poly(lactide), poly(lactic acid)	1-3	5-10	50
PET – poly(ethylene terephthalate)	3-4	30-300	150
ABS – acrylonitrile-butadiene-styrene	1-3	40-130	100
PC – poly(carbonate)	2-3	100-150	150
PA6 – poly(amide), Nylon-6	2-4	10-200	

Table 3.3 Thermoplastic polymers with chemical structures and general properties.

Thermoplastic	Young's Modulus (GPa)	Elongation to break (%)	Upper use temperature (°C)
PSU/PSf – poly(sulfone)	3-5	10-30	165
PPS – poly(phenylene sulfide)	1-4	10-60	200-260
PEI – poly(ether imide)	4-6	10-30	300
PEEK – poly(ether etherketone)	5-7	30-50	250

Table 3.3 Thermoplastic polymers with chemical structures and general properties.

One of the key drawbacks of current hobby and prosumer printers is the need for thermoplastic filament. The main feedstock used in the polymer industry is pellets. So, pellets must be converted through extrusion into a well-gauged filament. The consistency of the filament dimensions is of utmost importance as most machines feed a certain length of filament in the build and do not monitor variations in thickness or flowrate. Pellet printers that directly use widely available materials from the plastics extrusion industry are highly desirable, but are not common for small-scale printing. While there are drawbacks of deploying thermoplastics in relatively low-resolution printing processes, their engineering properties and low-cost still make thermoplastics desirable materials.

Thermoplastics can have a wide variety of properties, including water solubility. Many ME builds employ water soluble supports in dual printing schemes to enable complexity that is difficult to achieve with single-material builds. Water soluble thermoplastics such as **poly(vinyl alcohol)** (PVA) can be deployed in many dual extrusion thermal ME printers and have the melt-flow characteristics needed for support structures. By the same method of dual or multiple extrusion, multicomponent builds using thermoplastics are possible, although material fusion can be a challenge. Additionally, a number of dual head printers exist on the market, but more than two materials integrated into a fused filament fabrication scheme is not common. ME of thermoplastics yields the characteristic striations of the extruded, layered build of fused filament fabrication, along with the associated z-direction anisotropy (as described explicitly in ch 2).

PBF of PA11/12 and PEEK has begun to disrupt the production of high-performance polymer parts as a consequence of the high-fidelity manufacturing available from PBF and 100 or even 1000s of parts accessible in short run times. However, while PBF does incur anisotropy, its part count per build, reasonable surface finish, and acceptable tolerances make PBF one of the scalable routes to large-scale manufacture of polymer parts. PA11/12 (Nylon variations) and PEEK are also highly desirable thermoplastics that can be used in demanding applications from consumer goods to biomedical devices. Production of thermoplastic powders is usually accomplished by **cryogrinding** polymer pellets, although different methods of polymer powder production and the powder characteristics needed for effective polymer PBF are an area of active research.

Composites

Composites can be composed of a thermosetting or thermoplastic polymer and a "filler" or reinforcing inorganic phase, typically glass, carbon fiber, carbon black or ceramic particles like silica. There are many types of composite materials, but for the purposes of this discussion, we will confine the description of composites to those that contain polymer and fiber or particles and are processed in the realm of filled thermoplastic polymers. Because polymers are generally softer than other engineering materials, filling them with inorganic phases greatly increases their moduli and rigidity. Key to formulating composites is a coupling agent between the filler phase and the polymer matrix. Silane coupling agents or sizing agents have been specifically designed for currently available composite systems and are being leveraged to produce robust composite materials for AM. Chopped fiber or particle filled polymers are widely available, but can be abrasive during thermal ME, which is the most common method of processing composite polymeric materials. Some SLA resins are composites, but these are generally classified as ceramic photopolymer resins where the composite properties are less important than using the photopolymer function to shape the material.

While composite materials are critically important and widely used, their advance in the AM industry has been slow, primarily due to their difficult processing and the different formulations needed between molding and extrusion as compared to AM. Adding a polymer filler increases a polymer's melt viscosity and can drastically reduce interlayer adhesion. Additionally, many composites are processed under vacuum conditions to compact the material and avoid air pocket defects, which is difficult to deploy in AM. Composites have played a major role in the development of Big Area Additive Manufacturing (BAAM). Because most polymeric materials used in structure applications are composites, a process that produced filled composite materials was critical to large-scale printing. Currently, most BAAM materials are

10-30 wt % chopped glass or carbon fiber in ABS or other medium performance thermoplastics. As the adoption of BAAM and similar platforms has progressed, major plastics manufacturers like SABIC have introduced AM-specific lines in addition to boutique polymer compounding house's products, such as those available from TechmerPM, see Table 3.4. As an advantage of these composite feedstock materials, stiffer materials can combat warping during printing. Oak Ridge National Laboratory showed that carbon fiber filled materials resist thermal warping during printing compared to more flexible thermoplastics. So, even though composite materials are more difficult to process, there can be unique properties that can be leveraged for innovative processing schemes. Another example of unique facets of composite feedstocks is the use of external IR heating to promote interlayer adhesion. This type of pre-heating is helpful to promote interlayer adhesion, especially in large builds. Due to the presence of carbon fiber in many of these materials, the heating at the surface can be accomplished rapidly without long hold times at temperature that may oxidize the material.

Supplier	Material name	Description
SABIC	LNP™ THERMOCOMP™ AM, grade name 6C004XXAR1	PC/PBT resin containing 20% carbon fiber
	LNP™ THERMOCOMP™ AM, grade name AF004XXAR1	ABS resin containing 20% glass fiber
	LNP™ THERMOCOMP™ AM, grade name DC004XXAR1	PC resin containing 20% carbon fiber
DSM	Arnite® AM8527 (G)	glass-reinforced PET
	Novamid® ID1030 CF10	carbon fiber filled PA6/66 copolymer

Table 3.4 Commercially available composite feedstocks.

Finally, continuous fiber composites such as fiberglass and carbon fiber composites are some of the highest-performance widespread materials available for industrial and consumer applications. Aerospace components, automobile panels, wind turbine blades, sporting goods, and other lightweight, strong components are all composed of these continuous fiber composites. However, due to the layup procedures and vacuum consolidation used in production of these types of parts, processing continuous fiber composites remains a challenge. Markforged has pioneered continuous fiber AM using ME with layers of thermoplastic and thermoplastic coated Kevlar, glass, or carbon fibers. These parts have shown promise in light-duty structural aluminum replacement applications where loads are reasonable, but the intrinsically layered structure of this method and the presets in Markforged software presents challenges to custom part design. Conventional high-performance composites also have some interwoven character to the reinforcement, which is difficult to envision being deployed in standard AM. Z-extrusion and interlayer stitching methodologies have been reported in the literature, but have not made it out of the research laboratory, yet.

There have been attempts to adapt automated fiber layup machines, such as the Ingersoll Machine Tools MongooseTM machine. These types of concepts have been successful in printing on curved mandrels in sizes up to those of 100 m wind turbine blades, although free-forming large-scale components continues to be an unmet challenge.

Elastomers

Elastomers are a high-value class of polymers that can have hardnesses and strengths ranging from nearly glassy polymers with high impact strengths and high loading resistance to the softest silicones for vibration dampening and all familiar rubbery materials in between. Interestingly, elastomers can be composed of either thermoplastics, as in thermoplastic elastomers, or thermosets, as in thermally cured liquid silicone rubbers. There are a few key thermoplastic elastomers (TPE) on the market for AM, including the NinjaTek (Fenner, Inc.) family of products which are generally thermoplastic polyurethanes (TPU) with **durometers** of Shore 85A to 95A. These ME filament feedstocks are derived from injection molding grades of TPUs. Other TPEs on the market include Kraton® (Kraton Corp.) or Pebax® (Arkema Group)-based filaments sold under a variety of trade names. Since all of these materials were initially invented for traditional extrusion-based processing of polymeric materials, like injection molding, much is known about their performance across a wide range of applications and they are in common use. Soft elastomers with Shore 60A or lower durometers are difficult to adapt to traditional filament ME processes due to the mechanical deformation of the filament as it is fed into the extrusion die. Therefore, pellet-based ME of elastomers enables the use of a wide range of materials, although elastomer parts tend to be small with fine detail and the larger pellet-based ME technology is not necessarily suitable for these components.

Flexible SLA resins and MJ flexible photopolymer materials are widespread on the market. What is interesting about MJ elastomers is that due to the voxelization of the MJ process, the durometer of these materials can be dialed in during the design of the part – just by mixing hard and soft **voxels**, an element of volume in 3-dimensional space. Combined with the architectural complexity of additive manufacturing, material variations on the fly are an important advantage of this technology, albeit the photopolymerization of elastomers generally does not yield the properties of melt-processed materials.

Photopolymer elastomers can be widely customized during blending in the manufacture of the material or at the point of use. Because of the multicomponent photopolymer formulations, a wide range of properties can be achieved, however the elongational properties of these thermoset elastomers are not as good, in general, as the elongation of TPEs or thermally cured elastomers from direct in writing. Regardless, SLA and its vat polymerization variants give the surface finish and fine detail required for consumer products such as silicone watch bands and soft-touch headphone components. Direct ink writing (DIW) ME has been demonstrated for a variety of silicones from Wacker Chemie AG and Dow although due to the drawbacks of DIW, there are not commercial applications of these processes, yet.

TPUs are also being investigated in PBF and HP Multi-Jet Fusion processes as the powder feedstock. TPU powder is still under development by a number of companies, including Covestro. While PBF and HP MJF processes are routine for PA11 and other thermoplastics, the unique powder rheology and fusion characteristics of elastomers need to be revisited in terms of these known processes. Additionally, highly fused elastomer powders will likely suffer from low elongation to break and high defect concentrations which will limit their high-strain properties and fatigue resistance.

Polymer summary

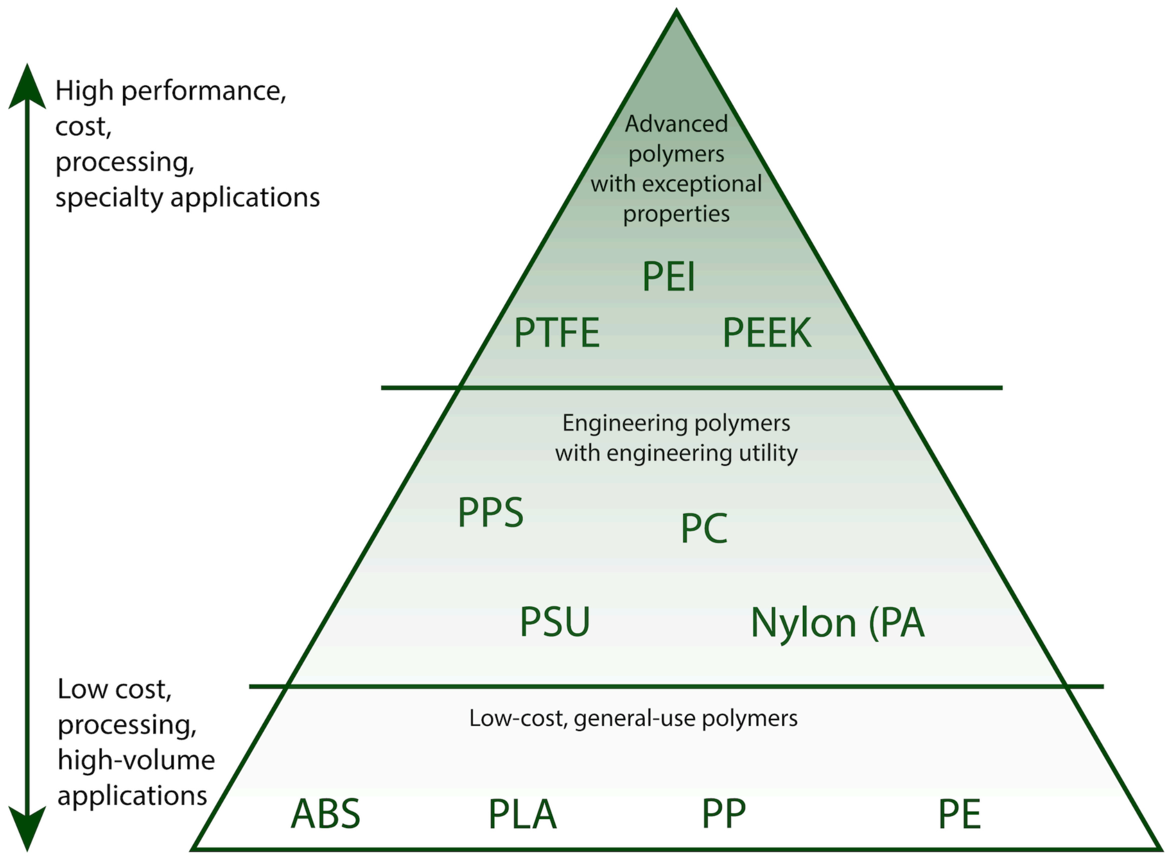


Figure 3.3 Polymer performance pyramid.

Additionally, there are some polymers that are widely used that have not been deployed in additive processes. Materials such at polytetrafluoroethylene (PTFE), polybenzimidazole (PBI), and other common polymeric materials, such as Kevlar, are not necessarily melt processible or cannot be formulated as a polymerizable liquid resin and will be difficult to integrate into AM feedstocks except in the case of composites.

The availability of high-performance, finished materials directly from the AM process (and associated post-processing) enables low-run production of end-use parts, full-functionality advanced prototypes, and one-of-one customization without sacrificing the materials performance that is expected from high-fidelity manufacturing techniques.

3.2 Metallic Materials

Learning Objectives

By the end of this section, students will be able to:

- Describe the range of engineered metallic materials available for AM.
- Describe the means of preparing and processing those materials for use in AM applications.

Over 100 different alloys are either commercially available or have been proven in the laboratory as suitable for AM. These alloys cover all the primary classes, with many being available for multiple processes, as summarized in Table 3.5. The majority of alloys currently used in AM were originally developed for casting, welding, or wrought (sheet, plate, forging, extrusion) processes for two reasons:

1. Using an alloy with a known chemistry and characteristics reduces the risk of unforeseen metallurgical issues, such as brittleness or corrosion issues.
2. It can be difficult to build a material supply chain for a new alloy. Hence, most of the alloys are similar or identical to existing ones, and are already produced as a wire, powder, or foil for another market.

This situation will change in the future as the AM industry grows and more alloys are developed. Note that the mechanical properties, cost, and other characteristics for a given alloy class can range widely; consulting a current comparison guide will be necessary. Relative cost is often expressed in terms of per kg, so in some cases the use of a lower density but higher cost alloy can be less expensive, keeping in mind that metal feedstock cost may only represent 10%-50% of the final part cost.

While most alloys are characterized by their composition, density, and mechanical properties, two other characteristics of importance to AM are **weldability** and heat treatment. Weldability is important because many AM processes are fusion processes, that involve melting the alloy and fusing it to the previous layers through solidification. Fusion based AM processes are often described as either 'making the part by welding' or 'making the part by micro-welding'. Heat treatment is important because certain alloys require a specific heat treatment to obtain optimum properties.

Heat treatment

These primary types of heat treatment are below, with the percent of melting point referring to the absolute melting point in K:

1. **Stress-Relief** – This is used for most alloys which undergo a fusion process to eliminate residual stresses that can lead to distortion, decreased fatigue lives, or reduced corrosion resistance. It generally takes place between 30% and 40% of the melting point. This is often performed on parts made using fusion AM prior to removing it from the build plate.
2. **Annealing** – This is used in austenitic (3xx series) stainless steels, copper alloys, and a variety of Al, Co, Ni, Co, Fe, and refractory alloys. The primary goal is to provide a more stable microstructure for a better balance of mechanical properties and corrosion resistance. Annealing temperatures are generally between 50% and 60% of the melting point
3. **Austenize**, Quench, and Temper – This is primarily used in alloy steels, tool steels, martensitic (4xx series) stainless steels, and some titanium alloys. It involves heating the material to around 60% of its melting point (austenize), rapidly cooling it (usually a water or liquid quench), and then reheating to around 300C (tempering) to remove brittleness.
4. **Solution Anneal**, Quench, and Age – This is most commonly used for aluminum alloys, PH (Precipitation Hardening) stainless steels, Ni alloys, some Cu alloys, Mg alloys, and some Ti alloys. It involves heating an alloy to around 90% of its melting point (Solution Anneal), rapidly cooling (Quench), and aging at around 25% of melting point to precipitate out phases that strengthen alloys, hence why it is referred to as **precipitation hardening**.

The actual temperatures, times, heating and cooling rates for any alloy often need to be quite closely controlled. Since the overwhelming number of alloys used in AM were previously developed for casting, wrought, and welding applications, the optimum heat treatment for the same alloy used for AM may be different. It should also be noted that the rapid (generally liquid) cooling in some of the heat treatments can induce residual stresses, distortion, and even cracking.

Another thermal treatment often used in conjunction with AM is **hot isostatic pressing (HIP)**. This consists of heating the material to around 50% of its melting point while under extremely high pressure (100MPa – 200MPa) in Ar gas for 2 to 8 hours, then cooling back to room temperature. The purpose is to close any discontinuities (pores, lack of fusion, or cracks) in the interior of the part. HIP is not effective for discontinuities that are open to the surface. Also, the presence of an inert gas in a pore (such as that which may become trapped during AM processing in and Ar atmosphere) may also keep it from fully healing. This is either because as the pore shrinks, the internal gas pressure will increase until it matches the HIP pressure, arresting further shrinkage and healing. In some instances, especially if the part is treated to a high-temperature solution annealing after HIP, the gas and the pore may then expand, as the temperature heats the gas and raises the pressure, while simultaneously lowering the flow stress of the metal. The overall relationship between pore size, gas content, alloy, pressure, time, and temperature is very complex with examples where HIP is successful and where it is not successful in the literature, with the current consensus being that it does provide a benefit.

Because of the high temperature and long time, HIP often doubles as a stress relief or an annealing operation. If the HIP temperature is sufficiently high and the cooling rate is relatively fast and controlled, it is possible to also use this as the solution annealing and quench step for precipitation hardened alloys that do not require a rapid quench. This is known as a combined cycle, and it is also possible after the quench to hold the part at an elevated temperature to age as well. Since HIP vessels are significantly more expensive to purchase and operate than heat treat furnaces, however, economics may still recommend performing these operations in different cycles.

Metallic Feedstock Types and Processes

Because AM by definition makes parts in layers, the metallic feedstocks used are small or thin, meaning powders, wires, or foils. While powder bed fusion (PBF) by definition uses powders, and sheet lamination (SL) by definition uses sheets or thin foils; directed energy deposition (DED) processes can use powder or wire, while binder jetting (BJP), material extrusion (ME), Material Jetting (MJ) and cold spray (CS) use powders. Typical feedstock types and sizes, along with their associated processes, are provided in Table 3.5. The different ways in which these feedstocks are manufactured has an impact on their subsequent behaviors in AM.

Feedstock		Process								
Type	Size	Laser Powder Bed Fusion	Electron Beam Powder Bed Fusion	Small Puddle DED	Large Puddle DED	Binder Jet and Polymer material Extrusion/ Jetting	Material Extrusion	Material Jetting	Cold Spray	Sheet Lamination
Powder	<15μm					X				
	15μm - 45μm	X				X				
	45μm - 105μm	X	X	X	X	X				
	105μm - 150μm				X	X			X	
	>150μm				X				X	
Wire	<1.5 mm diameter			X				X		
	>1.5 mm diameter				X		X	X		
Foil	~250μm									X

Table 3.5 Metallic Feedstock Types and Associated Processes

Wire Manufacturing

Regardless of the alloy system, wire is made in generally the same way. A cylindrical **ingot**, or cast simple shape suitable for further processing, of the alloy is cast in a melt shop, and then progressively reduced in diameter in a series of forging, followed by bar mills, until the bar is relatively small in diameter, with 25mm being near the top end. This bar is then pulled through a series of dies to progressively smaller diameters, known as drawing, until the final wire diameter is achieved. Because drawing is a cold-working process that progressively strengthens a metal and reduces its ductility, intermediate anneals are performed to reduce the strength and restore the ductility. Other steps involve the chemical removal of lubricants and oxide coatings. An operation done for some arc welding (generally Gas Metal Arc or MIG) wire is to add a thin Cu coating to conduct electricity from the weld electrode to the wire. Because of this, care must be taken when ordering wire if a Cu coating is not wanted.

Highly workable, non-reactive alloys such as mild and austenitic stainless steels will have an annealing station as part of a large, continuous wire drawing line that may produce thousands of kilometers of wire in a single day. Alloys that are more difficult to work, especially reactive materials, such as titanium alloys, will be drawn to the extent of their ductility, annealed in a vacuum furnace, and then further reduced as an iterative operation until the final diameter is achieved. Additionally, surface oxidation may need to be removed, which further reduces the amount of sellable wire. This means that in some alloys, small variations in diameter can result in significant increases in the unit cost of the wire.

Some variants on this process, especially for low melting point alloys like Al and Cu, will make the bar using continuous casting methods which can range from 10mm diameter to up to 75mm diameter. Another variant, generally for metals with very high melting points, known as refractory metals, such as tungsten, molybdenum, niobium, tantalum, etc, will press and sinter powders into a billet, which will then be fully densified using HIP, forging, or extrusion. This approach would also be used for metal matrix composites and alloys that cannot be cast, such as some nickel-based superalloys.

Foil Manufacturing

Foil manufacturing is much like wire manufacturing except that instead of round bar being drawn through a die, flat sheets are reduced in thickness using a rolling mill. Even without cold-working, the pressure needed to roll an alloy increases as it gets thinner. As a result, foils are produced in specialized mills with relatively small rollers that are backed with other rolls, known as Sendzimer Mills. Like wire, intermediate anneals are often necessary.

Powder Manufacturing

Whereas wire and foil are made using variants of the same process, a wide array of processes are used to make powder.

Plasma

These processes use a plasma to melt solid metal or alloy of the desired composition to form spherical particles. Barring the pick-up of undesired gases, the composition of the powder is the same as the feedstock. Generally, whatever you can get in bar, wire, or particle stock you can make into spherical powder. There are three processes in this category:

1. **Plasma Rotating Electrode (PREP)** uses a plasma torch to melt a cylindrical bar of the desired alloy. The rapid (>10,000 RPM) spinning of the bar causes the molten metal to fly away from the bar and form spherical particles. A combination of the alloy surface tension and the radial velocity of the molten alloy as it departs the arc determine the powder particle size. Attributes of powder from this process are a relatively coarse size distribution, nearly perfect spheres, almost no **satellites** (small powder particles adhered to larger ones), and almost no porosity.
2. Plasma **Atomization** (PA) uses a wire feedstock that is melted by plasma torches in place of forcing a molten metal and gas through an orifice. The wire feedstock is significantly more expensive than the billet or ingot feedstock used in gas atomization. The primary benefit of plasma atomization is that it has lower satellite and porosity content than gas atomization produces.
3. **Spheriodization** is a way to convert existing irregularly shaped or porous particles into spherical powder particles. In this process, the particles to be converted into spheres fall through a plasma. While they are falling due to gravity, the particles re-solidify into spheres. A combination of alloy surface tension and the initial particle size determine the powder particle size, thus making the initial particle size key to the powder size distribution. This powder can be finer than PREP but is generally coarser than atomized. It will have more satellites and pores than PREP but will generally be better in both categories than typical atomized powder.

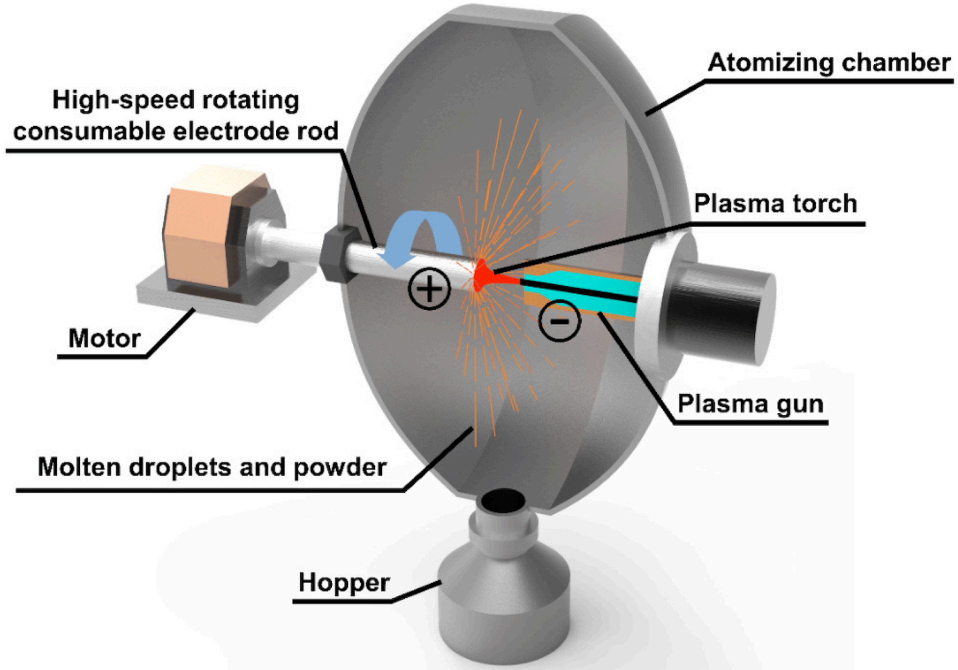


Figure 3.4 Plasma rotating electrode is a primary method of powder manufacturing. A bar is spun rapidly and heated by a plasma torch. The high speed of rotation ensures that the molten alloy flies away from the bar. Particle size depends on the alloy composition, the electrode diameter, and the rotation speed. (credit: modification of “PREP principle diagram” by Li et al in “High-Quality Spherical Silver Alloy Powder for Laser Powder Bed Fusion Using Plasma Rotating Electrode Process.” *Micromachines 2024*, 15, 396. CC BY 4.0)

Atomization

Atomization generally involves mixing a liquid metal stream with flowing fluid and forcing the mixture through an orifice to scatter the liquid, which then solidifies into generally spherical powders. Key variables that influence the size distribution of the powder are the size of the molten stream, the metal:gas ratio, their velocities, and additional gas flows, and the size of the orifice. Additional characteristics of the powder are sphericity, satellites and porosity. Depending on the variables and degree of control, a wide range of characteristics is possible.

Inert Gas Atomization (IGA) and Electrode Inert Gas Atomization (EIGA) are the most common processes for reactive and high-value alloys, such as titanium (reactive), aluminum (reactive), magnesium (reactive) nickel-base (high-value), and higher value tool and stainless steels. This is because the inert gas (almost always Ar) does not react with the base metal or any oxidation-sensitive alloying elements. It should be noted that using an inert gas provides protection from oxidation but is no guarantee of a powder with good flow and packing characteristics or homogeneity. Standard IGA melts the alloy in a crucible and pours it into a gas stream, while EIGA melts a bar with an electrode, with the molten metal impacted by the stream.

Gas Atomization (GA) is primarily used for non-reactive, non-ferrous alloys as well as lower-grade tool, stainless, and carbon steels. The typical gas used is nitrogen, but sometimes air is used. This process is not used for reactive metals, as the result would be catastrophic.

Water Atomization uses water as the fluid in place of the gas. This actually allows for more rapid cooling of the particles. Like GA, it is not used for reactive or higher-grade powders. This is the lowest cost process and produces a relatively coarse particle size distribution and irregular powders.

Ground/Machined

Ground and Machined processes take existing large stock (bar, plate, granules, etc) and use mechanical energy by grinding or machining to make powders. By adjusting the machining and grinding parameters, a wide range of shapes and sizes can be achieved. One of the benefits of using solid-state methods to make the powder is the absence of melt-related defects, such as gas pores, although care must be taken to avoid contamination by the cutting media.

Milling/Turning: In some cases, this is as simple as purchasing chips or turning scrap from a machine shop and subjecting them to additional grinding or cutting operations to make powder. In other cases, an engineered process to deliberately make powders may be used. A benefit of this is that almost any wrought alloy can be converted into powder without the complexities of melting and oxidation.

Hydride – Dehydride (HdH): This process is limited to titanium and its alloys, due to the unique combination of hydrogen absorption and embrittling characteristics. In this process titanium or titanium alloy particles are put in a hydrogen atmosphere at around 700C. After a period of time, a significant (>1%) amount of hydrogen is absorbed into the titanium, and embrittles it. The particles are cooled, removed from the furnace and ground to the desired particle size. After this, they are put into a vacuum furnace at around 700C, and the hydrogen evaporates out of the titanium or titanium alloy, leaving behind smaller, but irregularly shaped titanium or titanium alloy particles of the same composition as the initial feedstock. A variety of feedstocks can be used, such as machining chips (alloy), sponge (pure Ti), or even an alloy made using a direct reduced process. This powder can be used as-is, or spheriodized to make a spherical powder. In this case, the size of the powder is determined by the initial particle size and the time used to grind it. Porosity levels would reflect the initial feedstock. Impurity levels would also reflect the initial feedstock, so if machining chips are used, they must be well cleaned in advance to remove carbides and steel from any cutting tools; along with any cutting fluids.

Direct Reduced

Direct reduced powders range start with an oxide or other metal-containing compound and use reacting gases, liquids, or thermal decomposition to produce a metal powder. While they are generally used to make pure metals, some variants can produce alloys. The original processes were the use of hydrogen to reduce refractory metal oxides into metal powders, and thermal decomposition of carbonyl iron into iron powder. Some processes also use electrochemical methods. Multiple processes for making titanium alloys are in development, with some in the initial stages of commercialization. Most of these powders are irregular, and some can be spongy with a very low (<20%) **tap density** (density of a compacted container of powder, expressed as a percentage of fully dense alloy), and would require secondary processing, such as spheriodizing, to achieve a higher tap density and better flow characteristics.

Powder Attributes and Characterization

In addition to the chemistry and way of making powder, a variety of powder attributes impacts their use in AM. The attributes include overall size, the distribution of size, surface oxide, individual particle chemistry.

Not only do different processes use different types of feedstock, but the size of the feedstock varies as well. The size of the powders is generally specified as a range, where the lower number indicates the size that 10% of the particles are smaller than (called D10), and the larger indicates the size that 90% of the particles are smaller than (called D90). Some specifications place requirements on the powder size distribution (PSD), such as D2, D50, and D98. The size ranges provided in Table 2 are commonly used, but many processes and users specify powders in other size ranges. While spherical powder is currently preferred and is usually specified for PBF and DED applications, the ability to flow and spread evenly are the most important requirements. Sphericity is less important for the other processes, and in the case of BJP and polymer ME/MJ powders that don't flow as well are preferred, as they have better green (condition after printing) strength and brown (condition after binder removal) strength to better retain their shape during sintering.

When powder is manufactured, the overall PSD covers a range that resembles a Gaussian distribution that may range from under 5μm to over 250μm. The powder manufacturer will then sieve the powder into the specified size ranges. The challenge for the powder manufacturer is to align the powder they produce, the price they can charge, and the customers they have to maximize the revenue they obtain from each lot of powder they produce. Much like the lumber industry where heartwood costs more than bark (excepting cork), some PSDs have a significantly higher market price than others, even though the unit cost to produce each size range (grow the tree) is the same.

Another consideration in powders, especially reactive alloys (Al, Mg, and Ti), is that the surface of the powder particles is covered with a thin oxide layer that is generally of a constant thickness. Thus, the smaller the powder diameter, the higher the ratio of surface area (and oxide) to volume. This means that the smaller PSDs are generally higher in oxygen than the larger ones. This is important when purchasing powders to make sure that one is not trying to get very small powders with a very low oxygen content, which can result in either excessive cost or poor availability. This comes into play in processes that require recovery and re-use of powders, as each run through the AM and recovery processes can result in oxygen pick-up. If the starting oxygen level is high relative to the maximum allowed amount, re-use can result in the powder quickly going above the maximum amount of oxygen, requiring scrappage and excessive costs. A final consideration in handling and mixing powders is that many specifications prohibit blending powder that is above the maximum allowed oxygen (or any other element, for that matter) with powder below the maximum allowed oxygen to create a blend that is within specification.

In powder bed fusion, the diameter of the powder is limited by the layer thickness, as having individual powder particles larger than the layer thickness can interfere with the recoater and impact the homogeneity of the layer. At the same time, powder particles that are too small can experience displacement by the melt pool. Electron Beam has traditionally used a larger powder size, but both processes are capable of using sizes in the 15μm – 105μm range, or even larger for very thick layers. Likewise, in DED, powder particles and wire diameters that are too close to the powder diameter can negatively impact the stability of the puddle, hence the reason small (generally <3mm) puddle processes use smaller diameter wire than large (>6mm) puddle processes.

Binder jet and polymer material extrusion/jetting (ME/MJ) can use a wide range of powder sizes, with small sizes being preferred for resolution, surface finish, and sintering time, and larger sizes preferred for cost, shrinkage control, and handling safety. A blend of sizes is sometimes preferred to optimize for sintering time and shrinkage. Material Extrusion (commercially known as the MELD® process) uses bar, large diameter wire or very coarse powder, often referred to as granules. One variant of Material Jetting (Xerox/Vader®) uses wire. The foil size used in sheet lamination is a trade-off of having a flexible foil (thinner is better), layer thickness (thicker is faster), and alloy type (higher-temperature and harder alloys are more difficult to ultrasonically weld, hence thinner is better).

A final way of characterizing powders is whether each particle is of the target chemistry (pre-alloyed) or if the powder particles are each a pure metal, and the ratio of different powders is the target chemistry (blended elemental). While these represent the extreme ends, blends of pure metals and alloys are also used, with an example being a mixture of 90% pure Ti and 10% Al/V master alloy (with a ratio of 60% Al and 40% V) being used to make Ti-6Al-4V. Each has its own advantages and disadvantages. Like the example above on oxygen content, the benefit of pre-alloyed powder is that the risk of chemical inhomogeneity in the final part is minimized, since one does not have to worry about the powder segregating during handling or passage through the AM machine and recovery/re-use processes. As a result, almost all of the fusion AM processes use pre-alloyed powder. Blended elemental powders and their offshoots, on the other hand, have been successfully used in the powder metallurgy industry for decades. Some of the benefits of blended elemental powders are lower cost, reduced inventory for a facility processing multiple closely related alloys, higher green/brown strength and faster sintering. Because of this, blended elemental alloys will more likely be used in BJP or polymer ME processes. A final potential use of blended elemental powders and AM is the ability to change the composition of from one region to another of a single part. These are often referred to functionally gradient materials and have been demonstrated in both DED and BJP processes.

Feedstock Safety and Cleanliness

Other feedstock factors relate to safety and handling. Smaller powders are more of a fire and inhalation safety issue, with reactive alloys of most concern. Because contamination is a concern with powders as well, powder handling is moving towards always keeping them in a sealed container throughout the entire process chain (‘protect the operator from the powder and the powder from the operator’), especially as powder bed fusion and binder jetting require recovery and re-use of powders. Safety and cleanliness are less of a concern in polymer material extrusion because the powder is encased in a filament with >40% polymer and a low surface area. In the case of polymer material jetting, the powder particles are also encased in a polymer. Additionally, polymer material jetting tends towards small, precise parts so that there is little powder in a given area. The coarse powder used for Material Extrusion is of little safety concern. Foil and wire have little or no safety issues, and while cleanliness is the primary handling issue, even this is reduced since wire-based AM processes are once through, with no recovery and re-use. Larger diameter wires are more difficult to handle but have less surface area for contamination.

3.3 Metallic Materials Characteristics

Learning Objectives

By the end of this section, students will be able to:

- Differentiate several feedstocks of metallic materials, and how they relate to AM processes.
- Describe the relationships between metallic feedstocks, AM processing, AM post-processing, and the resultant AM part.

Aluminum Alloys

Currently, the overwhelming use of aluminum alloys in AM is for L-PBF, with DED, ME, MJ, CS, and SL all seeing their initial introductions. The difficulty in sintering low-density materials with adherent oxides presents challenges for BJP and Polymer ME/MJ. Aluminum alloys have a wide range of properties, falling into several different categories. All of the precipitation hardened alloys require quenching in either water or an engineered quenchant, so the potential for distortion and residual stresses must be addressed.

Figure 3.5 Fittings and other aluminum parts fabricated by ADDiTEC's ElemX™ 3D liquid metal printer sit upon a workbench onboard USS San Diego.(credit: U.S. Navy photo by Mass Communication Specialist 1st Class Brandon Woods on DVIDS, Public Domain)

The most commonly used alloys at this time are Al-10Si-Mg and Al-7Si-Mg. These are essentially the AM counterparts of A360 (a die casting alloy) and D356 (a sand, permanent mold, and investment casting alloy). The Si content provides good weldability, and hence is favorable for AM. The presence of Mg with Si enables them to be precipitation hardened to a reasonable strength:weight ratio. Related to these alloys are the 4xxx welding and 6xxx (usually 6061) wrought alloys. The 4xxx welding alloys are available in wire form, hence are readily available for wire-based processes. They contain Si for weldability with some variants having Mg. Variants with Mg can be precipitation hardened, while those without are only annealed. Since 6061 is a wrought alloy, it is readily available as bar for ME, but is also available in wire (for DED), powder (for L-PBF and Cold Spray), and foil form (SL). It can be precipitation hardened to slightly higher properties than the casting-based alloys.

Because of their weldability and excellent corrosion resistance, 5xxx alloys are primarily used for architectural and marine use, but the inability to heat treat them limits their mechanical properties. Common product forms would be bar, wire, and sheet/foil. Because 5xxx alloys respond well to cold-working, cold-worked foils and SL or bar and ME would provide higher properties.

The 2xxx series alloys were history's original precipitation hardened system and were the primary ones used to build in aircraft from the 1920s through the 1970s, with advanced variants still used. They can be heat treated to higher properties than the 3xx, 4xxx, and 6xxx alloys. The high copper content, however, generally gives them poor weldability due to hot cracking. Welding grades such as 2219 are the exception, and are available in wire, although bar is also available. A20X® is an AM variant of a casting alloy that offers 2xxx mechanical properties and is available in powder.

The high Zn and Cu content in 7xxx series alloys also leads to hot cracking problems, so they have generally only been considered usable for solid-state processes such as ME and SL. The attraction of the 7xxx system is the very high strength that can be achieved with precipitation hardening. The development of a 7xxx alloy that is suitable for AM has been the subject of considerable research, with the first variant, 7A77.50 being registered and in the process of commercialization.

Scalmalloy® is one of very first alloys specifically designed for AM, whose unique Al-Mg-Sc chemistry, takes advantage of the rapid solidification in L-PBF to develop precipitates that impart very high properties without the need for precipitation hardening. The ability to achieve very high properties without needing to solution anneal and quench can provide additional design freedom as it eliminates the concerns over residual stresses and distortion from quenching, although the Sc content makes it a relatively expensive alloy. It also provides for very good thermal stability at elevated temperatures.

The typical process flow for both a precipitation-hardened alloy and Scalmalloy® using L-PBF, starting with initiation of the build program will illustrate the unique processing aspects of precipitation hardened and non-precipitation-hardened alloys.

Precipitation-Hardened Alloy

1. Build part.
2. Remove part, build plate, and excess powder from machine.
3. Analyze log file from machine. Unless this is automatically performed at the end of the cycle, it will take place after

part removal so that machine is available for the next build.

4. Perform rough finishing. Depending on the supply chain, the actual order of these operations can be quite flexible, with the exception that some form of stress relief should be performed prior to build plate removal to prevent movement and distortion of the part during build plate removal. As mentioned above, HIP can serve as the stress relief operation. Depending on the type of supports, HIP vessel operators may require removal of the supports to ensure that there is no entrapped powder that could escape and cause damage to the internals of the HIP vessel, especially the heating elements.
    1. Stress relief
    2. HIP
    3. Build plate removal
    4. Support removal
5. Solution anneal, quench, and age. This is almost always performed after build plate removal to prevent the build plate and part from cooling at different rates during quenching and distorting the part.
6. Lot acceptance testing. Excise and test metallographic and mechanical test (usually tensile) coupons. This may also include removal of features built on the part to prevent distortion during HIP, solution annealing, or quenching.
7. Surface smoothing. This includes processes such as tumble de-burr, bead blasting, etc. Integrated finishing machines for AM parts are being introduced to the market, with some of the machines incorporating support removal in the same operation. This can also include manual operations, such as manual removal of support rash (protuberances on the part where supports were attached).
8. Interface machining. This is generally machining of higher-tolerance features for mating with other parts, although non-mating regions with high tolerances would also be machined here.
9. Part acceptance testing. Depending on the industry, a part acceptance testing can range from simple checks with a gage, to highly detailed measurements on a coordinate measuring machine (CMM), to extensive nondestructive testing methods. This will be more fully discussed in 6.2 Production Acceptance Testing.
    1. Radiographic nondestructive testing. This can range from simple film radiography to digital radiography to elaborate computed tomography (CT) testing. One benefit with aluminum is that its low density allows for lower, more sensitive X-ray energies, thicker parts, or a combination of the two. As AM parts become more complex, CT testing may sometimes be required to validate the locations and dimensions of internal cavities.
    2. Dimensional inspection
    3. Penetrant inspection. Penetrant inspection is highly dependent on surface roughness. That found in typical L-PBF parts that have not been smoothed will not allow for high-sensitivity fluorescent penetrant testing used in aerospace, and even makes lower-sensitivity dye penetrant testing challenging due to the high number of false positive indications. Aerospace grade penetrant inspection of aluminum requires a pre-penetrant etch of machined surfaces, which can require a unique chemical solution, depending on the alloy.
10. Chemical treatments (paint, anodize, etc.) - Chemical treatments for higher Si alloys (Al-10Si-Mg, Al-7Si-Mg) can be significantly different than ones with lower Si contents, and different non-Si alloys have different chemical treatments.

Scalmalloy® or 5xxx Alloy

1. Build part.
2. Remove part, build plate, and excess powder from machine.
3. Analyze log file from machine.
4. Perform rough finishing. Scalmalloy® requires an aging cycle that has different parameters than the HIP cycle, while a 5xxx alloy would not require anything except a stress relief.
    1. Stress relief
    2. HIP
    3. Build plate removal
    4. Support removal
5. Lot acceptance testing.
6. Surface smoothing.
7. Interface machining.
8. Part acceptance testing.
9. Chemical treatments.

Figure 3.6 An Air Force technical specialist compares 3D printed pump bracket to the older bracket that needs replacement. The new part used a stronger alloy to decrease the amount of repairs that are needed over time. (credit: U.S. Air Force photo by Airman 1st Class Jayden Ford on DVIDS, Public Domain.)

Carbon and Maraging Steels

As the most widely used material system on the planet, there are thousands of steel grades, with hundreds of them available in powder and wire form. Carbon, in a range of content from 0.08% up to 1% provides the strengthening agent, with austenize, quench, and temper as the primary heat treatment to provide strength. The use of a liquid quench brings in complications for distortion and residual stresses. The other alloying elements are generally used to provide hardenability (the ability to fully harden thick sections) or other property enhancements such as elevated temperature properties, corrosion resistance, toughness, etc. Carbon steels can be divided into 4 main categories:

Mild steels generally have under 0.08% carbon and relatively low properties. In wrought form, these are by far the most widely used class of metal on the planet because of their low cost, formability, weldability, predictable mechanical properties, and wide range of product forms. Because even 'high-cost' carbon steels are very low cost, and can have superior properties, mild steels are rarely used for AM. This could change in the future as AM moves into industries such as construction and shipbuilding.

Low alloy steels will tend to have around 1% alloying elements by weight and under 0.4% carbon. They can provide very high properties with heat treatment in thin sections, with alloy 4130 being a prime example. Their low cost and the broad experience in the powder metallurgy industry makes them attractive for BJP and polymer ME. Their lower hardenability is not a tremendous liability in AM, as section thicknesses tend to be relatively low. Higher carbon contents can result in cracking in fusion AM processes.

High alloy steels (around 3% alloying elements and up to 0.4% carbon, as in 4340) and tool steels (around 10% alloying elements and up to 1% carbon) are very much like low alloy steels in terms of the impact of carbon on fusion AM processes. Higher alloy and tool steels would be selected based on the need for enhanced properties, or occasionally for hardenability. One of the benefits of AM for making tooling is the ability to put in conforming cooling channels, shown in Figure F03_02_Conformal, so it can be imagined that the high hardenability of tool steels may become less necessary for AM tools. Both types of steel are available in wire and powder form, although the choice is not as wide as for wrought and cast products.

Maraging steels, which are carbon-free Iron nickel alloys, were developed to provide very high strength steels without the need for rapid quenching and the inherent cracking and distortion risks. They can also provide higher toughness than some tool steels. They use a variant of precipitation hardening known as Maraging. Maraging steels are of interest in AM because of the ability to provide high strength parts without the high carbon content that can cause cracking in fusion AM processes. Their higher alloying element content (up to 25%), however, means that the feedstock will be significantly more expensive in relative terms than low and high alloy steels. The rapid cooling present in most fusion AM processes also opens possibilities to avoid a high-temperature heat treatment after build and proceed to a stress-relief/aging cycle.

Processing considerations for medium and higher carbon steels made using a wire DED process can be quite different from L-PBF of aluminum alloys, as described below.

1. Build part. This may have to be stopped from time to time and the part sent off for stress relief to prevent cracking of any martensitic regions.
2. Remove part and build plate from machine.
3. Analyze log file from machine.
4. Perform rough finishing. Similar flexibility to L-PBF, with the exceptions that while supports are less common in DED processing, they would be larger, and would probably be retained until interface machining.
5. Austenize, quench, and temper.
6. Lot acceptance testing.
7. Surface smoothing. While tooling surfaces often need to be smoother than parts, this will often be done during interface machining, with the remainder of the surfaces left as built.
8. Interface machining.
9. Part acceptance testing. The higher density of steels makes radiographic inspection more difficult, while very high strength steels do not require pre-penetrant etch. Additionally, steels can be inspected using magnetic particle inspection.
10. Chemical treatments. While there are significant efforts to develop alternatives to Cr plating, the process still exists, and may be required for some applications. Additionally, some chemical treatments of high-strength steels present the risk of hydrogen embrittlement, so a low-temperature bake out may be required.

Stainless Steels

Their combination of weldability, corrosion resistance, and low relative cost make stainless steels one of the principal alloy systems used in AM. The widespread use of stainless steels in powder metallurgy, MIM, and welded chemical, medical, and food industry applications means widespread availability of powder, wire, and foils. The stainless steels used in AM fall into four primary classes based on chemical composition and method of hardening.

Austenitic (3xx) and **Ferritic** (4xx) stainless steels are relatively low-strength steels. Cold working in wrought versions can double the yield strength, but they are not strengthened by heat treatment. The difference between austenitic and ferritic is that former contains a significant (>8%) amount of Ni which gives the alloy a more formable cubic structure while making it nonmagnetic. These alloys are ideal for a wide variety of applications where resistance from oxidation or corrosion is desired, but high strength is not.

Martensitic stainless steels have a low (<0.2%) carbon content and are commonly used for molds and dies where resistance against corrosion is desired, especially where the part produced in the mold has a high surface finish requirement. Designs with conformal cooling channels would be an ideal AM application. Precipitation hardened stainless steels also obtain their properties by heat treatment and would be used where one would use an austenitic or ferritic stainless, but where higher mechanical properties are desired. Because the required cooling rate for PH stainless steels is lower than for martensitic stainless steels, there are fewer concerns with residual stresses and distortion.

1. Build green part.
2. Remove green part from machine and excess powder.
3. Analyze log file from machine.
4. Remove binder using thermal or chemical methods, resulting in a brown part
5. Sinter brown part to target density, checking furnace log file and taking simple dimensions as a quick cycle check.
6. Optional HIP if full density is desired. No final heat treatment is required.
7. Lot acceptance testing.
8. Surface smoothing.
9. Interface machining. This would include supports and excess material needed for support during sintering.
10. Part acceptance testing. If required, non-magnetic austenitic steels would require penetrant testing.
11. Chemical treatments. Passivation of the surfaces to properly form a protective oxide is often performed.

Titanium Alloys

Titanium alloys are highly valued by multiple industries due to their combination of high strength, low density, toughness, and corrosion resistance. This combination of properties comes at a steep price, as shown in Table 3.5, which is why titanium alloys were one of the first systems where AM was implemented. Not only are titanium alloys costly, but their toughness also makes machining expensive.

Like wrought and cast product forms, Ti-6Al-4V is the primary alloy used for AM. Its weldability and ability to absorb its oxide in vacuum means that it can be used in nearly every AM process. This includes both aerospace and medical applications. Some of the first implementations of Ti-6Al-4V in aerospace use large-puddle DED processing to add features to a piece of plate, which is then stress relieved, ultrasonically inspected, and machined to the final configuration. The benefit of using AM is in reducing the ratio of raw material used needed to make a finished part (referred to as the buy:fly ratio in aerospace). The reduction in the high costs of procuring and machining Ti-6Al-4V more than make up for the additional costs for the DED processing. It should be noted that one challenge in fusion AM of Ti-6Al-4V and similar alloys is their high strength to stiffness ratio, which can result in excessive distortion, residual stresses, and even a higher propensity to crack during build. Thoughtful design and processing, however, can minimize this. While it is possible to heat treat Ti-6Al-4V to obtain maximum properties, the need for a rapid quench and the residual stress issues make this relatively uncommon. It is generally stress relieved or HIPped.

Commercially pure (CP) titanium is primarily used in the chemical industry due to its excellent corrosion resistance, formability, and significantly lower cost than Ti-6Al-4V, especially in sheet products. Its use in AM would also be primarily in the chemical industry for valve and connector components. A variety of Near-Alpha, Near-Beta, and Alpha titanium alloys are beginning to see use in applications where higher strength or higher temperature capability then Ti-6Al-4V is needed, without moving to higher-density Ni-based alloys. Most of these alloys use a post-build heat treatment to obtain optimum properties, which may differ significantly from the standard wrought products. The combination of high temperature capability and design complexity from AM makes some of these alloys ideal for heat shields and ducts.

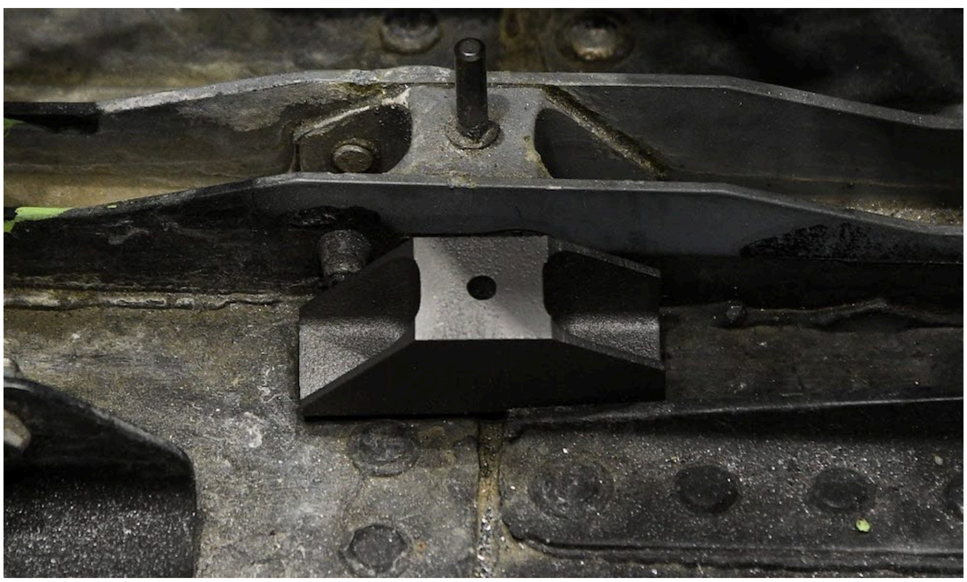


Figure 3.7 A new metallic 3D printed bracket alongside the aluminum part it will replace on an F-22 Raptor. The new titanium part will not corrode and can be procured faster and at less cost than the conventionally manufactured part. (credit: U.S. Air Force photo by R. Nial Bradshaw on DVIDS, Public Domain)

Processing considerations for Ti-6Al-4V made using a large puddle wire DED process differ slightly from that for carbon steels, as described below.

1. Build part. This may have to be stopped from time to time and the part sent off for stress relief to minimize distortion or prevent cracking.
2. Remove part/build plate from machine.
3. Analyze log file from machine.
4. Perform final anneal and/or HIP (if required)
5. Lot acceptance testing.
6. Pre-machining for ultrasonic inspection. This generally consists of simple, 3-axis milling to remove the crowns from the top of the part, unless inspection can be performed through the base plate. Locating features for finish machining may also be machined in at this point to reduce set-up time.

7. Ultrasonic inspection
8. Final machining. As can be seen in M4, all surfaces of the part are machined.
9. Part acceptance testing. Since ultrasonic inspection was already performed, this is limited to penetrant (with a different etching solution than used for aluminum alloys) and dimensional inspection.
10. Chemical treatments.

Nickel-Based Alloys

Nickel-based alloys are often used where titanium alloys don't quite have enough strength, stiffness, or temperature capability to meet requirements. They can also perform better than titanium alloys or pure titanium in some corrosive environments. While they are significantly lower in cost than titanium alloys, they are often more costly to machine, and their higher density often means more material mass is needed for the same application. Like titanium, use of AM for buy:fly and cost reductions will apply for some geometries.

Where lower mechanical properties are acceptable, 6xx (Ni-Fe-Cr) alloys are generally used where high temperature oxidation resistance is desired, and Ni-Cu (and Cu-Ni variants) alloys are used where corrosion resistance is more desired. Both of these alloy systems have excellent ductility and weldability, so lend themselves well to a variety of AM processes. Variants of these alloys will have either better temperature capability, oxidation resistance, or improved corrosion resistance.

Where either higher strength or higher strength at elevated temperature is desired, 7xx alloys are used. These use precipitation hardening with a relatively low cooling rate like PH stainless steels for significantly higher mechanical properties, as well as elevated temperature properties. Because they also have excellent corrosion resistance, variants of them are used in the chemical and petroleum industry in hot, corrosive environments. When even higher temperature properties are needed, superalloys containing Ni, Co, and other high-temperature elements are used. While these alloys sacrifice room temperature strength, they will have excellent resistance to deformation over long times at the elevated temperatures (creep) found in rocket and turbine engines. Some of the higher temperature grades, however, have lower weldability that can impact the ability to use for fusion AM processes.

Processing considerations for Ni-base alloys using a small puddle powder DED process differ slightly from that described above for Ti-6Al-4V.

1. Build part. While it is likely that fewer stress relief operations compared to other alloys due to the lower strength/stiffness ratio and lack of brittle phases will be needed, this is quite design dependent.
2. Remove part/build plate from machine.
3. Analyze log file from machine.
4. Perform heat treatment, which may include HIP and a solution anneal, quench and age for PH alloys. Large, thin, complex parts may require a fixture to support them during high-temperature heat treatments.
5. Lot acceptance testing.
6. Surface smoothing, generally a grit blast.
7. Final machining.
8. Part acceptance testing.
9. Chemical treatments.

Cobalt-Based Alloys

Outside of superalloys, cobalt-based alloys have seen most of their AM use in the medical industry, with some applications now appearing in aerospace due to their combination of weldability, ease of heat treatment, and corrosion resistance. These fit in between 6xx and 7xx nickel-based alloys in terms of properties, with generally lower material cost and a simpler heat treatment than required for 7xx alloys. In general, the process path for L-PBF CoCr parts is similar to other alloys, with the exception that current specifications for F75 medical alloy require a high-temperature homogenization cycle. This is an example of a heat treatment for a cast alloy that may not need to be as long for a part produced using AM with the very rapid cooling cycle.

Other Alloys

The wide range of processes and the geometric freedom provided by AM has found applications using a wide variety of other alloys as well. These include copper alloys, refractory metals, magnesium, metal matrix composites, and intermetallic compounds.

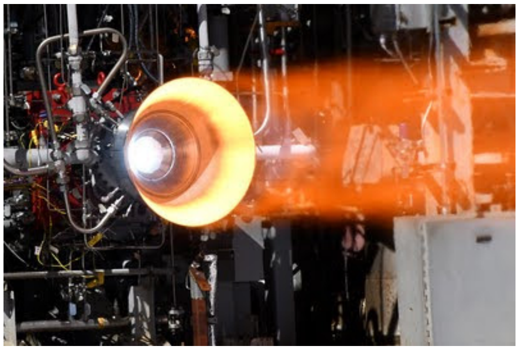


Figure 3.8 In this image, NASA successfully hot-fire tests a 3-D printed copper combustion chamber liner with an E-Beam Free Form Fabrication manufactured nickel-alloy jacket. The hardware must withstand extreme hot and cold temperatures inside the engine as extremely cold propellants are heated up and burned for propulsion. (credit: Modification of "NASA Advances Additive Manufacturing For Rocket Propulsion," by NASA/MSFC/David Olive on Flickr, Public Domain)

In addition to the Cu-Ni alloy system, copper alloys are often used for their high electrical or thermal conductivity. Precipitation hardened Cu alloys generally require liquid quenching.

Since the SL process for the heat exchanger takes place near room temperature and is a hybrid manufacturing process without melting, the process path is the shortest of all.

1. Build part.
2. Remove part/build plate from machine.
3. Analyze log file from machine.
4. Lot acceptance testing.
5. Final machining.
6. Part acceptance testing. This could include ultrasonic inspection.
7. Chemical treatments.

The process path for the cold spray propeller would be quite short, especially since Al bronze is a non-heat treatable alloy.

1. Build part.
2. Remove part/build plate from machine.
3. Analyze log file from machine.
4. Lot acceptance testing.
5. Surface smoothing and polishing.
6. Final machining.
7. Part acceptance testing.
8. Chemical treatments.

Refractory metals (W, Mo, Ta, Nb, etc) are being investigated for very high temperature applications. Because refractory metals are often brittle at room temperature and have high oxygen sensitivity, careful consideration must be taken, especially for fusion AM applications.

The low density, adherent oxide, and flammability of Mg have limited its potential in AM, although newer alloys with reduced flammability are being investigated.

Metal matrix composites (metals with either oxide, carbide, or boride reinforcements) are beginning to emerge from the laboratory into applications research. The high cooling rates of fusion AM could potentially allow for the fabrication of net-shape parts with a lower risk of the reinforcements agglomerating to the detriment of mechanical properties. Finally, AM has enabled the first widespread use of titanium aluminides, which have excellent creep resistance combined with low density. The rapid solidification and high, stable build environment of EB-PBF are enabling the fabrication of turbine blades. The process path would be similar to L-PBF of Scalmalloy®.

Future Alloys

Multiple organizations have initiated efforts over the last 5 years to develop alloys whose composition and processing are more compatible with AM, especially fusion processes. Much like Scalmalloy® does, these will take advantage of the rapid solidification in fusion AM processes to use chemistries with properties that one could not achieve using conventional ingot metallurgy. One concept would be to develop a precipitation hardened alloy where the rapid solidification and cooling in AM would leave alloying elements in solution, but where the stress relief would cause them to precipitate out, providing high strength without the need for a high-temperature heat treatment or rapid quench. While it typically takes 20 years for a new alloy to enter service, advances in computational modeling and the reduced scale-up needed for AM processes could result in these alloys being available sooner.

An ideal processing path for an alloy designed for L-PBF would be:

1. Build part.
2. Remove part, build plate, and excess powder from machine.
3. Analyze log file from machine.
4. Perform rough finishing and heat treatment.
    1. HIP
    2. Build plate removal
    3. Support removal
5. Lot acceptance testing.
6. Surface smoothing.
7. Interface machining.
8. Part acceptance testing.
9. Chemical treatments.

3.4 Ceramics and Other Materials

Learning Objectives

By the end of this section, students will be able to:

- Understand the range of engineered ceramic materials available for AM.
- Understand the range of other materials available for AM.
- Understand the different feedstocks of those materials, and how they relate to the different AM processes and the challenges associated with AM of ceramic materials.
- Understand the relationships between feedstocks, AM processing, AM post-processing, and the resultant AM part.

Ceramics represent one of the most challenging and least widely-developed category of engineered AM materials. Because conventional ceramic processing uses powders, feedstocks are widely available. The most common ceramic processes are BJP and MJ, with the polymer binder driven off during sintering, with VP processes becoming available. Because the ceramics are generally stable oxides, carbides, and nitrides, flammability concerns are minimal, although inhalation safety must be considered.

The processing path for a ceramic part made using BJP would also be shorter than a typical structural metallic part, as provided below:

1. Build green part.
2. Remove green part from machine and excess powder.
3. Analyze log file from machine.
4. Remove binder using thermal or chemical methods, resulting in a brown part.
5. Sinter brown part to target density, checking furnace log file and taking simple dimensions as a quick cycle check, with generally no final heat treatment required.
6. Lot acceptance testing.
7. Interface machining. For the mirror, this would include polishing of the reflective surface.
8. Part acceptance testing. Possibly radiographic to look for large discontinuities.
9. Chemical treatments, especially application of the reflective coating.

While fully densified technical ceramics remain a challenge, ceramic SLA resins and other type of photoceramic approaches are currently being deployed. Ceramic-filled resins are being sold by a number of vendors. These resins can be printed in an SLA-style printer at high resolution and fired using traditional ceramic processing approaches. Currently, there are a number of groups pursuing the best methods for producing densified ceramics from pastes and other photoceramic feedstocks.

In addition to conventional engineering materials such polymers, metals, and ceramics, other material systems are being used in AM. One of the first of these was heavy gage paper used in the original sheet lamination process, called Laminate Object Modeling (LOM). This process used adhesively backed or epoxy impregnated paper that was bonded to the previous layer. The outline of the part for that layer was then cut with a laser, and the excess material cut into 1cm x 1cm x 1cm cubes. After completion of the build, the cubes were broken off, and the part remained. This process was used for prototypes, visualization, and simple sheet metal forming tools. This type of sheet lamination has been extended to carbon fiber paper and a number of other type of sheet stock with various binders.

Concrete is another common material that is starting to be used in AM. Large-scale extrusion-type machines are being built that deposit concrete to build structures, eliminating the need for formwork. An example of housing made this way is shown in Figure 3.9. Finally, sand with a polymer binder is used in BJP to make casting molds in a form of indirect AM. Indirect versus direct AM gives designers and engineers choices on how to approach processing for different types of materials. Innovations in indirect AM and hybrid processes and assemblies have been useful in diffusing new design and processing flexibility across a number of important applications.

Figure 3.9 3D-printed housing using concrete in the lower floor. (credit: Modification of "3D printed house. Austin, Tx" by Lars Ploughman/Flickr CC BY 2.0).

Clearly, new materials are being brought into the AM sphere at a quick pace and materials innovations are one of the cornerstones of a growing AM industry as more product lines are being disrupted by AM strategies. While rapid prototyping started with brittle, unusable polymers, the industry has progressed to engineering metals and polymers that have long-lifetime applications. Work continues to additively manufacture high-value ceramic and composite components. While there have been some important breakthroughs in these areas, there is much left to do to industrialize many ceramic and composite parts.

Summary

It is clear that there are many materials available for AM, but in the larger world of engineered materials used in final applications, only a few dozen materials are regularly deployed for long-use AM components. This gap provides a tremendous opportunity for innovation in customizing material feedstocks for AM as well as exploring AM processes to bring new materials into the AM space. Polymers, metals, ceramics, and many different types of composite materials are being pursued for commercial deployment in AM and research is continuing at the intersection of AM processes and materials. The characteristics of thermoplastic and thermosetting polymers and the thermal and photo energy sources needed to process and shape these materials drive the AM technology choice for obtaining the desired polymeric part. Thermoplastics are most often encountered in ME using filaments or pellets. While the availability of high-quality filaments poses a barrier to bringing new thermoplastic materials into AM, the use of pellet extrusion AM is highly desirable as this feedstock is widely used in the plastics industry for molding. Photopolymer thermosets are the feedstock that enables both vat photopolymerization and photo material jetting, as in PolyJet systems. While other thermosets are beginning to be explored for industrialized AM, like liquid silicone rubbers and epoxies, these types of direct ink writing processes are usually confined to the research and exploratory domains.

While the total number of alloys available to AM are significantly less than those for conventional technologies, the full range of alloy systems are now available, and often for multiple different processes. As a result, having a suitable metallic material no longer limits a product team. As AM processes become more widespread in industry, niche' alloys that either deliver improved performance or lower cost for a given application will become available. The most likely candidates being more temperature and corrosion resistant alloys for heat exchangers, jet engines, and fluid systems, many of which will be designed to take advantage of either rapid solidification or solid-state processing to achieve properties previously unattainable via ingot metallurgy. Other candidate materials are metal-matrix composites for applications requiring higher temperatures or wear resistance. Finally, the wide range of solid-state metal AM processes means that fusion weldability is no longer a prerequisite for an alloy to be used for AM.

Ceramics is the least developed of the engineered materials. This is due in part to a number of factors, such as:

- Relatively simple shapes of many ceramic applications and limitations on complexity due to the brittle nature of ceramics
- Existing low-cost methods to fabricate shapes
- Typical challenges of sintering of ceramics are the same for AM, so the lead time savings is minimal

That said, the existence of a large range of available powder feedstocks combined with final processing likely being the same as for conventional products (sintering), mean that as AM equipment and expertise become more available to the ceramics industry that the range of material systems will become as widespread as there are for metallics.

Finally, there are a wide range of composite feedstocks available for AM, even though the composite nature of materials presents processing challenges. Many vat photopolymerization resins are in fact composites to introduce reinforcement into the generally brittle acrylate crosslinked material. Additionally, the available ceramic resins for vat photopolymerization are composites of photopolymers and ceramic particles that provide adequate, if not high-performance consolidation upon sintering. Composite material AM is challenging because there are many variables in formulating the composite material and usually composite fillers increase the melt viscosity of thermoplastics or flow viscosity of photopolymer resins. Regardless of difficulties in processing, many materials, especially plastics, are deployed as composites and there are some commercial thermal ME resins on the market from major manufacturers, such as SABIC, in order to meet the demands of applications in structural, automotive, and aerospace applications.

Review Questions

1. A powder particle size distribution denoted by D90=100 means what?
   a. All the powder particles are less than 90 microns
   b. 90% of powder particles are less than 100 microns
   c. 90% of powder particles are equal to 100 microns
   d. 100% of powder particles are less than 90 microns

2. Atomization is a process where
   a. plasma torch is used to melt a cylindrical bar of the desired alloy
   b. Existing irregularly shaped or porous particles are melted into spherical powder particles
   c. A liquid metal stream is pushed through an orifice and mixed with flowing fluid that forces the liquid to scatter, which then solidifies into generally spherical powders
   d. A wire feedstock is melted by plasma torches

3. Which AM processes use metal powders?
   a. PBF, BJP, DED, and cold spray
   b. SL Only
   c. PBF only
   d. DED only

Key Terms

3.1 Polymer Materials

ABS – acrylonitrile butadiene styrene copolymer, Crosslinking – chemical linking of polymer chains together to create an insoluble material, Cryogrinding – grinding material at low (liquid nitrogen) temperatures, Cyante Ester – chemistry for high-temperature polymers used in thermal post-processing of vat photopolymerization resins, Diluent – low viscosity component in polymer resin, Durometer – a measure of the hardness of a rubber, Glass transition temperature – temperature at which the glass to rubber transition occurs in amorphous materials, Melt Flow Index – mass or volume of polymer extruded in a given time at a constant temperature under a specific flow condition, PC – poly(carbonate), PE – poly(ethylene), PEEK – poly(ether etherketone), PET – poly(ethylene terephthalate), PLA – poly(lactide), PU – poly(urethane), PP – poly(propylene), PVA – poly(vinyl alcohol), Silane – silicon oxygen organochemistry for surface modification of glass, Thermoplastic – melt processible material, Thermoset – a polymer that crosslinks, Viscosity – flow characteristic of a fluid , Voxel – three dimensional constitutive unit

3.2 Metallic Materials

Annealing, Atomization, Austenize, Cold Work, Heat Treating, Hot Isostatic Pressing, Hydride-Dehydride, Ingot, Plasma atomization, PREP, Precipitation Hardening, Satellite, Solution Anneal, Spheriodization, Stress-Relief, Tap Density, Temper, Weldability

3.3 Metallic Materials Characteristics

Austenitic, Ferritic, Maraging

4

DESIGN FOR ADDITIVE MANUFACTURING

Figure 4.1 A student analyzes a component physically and using CAD software in the The UC Davis Translating Engineering Advances to Medicine facility. (credit: UC Davis College of Engineering/Flickr CC BY 2.0)

Chapter Outline

Introduction

Design for Additive Manufacturing (DfAM) fundamentally challenges the design engineer's way of thinking. It takes all the design rules and best practices learned over a century of the industrial age and turns the majority of them upside down. No longer is design freedom constrained by the traditionally held rules of fabrication processes like machining and casting. In fact, there are almost no fabrication penalties for complicated designs in AM given the flexible toolpath and layer-by-layer nature of the build process.

AM machines often use a laser, extruder, or other tool to selectively fuse or deposit material. The "toolpath" – as in the laser or extruder nozzle path – in an AM machine is not inhibited by the complexity of the part being designed. The AM toolpath is only constrained to that of the robotics of the machine rather than the shapes of conventional tools as in the case of traditional subtractive processes like machining, which remove material away versus add it layer-by-layer. A complex geometry, or in the machine's language, a tool path, has little to no bearing on how "hard" the machine works. Combined with the layering technique, the part in fabrication is never in the way of itself or the toolpath, yielding near-infinite geometrical possibilities.

However, despite the seemingly endless design possibilities with DfAM, there are considerations on how to approach the process the correct way in order to avoid expensive post-processing and support removal, for instance. This chapter details an approach for designing parts to be viably fabricated with additive manufacturing, acknowledging both the exciting potential and technical nuances to AM processes. Within this chapter, design content will cover metal powder bed fusion, directed energy deposition, polymer selective laser sintering, and polymer material extrusion.

4.1 Design Approach

Learning Objectives

By the end of this section, students will be able to:

- Differentiate key AM design terminology.
- Identify the AM Design Workflow process steps.
- Modify parts for AM design (MfAM).
- Understand how to approach conceptualizing AM designs from scratch (DfAM).

AM Design Workflow Process Steps

There are a number of steps required to move from having an idea to printing an AM part and readying it for use. The detailing of these processing steps is what is known as the AM Design Workflow, and the eight steps that are most frequently encountered are shown in Table 4.1

Process Step	Details and Components
1. 3D Model Design	3D solid model designed to meet requirements
2. Define Build Plan	Sliced model, Build orientation, Support structures, Toolpath
3. Prepare Material	Chemistry, Particle Size Distribution, Gauge, Certifications, Mixing
4. Prepare AM System	Calibration, Pre-use checks
5. Execute Build	Parameters, Data collection
6. Inspect	Dimensional, Metallurgical
7. Post-process	Heat treat, Machine, Surface treatments
8. Final Inspect	Dimensional, Surface, NDE

Table 4.1

Regardless of the specific printing process, most AM parts follow these 8 basic steps, although each step may vary. For example, a plastic part does not need to be heat treated in Step 7, but surface treatments could exist to smooth out rough edges or make a part watertight.

The content of this chapter focuses primarily on Step 1, but it is important to realize that if parts are designed to take advantage of AM's ability to create complex designs, the added complexity can negatively affect subsequent steps if not properly accounted for during design in Step 1. For instance, Steps 2, 5, and 7 can be adversely affected from a cost standpoint.

In Step 1 of the AM Design Workflow, a 3D model must be created. This step, much like conventional manufacturing, is the foundation of creating an AM part. Within this step, 3D solid models can be generated in any CAD software package. Generation of the 3D model can come from: (1) creating the original design in CAD as shown in Figure 4.2 (2) scanning an existing part to create a 3D model, (3) converting a 2D drawing like that in Figure 4.3 to a 3D model, or (4) downloading a model from an online design repository.

Depending on which of these four methods is selected, different levels of design requirements may be necessary. For example, if one were to create an original 3D design in CAD, the design requirements may come from the designer's own thoughts, or perhaps the design requirements are being received from a customer. When 3D scanning an existing part, converting an existing 2D drawing or downloading an existing design, the design requirements could have been established many years ago. As such, those antiquated designs may not be the optimal for AM.

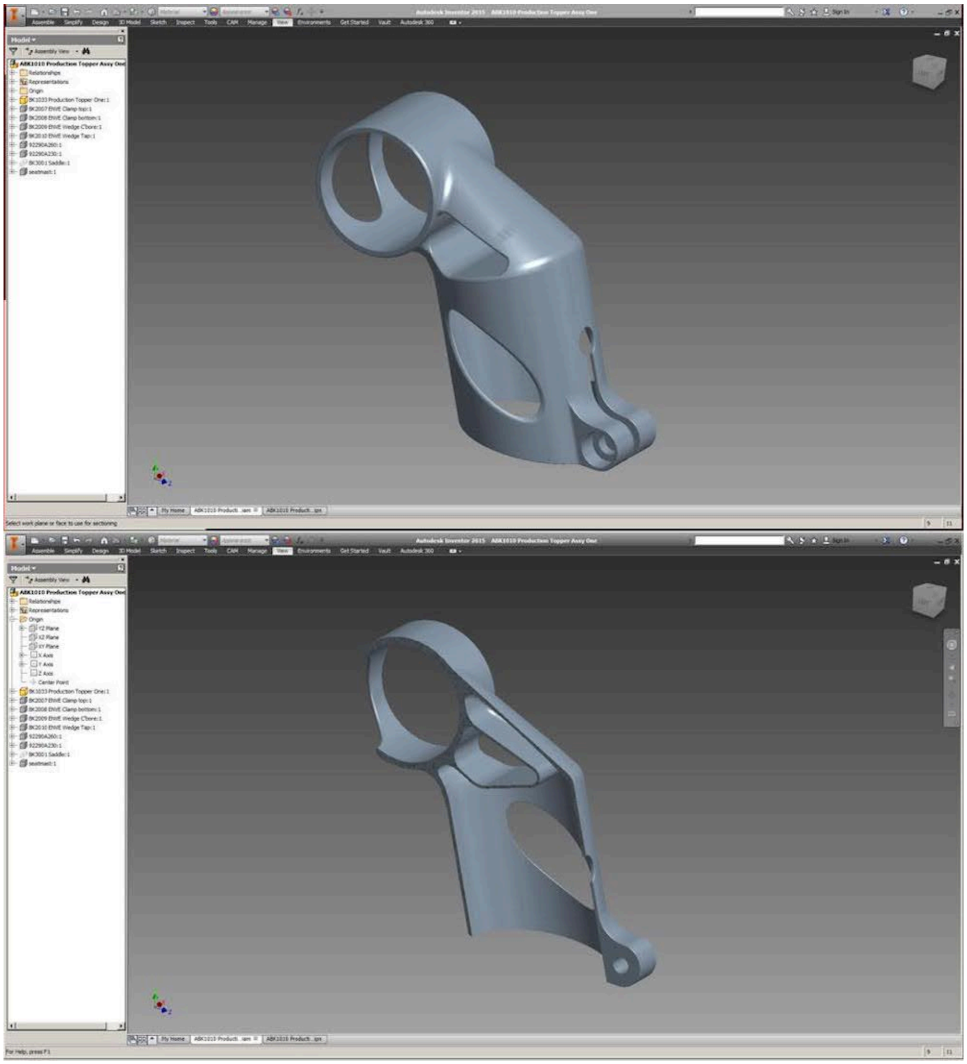


Figure 4.2 3D solid model in CAD (credit: Spencer Wright on pencerw.com, CC-BY 4.0 license)

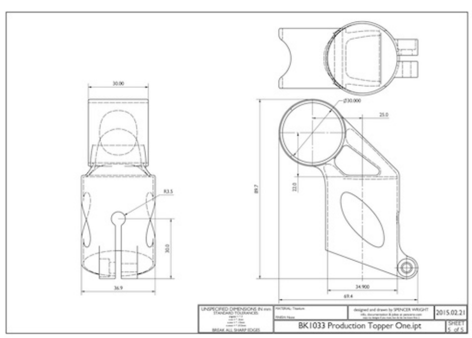


Figure 4.3 2D drawings must be converted into 3D solid models for AM (credit: Spencer Wright on pencerw.com, CC-BY 4.0 license)

There are many commercial software choices capable of creating 3D models. Many industrial companies and universities own specific software licenses, each having unique characteristics of functional performance. A list of major 3D CAD companies at the time of writing is found in Table 4.2. Note that product names and companies change often, and new or application-specific versions may be more appropriate for your needs.

3D CAD Software Name	Parent Software Company
Fusion 360	Autodesk
Inventor	Autodesk
Creo	PTC
CATIA	Dassault
SolidWorks	Dassault
NX	Siemens
Solid Edge	Siemens

Table 4.2

The Sculpteo Blog (https://openstax.org/l/AMSculpteo) maintains a relatively up to date list of open source CAD software that you can use, as well.

Since each software outputs its own coding structure, AM's primary working solution has been to use a common file language that AM machines can understand. To achieve this, 3D solid models are typically converted into a neutral **.STL file** that any AM build software can read and interpret. A .STL file is a faceted representation of the part that is created by **tessellation**, a process that approximates the boundary of an object with many triangles. Tessellation is an arrangement of polygons closely fitted together in a repeated pattern without gaps or overlapping, in this case triangles.

The STL File

The number of triangles of a .STL file depends on the user-defined output resolution from the CAD system. The more triangles created, the more accurate the tessellation, but the larger the .STL file size. Conversely, fewer triangles results in a smaller file size but a coarser approximation.

It is helpful for a designer to recognize what types of individual features the AM part will have and how .STL file resolution may impact the design. Without modification, the AM machine will print whatever the .STL surface is defined as. As such, coarse surfaces will look highly faceted after being printed. If the design involves many rounded features, then it may be worthwhile to define a higher resolution .STL output within your 3D CAD system prior to exporting to a .STL file. The higher resolution output settings can be accomplished differently depending on the CAD system. Some CAD systems require a triangulation factor value input prior to .STL file export. Other CAD systems simply output a .STL file based on the visualization settings. Explore each CAD system .STL file export settings carefully prior to .STL file creation.

While .STL is often still the primary solution for converting CAD into machine language for a specific AM system, other solutions are in development. Their main objective is to eliminate the .STL step and allow users to go straight from CAD to the AM machine.

Historically, the .STL file was the first type of digital format developed for the rapid prototyping technology, Stereolithography. This was first developed in the 1980's and the file protocol hasn't changed since.

Figure 4.4 shows different levels of detail in triangulations in an .STL file.

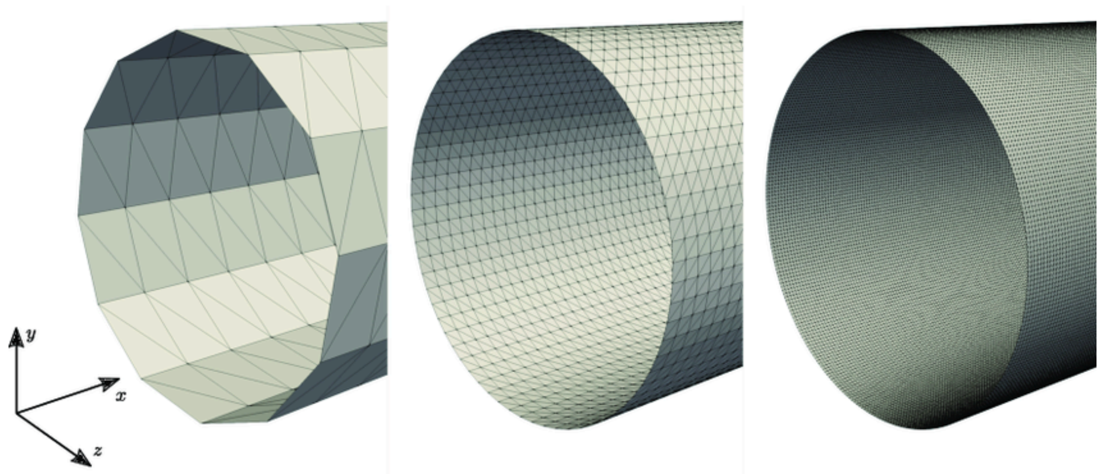


Figure 4.4 Triangulation of a .STL file. (credit: Modification of "STL triangulations of the pipe wall," in Morente, A. et al, " A Highly Scalable Direction-Splitting Solver on Regular Cartesian Grid to Compute Flows in Complex Geometries Described by STL Files." Fluids, Volume 8. 2023. CC BY 4.0)

Balancing .STL file size and accuracy is a challenge for complex 3D CAD models, especially, if the models have cellular features incorporated in them.

When exporting .STL files there can be a number of errors.

- Export Issues
  - Resolution tolerance too low, leads to low quality surface curvature
  - Multiple bodies/faces present during export – multiple shells, overlapping faces
- Conversion issues
  - Inverted normals
  - Bad contours, mesh holes
  - Overlapping/intersecting triangles

Though not all AM machines use them, the good news is that there are alternative formats to the .STL file that have been developed recently. One alternative format is the **Additive Manufacturing File (AMF)**. This file format is an XML-based format that includes information beyond the .STL file. Specifically, the AMF includes 1) units and object metadata 2) color and texture 3) multiple materials/gradients 4) optional curved triangles.

Another alternative is the **3D Manufacturing Format (3MF)** file format. It is also an XML-based format that includes 1) units and object metadata 2) color and texture 3) multiple materials/gradients 4) beam lattice elements 5) support structure information. Persuading AM machine equipment manufacturers to adopt these alternative types of formats can be difficult. Some machine manufacturers do and others do not.

Many of the large 3D CAD software companies are directly working with the AM machine manufacturers to export the native 3D CAD solid model directly to the machine code, thereby skipping the intermediate step of the .STL, AMF or 3MF formatting altogether. Though an incredibly promising advancement, only specific software companies have partnership agreements with specific machine manufacturers. This results in an unclear definition of which file format from which specific 3D CAD software is compatible with which AM machine type. Though incredibly inefficient and antiquated, the .STL file is the common language ubiquitous to software and machine manufacturers until further development.

Topology Optimization/Generative Design

Powder bed fusion allows for incredibly complex metallic structures to be created. This creativity unlocks design potential that is virtually impossible to fabricate using traditional manufacturing methods. There are two basic approaches to create organic structures for AM:

Topology optimization is a mathematical output from FEA (Finite Element Analysis). The FEA drives where material is placed such that the material layout is optimized within a design space, for a given set of loads, boundary conditions and constraints with the goal of maximizing the performance of the system for the given application. While accurate, topology optimization output can pose issues in terms of file format and detail resolution which limits viability, especially for very complex designs.

Generative design also encompasses the FEA behind topology optimization acknowledging the same criteria to optimize material, which it then utilizes to generate a viable design via an algorithm. It is often used as a design exploration strategy in which designers input multiple design goals in the form of parameters such as performance or spatial requirements, materials, manufacturing methods, and cost constraints. Historically, exploring a series of viable designs would require many hours from engineers to build them manually in CAD, but generative software uses machine learning to explore all of the possible permutations of a solution and quickly generates a number of design alternatives. The software tests and learns from each iteration based on what works and what does not.

Most of the software found in Table 4.3 offers either topology optimization or generative design as an approach to reduce weight, increasing functionality during 3D CAD model development in Step 1. Either approach is effective in creating structure that solves the objective function of design with the least amount of material necessary. Details of topology optimization and generative design can be found below.

Analysis

After a part concept has been generated using topology optimization or generative design, it is then critically important to validate that the design is structurally robust using finite element analysis (FEA) software. This software is a computerized method for predicting how a product reacts to real-world forces, vibration, heat, fluid flow, and other physical effects. Finite element analysis shows whether a product will break, wear out, or work the way it was designed. It is called analysis, but in the product development process, it is used to predict what is going to happen when the product is used.

Note that generative design software often uses artificial intelligence to perform multiple iterations of a design so that it is inherently performing FEA while the part is being generated. However, it is worthwhile to check structural robustness relative to the design intent using a different FEA software that would offer a non-biased perspective.

FEA/Topology Optimization/Generative Software Name	Parent Software Company
ANSYS Mechanical	ANSYS
SimScale	SimScale
COMSOL Multiphysics	COMSOL, Inc.
HyperWorks	Altair Engineering
Autodesk Simulation	Autodesk
Nastran	Hexagon MSC, Siemens PLM
Abaqus	Dassault
Hexagon	MSC
APEX	Hexagon MSC
Generate	PTC Creo
nTop Platform	nTopology
CogniCAD	ParaMatters

Table 4.3

When the design is validated using FEA software, the software identifies areas in the structure that need to be changed to ensure safe structural integrity to the overall part. This input is then fed back to the 3D CAD systems, and another topological optimization simulation is started. This iterative approach allows for a part to maintain a minimal amount of weight while concurrently being structurally validated, although iterating is sometimes easier said than done, and the workflow is ever-evolving. Certain topology optimization and generative software programs have issues resolving models and smoothing the 3D bodies for export to analyze, especially when the export output is .STL, since most analysis tools prefer CAD or .STEP type files. STEP, which stands for STandard for the Exchange of Product Data file, is a text file that contains three-dimensional model data in a standard format.

Fortunately, optimization programs such as ParaMatters and MSC Apex run the FEA simulation as a part of the generative design process and then automatically apply smoothing for better model resolution. MSC Apex, for example, has aimed to rebuild the optimization platform in such a way that it intelligently smooths surfaces within a CAD environment to yield high-fidelity export options. Once the designer and structural engineer have agreed on the design concept, and the optimized model quality is acceptable, the part must be prepared for fabrication. A .STL file (or compatible build set up file such as .STEP or .3MF) is created and imported into build

Build Preparation

Step 2 of the AM Design Workflow is a digital build plan that prepares the part for fabrication in the AM machine. A **build plan** specifies the orientation and layout of the part(s) on the build platform, including layer thickness, support structures (if needed), and the toolpath for each layer. See Figure 4.5 for examples of build plans.

Often the build plan is fulfilled by a manufacturing engineer, but it is important for design engineers to be aware of the implications of the build plan on the AM part being produced. Build orientation and layout decisions will impact:

- Build time and material utilization
- Build height and number of layers
- Surface roughness, including **staircasing**, which is a regular interruption in the part surface that looks like a staircase.
- Thermal cycling and residual stresses
- Microstructure and mechanical properties
- Post-processing (e.g., support removal)

AM build plan software is in development with most of the large commercial 3D CAD companies.

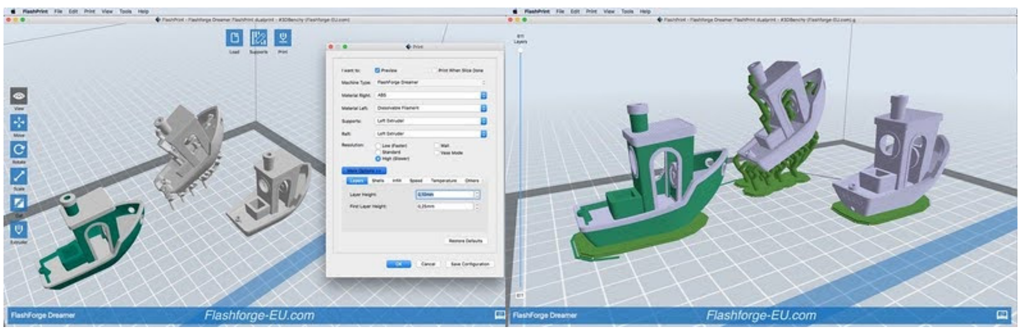


Figure 4.5 In the preparation step, the designer can choose to display and adjust the entire build, including the supports. In this example from Flashforge, a simple interface allows the user to control which supports to display. The two Benchy (boat) examples that lie flat require no extensive supports, but the one that is tilted upward at an angle requires supports to print in that orientation. (credit: Modification of "Flashforge_Dreamer_FlashPrint_#3DBenchy_Screenshot_GCode_preview" by Creative Tools/Flickr, CC BY 2.0)

Build Orientation and Nesting

In the build plan, it is critically important to understand how AM part orientation and nesting can influence part cost. In general, the more parts one can nest in the build volume, the less costly the parts become. In a similar fashion, the shorter the build height and the less sacrificial support material required, the less costly parts become. The less time the laser/extruder is active during the build process and more minimal support structures thus post-processing steps are, the less costly parts become.

With the above general cost considerations in mind, there are also a number of process specific build preparation rules of thumb.

The table below highlights the differences in how build preparation can be different relative to the type of AM process. Note that these are general guidelines and that each type of AM machine and material combination can have special requirements that limit or enhance design freedom.

Approach	Metal		Polymer	
	PBF	DED	FDM	SLS
Build Orientation	Minimize support material required. Keep features < 45 degrees from vertical z-plane	Minimize material required. Features must self-support.	Minimize support material. Keep features < 45 degrees from vertical z-plane	Minimize stair stepping features by identifying surfaces with low build angles
	Keep critical features away from downward angled facing surfaces	Incorporate build plate in part features	Minimize build height	Keep long aspect ratio surfaces vertical to prevent distortion
	Avoid parallelism of parts relative to machine re-coater	Orient holes in X-Y build plane	Orient holes about X-Y build plane	Orient holes in X-Y build plane
	Orient holes in X-Y build plane	Consider using deposition baseplate for symmetric parts to minimize distortion	Minimize stair stepping features	Build feature mass gradually. Angle your part relative to the build plane to avoid starting your part with bulk laser exposure of a large amount of material initially
	Minimize build height	Build feature mass gradually. Angle your part relative to the build plane to avoid starting your part with bulk laser exposure of a large amount of material initially	Anisotropic material, avoid structurally significant features in Z-axis of build	Minimize build height
	Avoid trapping powder in encapsulated volumes. Make sure that any enclosed volume has the ability for powder egress	Design large Radii at the transition point between the baseplate and start of the part to increase bonding strength	Large flat surfaces will tend to curl. Avoid orientation of parts so that large flat areas interface the base sheet and the part start	Avoid trapping powder in encapsulated volumes. Make sure that any enclosed volume has the ability for powder egress
Nesting	Maintain spacing > .125 inch	Maintain spacing > .5 inch	Maintain spacing > .100 inch	Maintain spacing > .175 inch

Table 4.4

Approach	Metal		Polymer	
	PBF	DED	FDM	SLS
	Consider exposure sequencing of parts to limit metal spatter from becoming contamination of adjacent part downwind of the gas flow	Avoid placing parts too far apart while nesting to minimize gantry travel time	Pack as many parts on a build sheet possible to lower unit costs	Pack as many parts in the machine as possible per build to avoid powder recycling inefficiencies
	Nest mainly in X-Y plane only, EBM allows for limited 3D nesting	Nest in X-Y plane only	Nest in X-Y plane only	Nest in 3D space, no support material required

Table 4.4

Process Simulation

Once a build plan is established and the part build orientation and support generation strategy are defined, designers need to understand if the actual fabrication process could produce issues due to common failures or issues specific to the machine, material, or process. Even if everything is planned correctly, an issue in fabrication will not only waste time and material, but could actually damage the machinery.

For example, with AM metallic processes, internal residual stress accumulates with quick heating of feedstock to melting and cooling back to solid metal during AM fabrication. As a result, parts will tend to distort during and after printing and after thermal post-processing. In addition, improperly designed support structures can delaminate from the build platform during fabrication if too much residual stress accumulates. This is especially true with large titanium structures, which have been known to distort and even crack during the build. If this happens during the powder bed laser process, there is a significant risk of the powder recoater feature in the AM machine to collide with parts that have distorted and separated from their respective support structure while printing, causing build failure. Therefore, AM Process Simulation is used to help understand the effects of the AM process on the part geometry and its fabrication.

AM Process Simulation is the analysis of the complex AM machine and material interaction using 3D CAD software specially designed to predict part distortion to parts during AM fabrication. Figure 4.6 highlights a process simulation that allows precise control over which aspect of the build is being considered, including its relationship to other parts. The simulator used here – by Siemens – accounts for collision avoidance with the laser deposition head.

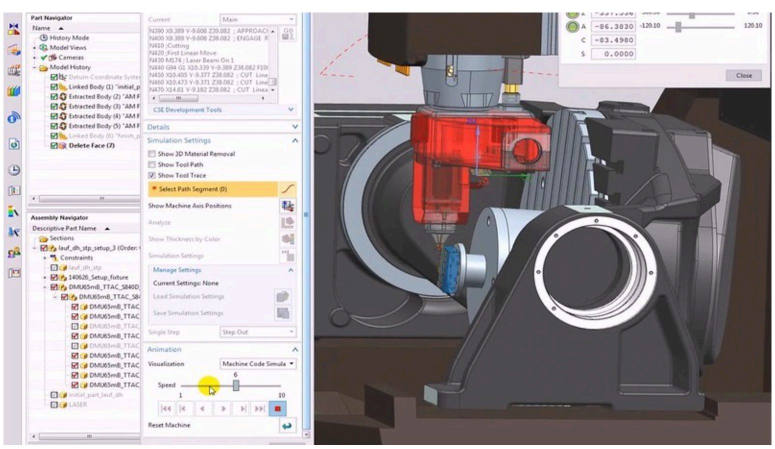


Figure 4.6 AM Process Simulation Example. (credit: "NX CAM Hybrid Additive Manufacturing – Simulation and Machine Support" by Siemens PLM Software/Flickr CC-BY-ND 2.0)

The distortion of features during an AM build depends on many factors such as the feature orientation, thick to thin transition zones, thin walled structures, material type, layer thickness, process parameter settings, heat treatment selected, etc. As such, software is used to simulate the amount of residual stress inherent to the AM build and digitally pre-compensate the geometry so that after printing and heat treatment, the parts will be closer to original design intent in the 3D CAD model. Table 4.5 lists several process simulation software packages that are now readily available.

AM Process Simulation Software Name	Parent Software Company
Simufact Additive	Hexagon MSC
Amphyon	Additive Works
AM Simulation	ANSYS
NX	Siemens
NetFabb	Autodesk
Geonx VirFac	GE Additive

Table 4.5 Examples of AM Process Simulation commercial software.

Inspection

After AM parts are fabricated, they must be inspected for dimensional compliance and mechanical integrity (step 6 of the AM Design Workflow). In addition, mechanical and metallurgical samples that were constructed concurrently with the part are collected and tested as a witness to the AM process. AM parts can be difficult to inspect with conventional coordinate measuring machines (CMM) due to part complexity and presence of internal features. AM parts are often inspected using light inspection techniques, or Computed tomography (CT) using x-rays, for instance (See Radiographic Inspection section in 5.2 Nondestructive Testing (NDT)).

There are many aspects to part inspection, and a sample list of common inspection techniques used for AM follows.

- Surface Roughness
  - **Profilometry**, which is the measurement of surface roughness at a fine scale – affordable and fast, but limited effectiveness at higher surface roughness values
  - 3D laser scanning microscope – expensive and slow, but highly accurate
- Dimensional Inspection and Metrology
  - Contact methods (e.g., CMM with touch probe)
  - Non-contact methods (e.g., 3D scanner with laser, structured light)
- Fluorescent Penetrant Inspection (FPI)
  - Uses fluorescent die to highlight surface irregularities – AM surface finish makes inspection difficult
- Radiographic Inspection
  - Used to find internal cracks, voids, or trapped powder – Limited use with dense parts
- Computed Tomography (CT) Scanning
  - Able to see in high-density materials
  - High-resolution digital data set for interpretation or measurement

From a design engineering perspective, it is important to understand that using extreme design complexity that AM affords may require more expensive inspection techniques.

AM Design Terminology Differentiation

As AM becomes more prevalent in industry, a common vernacular should be established within the company regarding the process and expectations for Design for Additive Manufacturing (DfAM). The views on DfAM vary widely on social media posts, company promotional materials, academic publications, and industry-led groups and professional organizations. It is important to resolve these differences within your own organization to describe the specific design actions taken when developing concepts and preparing AM parts for fabrication. This way, everyone in the organization speaks the same technical language, even when simply reproducing a part of an existing design with AM.

In this chapter, we define three distinct categorizations of design as it relates to AM:

- Direct Part Conversion
- Modified for Additive Manufacturing (MfAM)
- Design for Additive Manufacturing (DfAM)

Direct Part Conversion is defined as the exact AM reproduction of an existing design. No modifications are made to the part design as the goal is to reproduce a part that is traditionally made with existing fabrication methods. This technique is common with parts that have quick fabrication needs, parts that are 3D scanned to be reverse engineered, or legacy parts that cannot be sourced or redesigned without significant re-certification challenges.

Modified for Additive Manufacturing (MfAM) entails slightly modifying features of an existing design so that the part may be fabricated more easily and/or cost effectively with an AM process, without significantly altering the design intent. This approach often targets features that require support structures to reduce post-processing of the AM part or features that may lead to build failure (e.g., thin walls).

Design for Additive Manufacturing (DfAM) involves the complete re-architecting of design intent to create a new product from scratch that can only be manufactured using AM. This type of approach often leads to subsystem redesign as opposed to component (re)design occurring in MfAM or Direct Part Conversion. It is important to note that when DfAM is correctly applied, a designer would also include aspects of MfAM in the design.

It is incredibly important to distinguish between these types of definitions as each requires significantly different levels of a) certification requirements b) non-reoccurring labor expense for design c) design cycle times d) mechanical testing costs e) software investments.

Modifying Parts for AM Design (MfAM)

As direct part conversion does not permit any design changes, let us first examine MfAM. It is a common and natural inclination of many companies that are transitioning a part's manufacture from conventional to AM, to dip a toe in the water by the way of MfAM. As opposed to completely overhauling a part design, Parts are transitioned from a traditionally manufactured component to AM. Modifications are made to a part so that it can be fabricated with an AM process successfully and most cost effectively while concurrently matching original design intent.

AM processes can individually be quite different and the MfAM approach may also be different. As such, let us consider four different AM processes when applying MfAM. These AM processes are:

- Metallic Laser Powder Bed Fusion (PBF)
- Metallic Direct Energy Deposition (DED)
- Polymer Material Extrusion Additive Manufacturing (MEAM)
- Polymer Selective Laser Sintering (SLS)

AM Features

AM feature modifications are unique depending on the specific AM process used. Table 4.6, highlights rules of thumb for AM feature modifications needed to fabricate AM parts successfully.

Metal		Polymer	
PBF	DED	FDM	SLS
Change holes and cavities in Z axis to a teardrop profile to avoid support material	All structure needs to be accessible for subsequent machining operations	Avoid sharp corners in favor of large radii	Avoid sharp corners in favor of large radii
To reduce support material, change 90 degree features to self -supporting chamfers	Minimize the amount of material to be machined	Change holes and cavities in Z axis to a teardrop profile to avoid support material	Avoid thick to thin wall transition areas

Table 4.6

Metal		Polymer	
PBF	DED	FDM	SLS
Avoid sharp corners in favor of large radii	Avoid sharp corners in favor of large radii	Avoid thick to thin wall transition areas	Maintain minimum gap width spacing of features > .031 inches
Avoid thick to thin wall transition areas	Avoid thick to thin wall transition areas	General tolerances +/- 0.004 inches in the XY-direction	Minimum wall thickness > .028 inches
General tolerances are ±0.005 inch. If CNC tolerances are required, parts will require post-machining.	Can be used to weld repair and add features to existing products	General Tolerances +/- 0.010 in the Z-direction	Minimum hole size > .068 inches
Maintain minimum gap width spacing of features > .020 inches	General tolerances are ±0.008 inch for blown powder systems. CNC tolerances during post-machining.	Minimum walls thickness > 0.047 inch	General tolerances are ±0.012 inch.
Minimum wall thickness > 0.016 inch	For wire fed systems, generous net shape tolerances expected. CNC tolerances during post-machining.	Minimum hole size > .040 inches	Holes for powder egress should be > .140 inches
Minimum hole size > .020 inches	Blown powder minimum hole size > .2 inches, wire fed, > 1 inch	Maintain minimum gap width spacing of features > .020 inches	Minimum feature size shall be > .031 inches

Table 4.6

Design for AM (DfAM)

As defined earlier, DfAM is the complete re-architecting of design intent to create a new product from scratch that can only be manufactured using AM. That product can be a part, assembly, sub-system, or whole system. DfAM pushes the design envelope with the freedom that is made possible by AM build processes. It encourages designs to encompass multiple parts and assemblies that make up a system to reduce part count and touch time, while possibly also improving performance. That level of freedom reaches beyond what most conventional fabrication technologies can process. The highest levels of design freedom are most enabled by powder bed AM build processes such as metal and polymer PBF and Binder Jet. Design freedom is more limited in blown powder DED systems and largely absent from wire fed DED systems.

Often, people are aware that AM can produce very novel and organic looking structures, but they are not quite sure where to start in the process when designing from scratch. This is especially true for more seasoned design engineers that have had Design for Manufacturing and Assembly (DfMA) principles engrained in their design approach for many years. These techniques involve a lot of part substitution and reuse to lower costs. As such, it can be challenging and uncomfortable to break away to a level of design freedom not experienced before.

Concept Ideation

The first step to beginning re-architecture of a design for AM is to understand clearly the product requirements. A good way to begin understanding these requirements is to develop a **morphological analysis**, a method for exploring all possible solutions to a multi-dimensional, non-quantified problem. “A Morphological Analysis defines a process for generating solutions to problems by first breaking down a problem into its parts (or subcomponents or subfunctions), generating ideas for each part, and then exploring combinations of the resulting ideas to develop a solution or concept”

(Daley et. al, 2016) This approach works well for system-level design for DfAM. To create a morphological chart, you begin by listing the identified subfunctions that satisfy customer requirements. Next, you develop solutions for each subfunction.

To efficiently generate ideas for new concepts, it is helpful to conduct the exercise in a team brainstorming session to create a list of subfunctions to build the morphological chart. Ideally, the skillset required within the team should include AM design, conventional product design, AM process manufacturing, and customer representation. As DfAM structures can often become organic in nature, the AM designer shall also be well versed in the skills of biomimicry.

Biomimicry

According to the Biomimicry Institute, **biomimicry** can be defined as “an approach to innovation that seeks sustainable solutions to human challenges by emulating nature’s time-tested patterns and strategies. The goal is to create products, processes, and policies—new ways of living—that are well-adapted to life on earth over the long haul.” By integrating biomimicry principles that emulate nature’s structures into concept ideation, products will inherently become more structurally efficient.

DfAM of the same part shown in the MfAM section, except now the design has been completely overhauled and optimized via light-weighting that utilized biomimicry in the upper web-like structures. The ratio at which the branches grow uses the same strength ratios seen in the natural log of a tree.

Figure 4.7 Biomimicry is exemplified in the creation of artificial feathers, initially at a much larger scale than actual feathers. This design includes most aspects of the feathers, including the hooks at the ends of the barbules, which in natural feathers are invisible without magnification. (credit: Modification of “20180322-MeyersLab-Feathers-3492-export-8MP” by UC San Diego School of Engineering/Flickr, CC BY 2.0)

Functional requirements communicated directly from the customer are known as the **Voice of the Customer** (VOC). Based on this input from the brainstorming meetings where customer feedback is directly communicated, concept ideas are refined and modified to reflect true requirements. These requirements can be weighted within the Pugh Concept Selection Matrix, or **Pugh Matrix** for short, based on VOC rankings. The Pugh Matrix is a rating analysis tool that results in ranking of ideas to generate an optimal concept or selection.

Once ideas are generated, the concepts should be evaluated relative to the customer-defined requirements. Using a

Pugh matrix, each idea is compared to a baseline design for each requirement as shown in Table 4.7. Ideas are then scored as better (+1), similar (0), or worse (-1) than the baseline design for each requirement. The scores are then weighted and summed, and the best concept has the highest consolidated score. With this approach, the team not only selects the best concept but also keeps track of their decision-making process should questions arise later.

	Existing Baseline Design	VOC Weighting Factor	Morphological Analysis Chart Concept			
VOC Requirements			A	B	C	D
Mass Reduction	0	5	–1	1	0	0
Cost	0	2	0	1	–1	–1
Thermal Performance	0	4	0	–1	1	0
Ease of Installation	0	3	–1	0	–1	1

Table 4.7

In the example provided in Table 4.7, concept ideas generated in the morphological analysis brainstorming sessions are listed at concept A, B, C and D. The VOC requirements are shown on the left. Also, note the VOC relative weighting of each of the requirements on a scale of 1-5 with 5 being the most important. An existing baseline product (either a competitor's or an older design) is listed with a baseline of 0 for all requirements. Under each concept idea the team provides an assessment score for each concept as being worse than the baseline (-1) or better than the baseline (1) or the same (0).

Next, each assessment score is simply multiplied by the VOC weights to create a sum of weighted scores as shown below.

	Existing Baseline Design	VOC Weighting Factor	Morphological Analysis Chart Concept			
VOC Requirements			A	B	C	D
Mass Reduction	0	5	–1	1	0	0
Cost	0	2	0	1	–1	–1
Thermal Performance	0	4	0	–1	1	0
Ease of Installation	0	3	–1	0	–1	1
		Sum	–8	3	–1	1

Table 4.8

In this case, concept idea A is far worse than the baseline design, with concept design B being better. Concepts C and D are slightly worse and better than the baseline, respectively.

Topology Optimization and Generative Design

Now that VOC requirements are understood, ideas are generated, and concepts are sorted using the Pugh Matrix, generative design or topology optimization tools can be used to embody the concept. Alternatively, biomimicry or other approaches could be used to generate different embodiments for each concept. Keep in mind that just because one can produce complex structures with AM, does not mean one should do so unless it helps satisfy the VOCs.

Concept B appears to have an edge over the baseline design on paper, how long will it take to optimize for topology or use generative design? On occasion the objective requirements provided by the VOC might be satisfied solely with traditional fabrication methods. However, if they cannot be satisfied with traditional fabrication, then one must turn to additive manufacturing.

Below is the process flow that takes digital definition from VOC 3D CAD definition all the way to inspection. Many types of software exist at each of the steps of the digital chain.

The existing CAD will be assessed, FEA analysis run (within the optimization software), optimization applied, and then additional analysis run on the optimization. The optimized design will be prepared for build. The build plan will be simulated for build feasibility. The part will be built, and later inspection will provide empirical data to help the designer understand how accurate their digital tools are, and design improvements that can be made in the future. What is most important from a DfAM standpoint though, is the transition from CAD Definition to Topology Optimization (or Generative Design).

Another DfAM nuance is applying systems-level thinking when using generative design tools. Designer's concepts can be used for part consolidation as well as making a structure lighter.

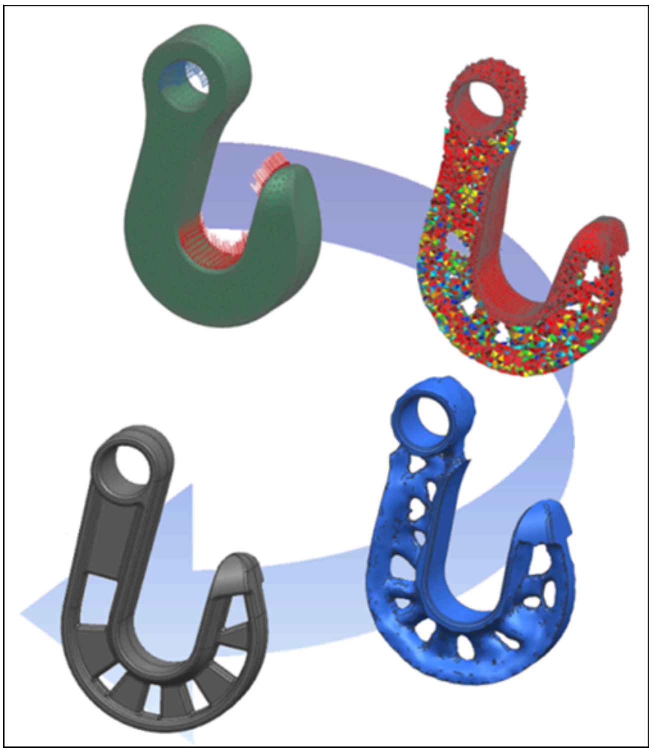


Figure 4.8 Using a generative AI process, a part can be optimized for weight while maintaining strength and shape. (credit: "NX8 Simulation - Opt" Siemens PLS Software/Flickr CC BY ND 2.0)

Generative design offers a glimpse into the future direction of hardware design. Using AI inspired software to derive a large number of design permutations will lead to faster product design cycles that are more optimized for the hardware requirements.

The basic generative design or topology optimization workflow is:

1. Define retained bodies – in other words, volumes on the part that should not be optimized
2. Assign material type – this loads the property inputs for the optimization algorithms
3. Set load cases and boundary conditions – these are the forces or loads the part will see, and surrounding boundaries that contain the part to a certain location in space
4. Set the objective – usually mass reduction
5. Set constraints such as volume fraction, model resolution, design speed, and manufacturing overhang angle
6. Optimize! Sometimes this can take hours or days depending on complexity and computing power

The digital chain is completed when the chosen design is input into build preparation software to create a build plan, which is then run through a process simulation tool to assess buildability. Once deemed feasible to build, the part can be sent to the machine to be built. After building, empirical results from inspection are then compared to simulated process results to advise and correct future designs and process simulations.

4.2 Design Optimization: Implementation while Considering Build Constraints

Learning Objectives

By the end of this section, students will be able to:

- Understand design nuances of powder bed fusion AM processes.
- Learn a number of different types of AM features used to lighten designs and add more functional efficiency.
- Describe the nuances of directed energy deposition AM processes.

AM provides a vast amount of design and manufacturing opportunities, and there is an abundance of tools and programs to help. But there is much development yet to take place in the industry, which creates unique challenges for optimizing the performance of AM parts. This section provides additional guidelines and strategies for overcoming specific build process constraints and achieving the most optimal designs. It demonstrates how to leverage both MfAM and DfAM skills at the same time for greater success.

Internal Passageways

When designing for AM processes such as PBF, binder jet, or polymer SLS, one of the major benefits of AM is the ability to create **internal passageways**, or open cavities that pass through the inside of the part. However, there are some nuances when designing these types of features. For example, AM PBF creates walls that are inherently rough. If the internal passageway needs to be smooth, expect to add cost with a post-processing step to smooth out the passageways. And even with the extra post-processing costs, don't expect mirror finish smooth surfaces like those of machined parts.

Also for processes that require support material, the profile of an internal circular channel will most likely need to be MfAM'd so that it is self-supporting during the fabrication process. If support structures are left in the passageways, they may be difficult (or impossible) to remove and will impede the flow through the internal passageway. Note that redesigning internal passageways is not as much of an issue with polymer SLS and binder jet, where the powder alone is supportive enough without excessive solid support structures.

Complex Sweeps and Surfaces

With AM, geometries don't need to be made using simple extrude, sweep, and revolve commands found in traditional 3D CAD software methods. Complex curves and surfaces can be used to generate unique geometries and organic shapes; provided designers know how to use the tools to create these structures.

It is important to maintain the orientation of the internal passageway, which is a diamond shape, so that it remains self-supporting as discussed in the previous section. Otherwise, the interior may need support structures which will be impossible to remove.

A **Cellular feature**, or type of mechanical structure that repeats a specific structural pattern, in order to offer a lightweight design solution. These repeating patterns encompass 3D or 2D space and are adjusted to accommodate different loading conditions. Of cellular features, two of the most common found in DfAM are honeycomb structures and lattice structures.

Honeycomb structures follow a form of biomimicry which draws inspiration from bee honeycombs. These types of structures are typically used in the aerospace industry made from metal or composite to form a core.

"**Lattice structures** are topologically ordered, three-dimensional open-celled structures composed of one or more repeating unit cells. These cells are defined by the dimensions and connectivity of their constituent strut elements, which are connected at specific nodes". (L. Hao, et al., 2011). These types of structures fulfill specific stiffness requirements, and simultaneously achieve weight reduction relative to bulk structure. An AM example is shown in Figure 4.9.

Creating honeycomb or lattice is becoming a very popular AM design engineer's tool in the toolbox as these types of features can be created in polymer SLS or Material Extrusion (FDM), as well as metal PBF and BJP technologies. However, there remains some challenges in using these structures in a part that exhibits high loading requirements or stringent inspection criteria.

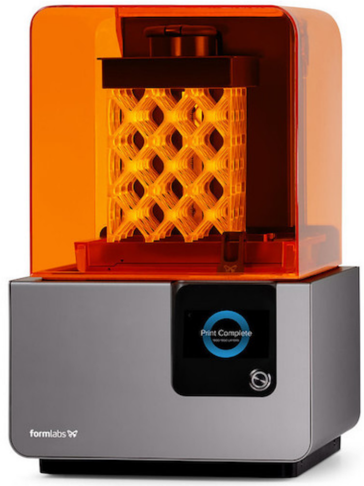


Figure 4.9 An example of a lattice structure. (credit: Modification of “Form 2 closed lattice” by Creative Tools/Flickr CC BY 2.0)

First, these features are difficult to produce with traditional 3D CAD software. On the other hand, they can be produced, but should they be? Honeycombs, lattices, and other lightweight features are great for additive, but they can be difficult to create and analyze in current tools. Software such as nTopology makes the process of creating cellular features easier as they have approaches that generate the geometry in more efficient ways. The program easily computes and displays complex lattices and organic structures.

The second challenge is structural evaluation. Just as creating these structures is difficult in 3D CAD, they are even harder to mesh in FEA software. Simply exporting these types of structures into FEA software is a challenge. At a higher level, structural analysts see every surface profile as ‘defect’ potential for a stress fracture. The rougher the surface, the higher risk of failure, especially with high and low cycle fatigue conditions. With honeycomb, lattice or cellular features, the designer exponentially increases the potential of premature failure if any significant load is passed through these types of rough surface structures. On the other hand, as a way to increase heat transfer efficiency, that same increase in surface roughness might be a desirable feature for complex heat exchangers composed of lattice.

The third challenge is inspection. If a part consists of many cellular or lattice features, how will it be inspected for conformance to design intent in a cost-effective way? With the current state of inspection technology available, it would be difficult to find an inspection method that could be used on these types of structures in a serialized production environment.

From a design standpoint, if a designer were to use honeycomb, lattice or cellular features, the best approach would be to place them in non-load bearing areas of structures to avoid the critical evaluation and software challenges described above.

Isogrids

Isogrid features are stiffening ribs, typically triangular in shape, protruding from a surface at a defined distance from the surface. These features have been used for several years in industry as a light weighting practice for CNC machining and composite fabrication industries.

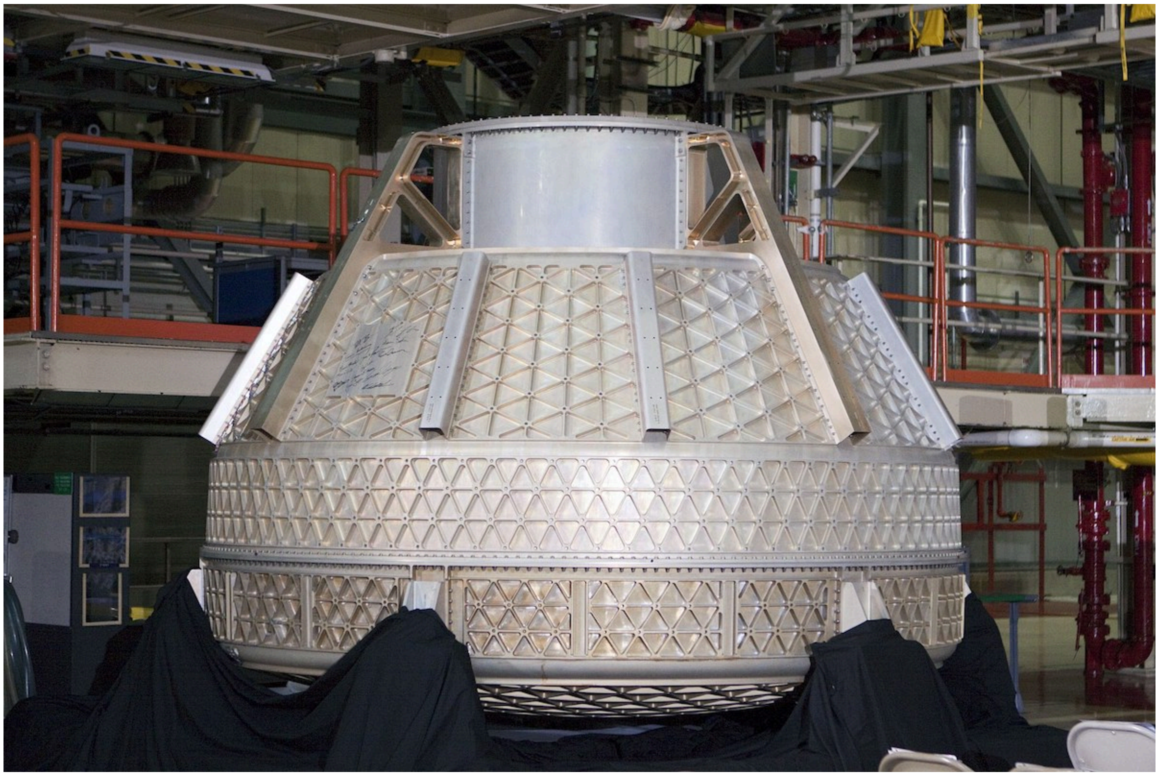


Figure 4.10 Isogrids on the pressure vessel for the CST-100 spacecraft. (credit: NASA, Public Domain)

Whereas lattice and cellular features are linked to PBF processes, isogriding offers flexibility across AM process types. This type of feature offers structural stiffness with reduced weight. It is also noteworthy that since applying isogrid features has been used in industry for a number of years, structural analysts will have greater ease analyzing this type of structure relative to cellular or lattice features. As a result, this type of design sees less certification scrutiny and analysis.

The discussed design features optimize AM shapes and performance, not without certain challenges. With those challenges and tips for overcoming them in mind, there is still more to master in design optimization as it pertains to the different AM fabrication processes. The remaining sections of this subject will outline basic design allowables according to each AM process as they exist today. Note that process development could always expand these guidelines in the future.

PBF Machine Process Constraints

When designing AM parts for PBF processes, there should be a focus on how the process may be constraining. This first obvious constraint is the overall build platform volume. This limits the size of AM part one can build in the process. Each year, equipment manufacturers develop machines with larger build volume sizes than the previous year. There can be large scaling differences for some AM processes. For example, an FDM type machine can exist in the range of 8.6 inches x 8.6 inches x 9.5 inches on the small end consumer printer to 240 inches x 90 inches x 72 inches for the large Cincinnati BAAM system. For PBF metals, one is the larger GE Concept Laser Xline with a build volume of 31.5 inches x 15.75 inches x 19.68 inches. As mentioned, these machine sizes will likely be surpassed by new models or newer processes each year. Most all AM equipment manufacturers will post the build volume sizes on their websites, so be sure to check the AM companies' website on how large of an AM component can fit inside the machine to establish scale constraints.

DED Machine Process Constraints

Depending on the type of DED process, the scale of the machines may vary. Blown powder deposition machine sizes can beas large as 5 feet x 5 feet x 7 feet with wire fed machines as large as 19 feet in length, 4 feet wide, 4 feet high, and 8 feet in diameter for some machines. However, similar to the PBF, manufacturers are constantly increasing the physical size of the build volumes. AM equipment manufacturers will post the build volume sizes on their websites, so be sure to check the AM machine companies' website on how large of an AM component can fit inside the DED machine to establish scale constraints for parts fabricated from AM DED.

Hybrid vs Conventional

Hybrid DED machines integrate a milling step during the layered process of fabricating parts and as a result, offer superior surface finished parts than conventional DED machines. This process approach allows for the AM part to exhibit machined finish across all surfaces of the part if desired. Traditional DED machines require a part to be milled after a part is produced and removed from the chamber.

The upside to using a hybrid DED process is the absence of a post-process milling operation and the avoidance of tooling setups for secondary milling operations. This allows for faster throughput of the overall AM fabrication cycle. However, the downside to this approach is the added complexity of programming requirements for a hybrid DED process and hybrid DED machines are typically smaller in build envelope compared to conventional DED machines due to the added complexities of the hybrid machine. The catch-all nature of the process also precludes the part from going through a stress relief cycle or heat treatment before machining, which can be problematic for final dimensions staying in tolerance.

Also, both hybrid and conventional blown powder DED machines offer the capability of a tilt table for the base plate, thereby allowing 5 axis manipulation of the baseplate. This is a significant advantage from a design standpoint. Recall that all DED machines produce geometry without support material. By fabricating a DED part on a machine with a tilt table, this allows for part features to be designed parallel to the baseplate thereby allowing the part to shift planes during fabrication. With this approach, designers will inherently have more design freedom and not have to design wasteful sacrificial support structure to stabilize part features during printing.

Wire Fed vs Blown Powder DED

DED systems have different deposition rates and use different material feedstocks (wire vs. powder), which have implications on design and post-processing. This allows for flexibility if a part need be constructed in freeform or have features added in a repair or modification scenario.

Typically, large scale systems deposit a thick melt puddle in scale and are wire fed. From a design perspective, if a part needs to have features less than .39 inches (10mm) thick, then recognize that these features would be difficult to produce using large scale wire DED systems without post-process milling operations. In addition, due to the relative thickness of the melt puddle, note that sharp transitioning, overhanging features are problematic to produce with wire fed DED systems.

However, there is an upside to large scale AM DED wire fed systems. For these larger metal components, DED may be the only answer. In Figure 4.11, nearly 400 lbs of material was deposited to make the 7-foot boom on this mini excavator. The boom was built vertically; so, the substrate was not integral to the structure. Holes were designed to be self-supporting, and the geometry was hollowed out and symmetric to mitigate warping during the build. After deposition, only the mating interfaces had to be machined at the connection points. “The 7-foot-long, 400 lbs. ‘stick’ was printed entirely of low-cost steel on the Wolf Robotics Wolf Pack printer in only 5 days.”

Features of this build included:

- “Throw Away” build substrate
- Hollow symmetrical structure mitigated distortion
- Holes designed with “tear drop” shape to accommodate self-supporting angle of DED process
- Minimal machining (i.e., mating surfaces)

Figure 4.11 Large-scale DED excavator boom 3D printed at the U.S. Department of Energy's Manufacturing Demonstration Facility at Oak Ridge National Laboratory (credit: Modification of "Project AME" by Oak Ridge National Laboratory/Flickr CC BY 2.0)

For large scale wire fed DED design, it is very important to consider the build plate substrate as a sacrificial element to the design. This is why it is helpful to pick AM candidates that are symmetric about a build plate as the build plate becomes the part during the fabrication process.

Medium scale systems typically require blown powder feedstock and can be hybrid or utilize conventional DED processing. From a design approach, these blown powder DED machines allow for easy buildup and repair of conventionally manufactured parts. Compared to conventional repair technologies such as welding, blown powder DED yields exceptional metallurgical bonding, less warping and distortion, lower dilution rates, is capable of automation, and lower heat input due to a smaller heat affected zone.

However, the most fascinating aspect of blown powder DED systems is the ability to have multiple powder feedstock input streams. This allows for multiple materials to feed the laser deposition concurrently. In a practical sense, this allows designers to customize materials within a single part. Being able to gradually blend different composition of materials throughout a part produces what is known as **Functionally Gradient Materials (FGM)**. From a design perspective imagine if a part had features that were 99% Tungsten to withstand abrasion or thermal loads, while on a different area of the same part could be comprised of 99% Titanium for its lightweight nature. Between the two areas of the part would be a gradual blend between Tungsten and Titanium. If these two materials were able to be functionally graded without adverse cracking effects, perhaps this could be possible. There exists an entire field of materials research looking into alloy and material compatibility for FGM. It is remarkable that a technology such as blown powder DED could enable the application of FGM into physical hardware.

The small-scale blown powder systems offer a finer deposition melt puddle width achieved through a blown powder, but are typically reserved for smaller laboratory scale research. These smaller systems offer most of the functional capability of the medium scale systems, however, in a smaller format machine size.

At the time of writing the below offers a snapshot of the manufacturers offering each type of system.

Manufacturers of wire fed large scale DED systems include:

- Sciaky
- Norsk Titanium
- WAAM

- Lincoln Electric
- EVOBEAM
- Prodways
- Gefertec

Manufacturers of blown powder large scale DED systems include:

- DMG Mori (hybrid)
- BeAM
- RPM Innovations
- Formalloy
- MAZAK (hybrid)

Manufacturers of blown powder small scale DED systems include:

- Optomec
- RPM Innovations
- Formalloy

Material Extrusion

Material Extrusion, commonly known as FDM, operates under very similar constraints as the other AM processes. While the general golden rule to build at 45 degrees or steeper still applies, design for this process can be more lenient as the support structures can be made to breakaway easily or in some cases, are liquid soluble. Much like other nozzle-driven processes, the smallest feature size is constrained to the nozzle diameter. No feature can be made smaller than the width of material laid. This makes complexity of the design, nozzle diameter dependent. This is important to keep in mind when designing for a specific machine. Another important acknowledgement of nozzle diameter is how it will affect the surface roughness. When building relatively small-scale parts, as Material Extrusion is often utilized for, the nozzle diameter can impact surface roughness greatly. If a rough surface is problematic to the application, it should be compensated for by inflating or adding stock to surfaces to have material removed later. Post-process material removal can be done in a variety of ways such as a chemical bath for uniform smoothing, CNC machining of specific surfaces, abrasive flow for passages, and so on. The exact process used to achieve surface smoothing goals should be planned for specifically. Much like it should be in any AM processes.

4.3 AM Industry Design Challenges & Strategic Solutions

Learning Objectives

By the end of this section, students will be able to:

- Comprehend design challenges around software.
- Learn about alternative file formats to the .STL file.
- Acquire knowledge about adopting AM within industry.
- Understand the design maturity phases according to a maturity model.

As stated previously, a new technology does not come without its caveats. Successful designs in AM acknowledge and address both technical and non-technical risks to implementation. This section discusses risks to design software users, and development on the horizon to mitigate them. Also discussed is the cultural resistance to AM that impedes adoption, and how to strategically address those. Phases of AM design maturity are defined and matched to a specific design optimization technique.

Software Interoperability

From a design perspective, perhaps the largest challenge in industrializing AM revolves around the overall difficulty of moving from a CAD concept to a software code that an AM machine can interpret. The **software interoperability** is defined as the functionality of different programs to exchange information, share files and use the same protocols. Within AM, this process flow path is what is known as the **AM digital value chain**. This digital value chain difficulty is typically more problematic with metal PBF and DED processes as these processes can incur more thermal distortion, require additional post-processing steps and cost more to fabricate. Therefore, the software landscape necessary to perform all of these functions is convoluted.

The landscape of disparate software programs that don’t communicate well with each other is the result of many things, from developers rushing products to the market, to lack of investment by private investors to evolve or maintain products. This results in working with an assortment of Minimal Viable Product(s) (MVP). MVPs can leave consumers at risk.

Furthermore, because the AM industry developed so rapidly, individual software startup companies focused on single basic functions. For example, startup software ‘X’ focused on build planning while software company ‘Y’ focused on build process simulation, while software company ‘Z’ focused on cloud-based systems that focuses on digital encryption of AM data.

Given such a market, the AM software landscape is an assortment of large and startup software companies attempting to meet consumer needs, while larger well-established companies continue to acquire startups. However, after acquisition, true integration is a major time investment, so, often, modules of software or simply the MVP of the startup is repackaged with a large company’s branding. This results in the AM designer being flooded with software solutions from companies both large and small for various steps of the process, with varying degrees of overlap from product to product. The designer is left with questions such as: Which software has more functionality? Which software is more reliable? Which software is the least expensive? Can’t I simply have one software to represent the digital value chain from concept generation to part fabrication?

Recall from earlier in this chapter the tables that showcase the different software companies that offer AM toolsets. You can see that a single designer could utilize up to 6 different types of software to get from DfAM concept through hardware inspection! This is a significant challenge for interoperability of digital files transfer and huge annual software maintenance costs to maintain.

From an interoperability standpoint, imagine that you are a designer and you create a metallic AM Laser Powder Bed concept where you want topological optimization, cellular features, and smooth surfaces in your 3D CAD program of choice. After realizing that your 3D CAD software doesn’t create these feature types easily, you need to export to a standalone software to create these features so you import the 3D CAD definition into the standalone software to create these features separate from their native format. It is important to acknowledge that at each step there are risks of unintentionally altering the part model when entering a new software different than the native 3D CAD program. Fortunately, leading developers are working on answers to these problems, mainly by providing platforms that allow users to remain in native 3D CAD throughout the digital chain. The table below outlines the existing risks to users, and acknowledges the solutions being developed today.

	Software Process Function	Risk	Development
Step 1	CAD → Top Opt	Top opt software doesn't import geometry correctly	Rolled into one CAD environment, no import needed
Step 2	Top Opt → CAD	CAD software must change 'dumb' solid model correctly	Rolled into one CAD environment, no import needed
Step 3	CAD → FEA	If part features too complex, FEA sofware may not mesh correctly	Rolled into one CAD environment, no import needed. Special meshing and smoothing algorithms are being developed
Step 4	CAD → FEA	FEA sofware may not mesh correctly on 2nd attempt	Rolled into one CAD environment, no import needed. Special meshing and smoothing algorithms are being developed
Step 5	FEA → CAD	.STL file may be too large depending on triangle resolution	Rolled into one fluid CAD environment that better handles high resolution models. Special meshing and smoothing algorithms are being developed
Step 6	.STL → Build Plan Software	Build planning software may struggle with large .STL file size	Rolled into one fluid CAD environment that better handles high resolution models.

Table 4.9

	Software Process Function	Risk	Development
Step 7	.STL fixing/ support structure	Support material may not be generated correctly	Rolled into one fluid CAD environment with intelligent, parametric support structures.
Step 8	Build plan software → Process Sim	Process sim software may not capture all post-process effects	Further developing known failure modes and simulation algorithms via machine learning.
Step 9	Process Sim → CAD	Pre-compensation may not be accurate, displacement of features inaccurately in CAD	Further refining compensation given empirical thermal data out of the machines.
Step 10	CAD → Build Plan Software	Support material may not be generated correctly	Further developing known failure modes for robust support generation.
Step 11	Build plan software → Process Sim	Process sim software may not capture all post-process effects	Further developing empirical data capture and analysis for improved sim.
Step 12	.STL file → Build Plan Software	Build planning software slicer inaccuracy	Always possible
Step 13	Build plan software → AM PBF machine	Data storage and configuration management of data	Solutions are in development to provide intelligent storage with reporting for increased user visibility

Table 4.9

After following the digital workflow, the loop must be closed with feedback or empirical data from physical part inspection. The inspection process is a light scanning machine that uses a different software to analyze the dimensional conformance to the original 3D CAD definition. If fortunate, the part will pass dimensional inspection and you will not need to further refine the part. If it is the first time attempting to fabricate your part, chances are that you will need to modify it somewhere in the aforementioned digital chain.

Adoption of AM

Since DfAM is such a disruptive way of design thinking, it is often difficult for companies to change best practices and standards that have been set in stone for many years. Similar to Lean Manufacturing Systems and Six Sigma practices that require cultural changes to occur before becoming effective, DfAM behaves in a similar fashion. The availability of designers that have the DfAM way of thinking is a challenge and it takes time to acquire the appropriate software, train employees, set up capital investments, and conform to regulations and standards. Since re-architecting a product from scratch is the essence of DfAM, each DfAM project can take many months to accomplish with many stakeholders involved in meetings to discuss concepts. Often this additional labor cost and time is overlooked by executive leadership seeking to cash in quickly on sensationalized organic designs that impress customers. So, it is essential to have knowledgeable executive sponsorship when undergoing such projects.

In addition, it is helpful to broadly educate the benefits of DfAM within companies so that everyone can share the vision of enabling new product designs. And because there is change, there will be skeptics. After all, the designs don't look anything like what has been sold in the past, there is limited information for servicing complex, organic designs, and more data is needed to prove such processes as DED hold up against traditional weld repair. Doubts will persist, but agents to change will continue to conduct tests and draw data-driven conclusions to overcome such concerns. Recognize that you aren't alone in your journey to DfAM implementation and that the best approach is to prove your designs through testing and simulation.

Aside from the change management aspect, one of the biggest challenges remains in the lack of awareness of AM designing within companies.

Additive manufacturing is a relatively new fabrication process on the historical timeline of fabrication processes. Sand casting and investment casting has been on the earth for thousands of years. Machining has been around for a few hundred years. Additive manufacturing has been around for merely a few decades. As such, one must appreciate the large amount of legacy knowledge existing in traditional fabrication methods and the relative lack of knowledge with AM.

Because of a relative gap in knowledge in AM processes in industry, let alone how to design for it, many industrialized companies are in different phases of their AM design journey, which are characterized using a maturity model. A design maturity model helps engineers and executives alike effectively strategize and streamline their AM efforts.

For example, the Powder Bed Fusion Maturity Model progresses in five phases, increasing the value of AM contribution with each successive phase.

- Phase 0: Rapid prototyping and tooling
- Phase 1: Direct part conversion
- Phase 2: Part design integration
- Phase 3: Structural (topology) optimization
- Phase 4: Full system optimization

In Phase 0, most companies see the benefit of using AM for rapid prototypes and tooling in the form of polymer tooling and design aids meant to showcase design intent. Limited value is gained by a company focusing solely on the fringe.

Next, in Phase 1, companies eventually try to run case scenarios where they attempt to build existing products the company already makes with AM. There are situations where value can be gained from this approach. Specifically, this benefit would include difficult to source parts and/or quick response part fabrication. However, often this approach doesn't favor AM from a business case standpoint as AM machines can be quite expensive to operate and the cost of an AM part can be pricey compared to the exact same part made from a conventional manufacturing process. In recognizing more inherent value in merging the design of conventional parts/features together in a single AM part, the company begins to understand more of what AM's design capabilities are and moves to the strategy of Phase 2 – part design integration.

Realizing that the parts that were merged in Phase 2 are now quite heavy, perhaps they could be lightened using advanced topology optimization software to produce an organic-looking structure that is both structurally sound and lightweight. This leads to the epiphany of Phase 3, topology optimization. After a company becomes proficient using advanced topology optimization or generative techniques, then they begin to realize that new products should be designed from scratch using the design freedom AM affords to enable products that offer full product differentiation from any conventional designs used in the past.

This brings us to Phase 4, full system optimization. From this point, new products are architected keeping AM as the primary fabrication method using system level requirements to drive optimized product design to a new potential.

The maturity model phases are useful in navigating the adoption of AM, as well as defining a company's or design engineer's strategy for using AM. It should be considered a helpful tool for all levels of an organization, especially when trying to encourage adoption of the technology.

Acknowledging the industry current and future states, especially in terms of software tools is critical to success with AM. Maintain awareness of risks and development on the horizon as the technology swiftly evolves, so as not waste time on dated workflows. This practice in conjunction with AM design maturity phase analysis will help ensure adoption and success with AM technology in a lasting way.

Summary

In summary, it is important to note AM design terminology and how they apply to product benefits.

- Direct Part Conversion – Reproducing a conventionally manufactured product using AM.
- MfAM – Modifying a conventionally manufactured product to be successfully fabricated with AM.
- DfAM – Re-architecting a product form to take advantage of AM design flexibility.

As a company shifts from a strategy of direct part conversion to DfAM, more value is driven into the product in terms of performance, part count reduction, assembly labor reduction and lighter weight.

MfAM of parts is a common transition when a company is working to leverage all the benefits of AM. Mainly this includes MfAM of features to ensure that an AM part is able to be fabricated successfully, in which the main drivers are cost and time savings. Though there are similarities when using MfAM for various AM processes, there are also many process specific rules of thumb to keep in mind when modifying parts for AM.

DfAM could be considered a more mature state in the transition to leverage all of AM's benefits. It is a systems level rethinking of a product that starts with concept ideation with the VOC. Ideas are developed by a multi-skilled team to perform a morphological analysis that decomposes system level functions to ideate new concepts. These concepts are sorted using the VOC on a Pugh Concept Selection Matrix. Concept solutions are then evaluated for what software is needed to construct the concept, following generally along the same digital chain. Generative design and/or topology optimization are used to guide AM hardware concepts that are later refined in analysis to be printed, and later inspected for iterative improvement.

Exciting design tools are available in the world of AM to increase performance, reduce weight and provide thermal solutions currently not manufacturable with conventional fabrication technologies. From cellular features found in metallic PBF to Functionally Gradient Materials found in DED blown powder systems, to support-free designs in polymeric SLS and material extrusion. incredible options exist to use AM as a way to enhance product offerings.

However, there are some caveats to heed. These would include modifying existing internal passageways, being mindful of inspection and certification of cellular features, and the machine sizing considerations for each process.

Design for Additive Manufacturing (DfAM) fundamentally challenges engineers' and companies' ways of thinking when it comes to advancing their products. Unconventional build processes permit unconventional shapes that improve designs, product or system performance, lead time, and part counts. Specifically this is achieved through a flexible toolpath and layer-by-layer nature of the build process.

This chapter discussed the general approach to DfAM, the tools available to aid the process, intermediate steps such as MfAM when working towards fully advantageous DfAM designs, tools and techniques based on build process and software constraints, and strategies for overcoming developmental challenges that the present industry is faced with.

Mastery of these methods and understanding the progressive design maturity phases of AM enables companies and designers to viably fabricate with additive manufacturing to fully leverage the many benefits and opportunities the technology has to offer today.

References

Daley et al, *Journal of Mechanical Design*, October 2016, Vol 138 http://www-personal.umich.edu/~gonzo/papers/daly-comparing-ideation.pdf

L. Hao, et al., "Design and additive manufacturing of cellular lattice structures." *The International Conference on Advanced Research in Virtual and Rapid Prototyping (VRAP)*, Taylor & Francis Group, Leiria (2011)

Review Questions

1. Describe the differences between Direct Part Conversion, MfAM, and DfAM.
2. What is a build plan and why is build orientation and nesting important in AM design?
3. Walk through a DfAM exercise to develop a new product. List the individual steps required to get from concept to hardware.
4. What type of specific AM systems align with DfAM, why not other systems?
5. What are three design tools a design engineer can use to increase performance or make an AM part lighter?
6. What are some techniques used to avoid placing support material in internal passageways?

7. In your own words, list pros and cons of using DED systems in AM design.
8. List the challenges associated with the .STL file. =
9. Describe the challenge with software intoperability in the AM industry. How can it be changed?
10. Why do companies resist new approaches such as DfAM?

Discussion Questions

11. Why is it important to distinguish between Direct Part Conversion, MfAM, and DfAM?
12. Why would MfAM of metallic DED be different than polymer SLS?
13. Why is VOC so important when considering new designs?
14. From a design standpoint, describe a situation where you may want to use a hybrid DED blown powder system with a tilt table.
15. Rationalize an application where FGM may be useful in product design.
16. Think about the digital value chain in its current state and come up with different approaches to streamline the value chain beyond what is stated in the chapter.
17. Do you think the company investment to move up in value in the design maturity model increases or decreases? Why?

Case Questions

18. Disassemble a simple consumer product (i.e. computer mouse, bicycle air pump, etc.) and evaluate how you would orient and nest each component within a specific AM process. What MfAM adjustments would you have to make to ensure quality fabrication?
19. From the previous question, perform a morphological analysis and sketch a few concepts. Set up the concepts in a Pugh Concept Selection matrix and score them relative to the simple consumer product you originally chose as a baseline.
20. Explore www.Thingiverse.com and search ‘lattice’ on their website. Pick 10 different designs and label each lattice design as ‘functional’ or ‘aesthetic’. What does this exercise tell you about lattice systems used in product design?
21. Many companies are applying cellular features to heat exchanger design with published documents available from NASA, Lockheed Martin and others. Explain the benefits and the shortcomings when using cellular features to generate these structures.
22. Are you familiar with a company using 3D printing or additive manufacturing? Share your thoughts on what particular Phase that specific company is on the AM maturation model.
23. From the case company identified in the previous question, what steps would the necessary for that company to move up to higher Phases to enjoy more value out of AM design?

Key Terms

4.1 Design Approach

3MF, AMF, AM Process Simulation , Biomimicry, Build Plan, DfAm, Direct Part Conversion, Finite element analysis (FEA), Generative Design, MfAM, Morphological Analysis, Profilometry, Pugh concept selection matrix, Staircasing, .STL file, Tessellation, Topology Optimization

4.2 Design Optimization: Implementation while Considering Build Constraints

Cellular feature, Functionally Gradient Materials (FGM), Honeycomb structures, Internal Passageways, Isogrid, Lattice structures

4.3 AM Industry Design Challenges & Strategic Solutions

Software Interoperability

5 CERTIFICATION

Figure 5.1 An engine specialist checks the fit of a 3D-printed valve onboard the littoral combat ship USS Indianapolis. The ship is 115 meters (378 feet long), with a typical crew of about 75 people, and carries several helicopters, surface vessels, and submersible vehicles. For AM parts to provide core engine functionality on such a massive platform, the crew must be certain they have been manufactured to exact specifications and pass multiple tests. (credit: U.S. Navy photo by Mass Communication Specialist 3rd Class Austin Collins on DVIDS, Public Domain)

Chapter Outline

Introduction

The topics of Certification and Qualification feature prominently in the future of Additive Manufacturing (AM). This is because AM is being developed in a wide range of industries to produce products with superior performance (weight, efficiency, cost, etc.), with the same reliability that conventional manufacturing has delivered for their customers. While the many regulatory bodies and certifying agencies have very detailed definitions unique to their field, in their simplest form the two terms are:

- **Certification** – component meets design intent and is fit for service in a system
- **Qualification** – the entire manufacturing process meets design intent, including the supplier, machine, and processing

Certification and qualification are not unique to highly regulated industries such as aerospace and medical. Because of the severe consequences of unanticipated failure, these industries have some of the most codified requirements. At the same time, not every industry, production process, or development team may refer to the terms separately or require every step in the processes. For example, if a part is being made as a model only, or is being developed as a proof of concept, it may require very specific (or limited) certification and qualification. In this chapter, we will discuss certification in terms of AM, and how it applies over the full range of applications from both safety-critical to those that are relatively mundane. Since part and system certification methods can be very industry-specific, it will be covered in general terms, along with common types of certifications (material, part, operator, etc.). We will cover qualification in the next chapter.

5.1 Certification

Learning Objectives

By the end of this section, students will be able to:

- Discuss the range of product certifications.
- Apply how certification impacts on the design, manufacturing, and use of additively manufactured components.
- Describe the importance of material, part, and operator certifications.
- Differentiate between average material properties and design values.

Certification is the act of saying (certifying) that a product meets the requirements it was produced against. Certification can cover a wide range of products in an industry, from something as complex as an airplane, to something as simple as the raw material used to produce a part in that airplane. In this section, we will discuss the full range of certifications that would be encountered in the production and delivery of an additively manufactured part.

The typical certification process starts before manufacture, when the user/customer/regulator states the requirements that the system must meet. In the case of a military aircraft, the user, customer, and regulator are the same, that being a country's air force. In the case of a civilian aircraft, they are different, where the user and customer are the same (airline) but the regulator is an airworthiness authority (FAA, EASA, etc.). In the case of a medical device, such as a hip implant, the user is the patient, the customer is the hospital, and the regulator is a medical agency (Food and Drug Administration, Public Health Division). In non-regulated industries, it can be even more complicated.

Two more examples follow:

- In the offshore oil and gas industry, the oil company is the user, an oilfield equipment company is the customer, and a third-party is the reviewer, such as Lloyd's of London.
- In the case of an automobile company, while various government agencies have regulations regarding emissions, safety, and other aspects that provide basic requirements, the customer is the person who buys the car, and the head of marketing for the auto company essentially sets the system requirements to be something they can sell at sufficient profit.

It is typically the job of the chief engineer to integrate the different requirements into a successful design. In the case of civilian aircraft, it needs to be safe to meet the regulator's requirements, while also being efficient, reliable, and comfortable, to meet the airline's requirements. In the case of automotive, the car needs to be efficient, comfortable, safe, and reliable, especially when one considers the cost of recalling and repairing a million vehicles.

Once the overall system requirements are defined, it is then necessary to determine the requirements for the subsystem, followed by the individual components. This includes **criticality** (impact if the part fails), envelope, and reliability. With requirements established, components are then designed and analyzed. This marks the end of product definition and is followed by construction (building of parts and assemblies). The final phase is testing to verify that the part/subsystem/system meets requirements. This begins with part qualification, followed by sub-system testing, and finally system certification. In the case of system certification for civilian aircraft, this can include hundreds of flight tests, full-scale static and fatigue testing of the airframe, stand testing of the engine, along with analyses and simulations.

Another aspect of certification that is especially applicable to a new manufacturing technology such as AM is known as a building block approach. When introducing a new material, manufacturing process, or both for either a new or existing system, development and certification proceeds in a series of building blocks, starting at the bottom in the following order:

1. Selecting the material and process combinations that have the most promise to meet requirements
2. Developing those materials and/or processes to lock them down and stabilize them
3. Determining the design values
4. Performing structural tests starting with small elements and joints, and moving to subcomponents
5. Performing final component and system tests for qualification and certification

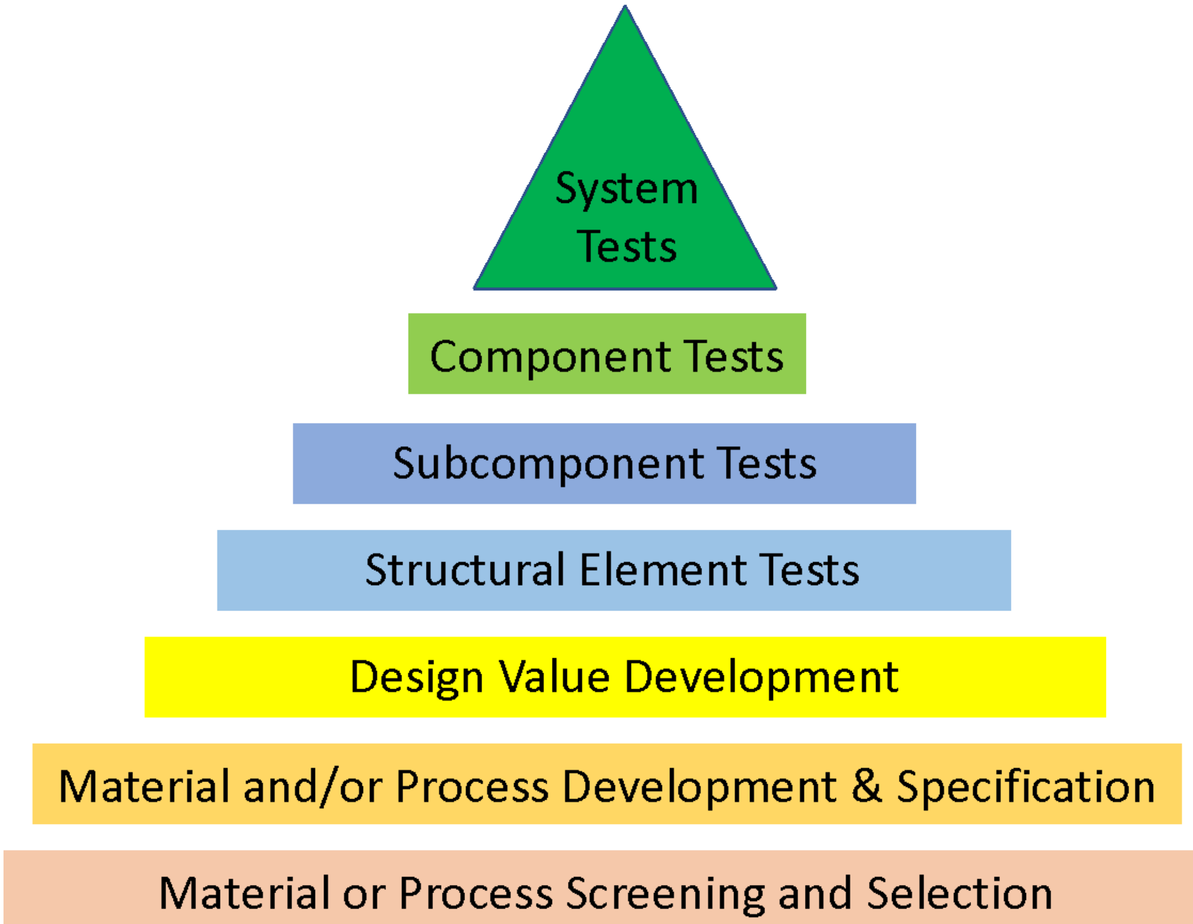


Figure 5.2 The building blocks to certification

System-level Certification

As the highest level of certification, system certification is the farthest removed from the manufacture of an AM part. As mentioned above, a large part of certification has to do with system tests (flight tests in the case of an aircraft, crash tests for automobiles), full-scale structural tests, subsystem tests, simulations, and software testing. When the AM part is either carrying load or necessary to operate, a test of the system or subsystem is necessary for system level certification. However, many parts in a system may not be fully loaded in a certification test.

Let's use an example: A bracket that attaches the overhead bins in an aircraft. The brackets are required to not fail and drop luggage on the passengers if the aircraft undergoes a hard landing. Because of the difficulty and risk entailed to correctly perform a test that fully simulates a hard landing, that part of the certification is done by analysis. That is to say, the calculations related to the design, loads, and material properties are analyzed to show compliance with the requirements.

In the case of an AM part used in the overhead bins, we are concerned with analyzing two aspects: 1) the design of the part itself and how it attaches to the surrounding structure, and 2) the strength of the AM material comprising the part. Because one of the benefits of AM is the ability to design parts of new, and more efficient geometries, additional structural analysis and verification may be necessary. This may require subsystem tests in a lab on the part of the overhead bin attachment hardware that includes the AM part. The part would be tested to a load greater than would be encountered in such a crash landing. The other way in which the use of AM is involved in certification is the determination of the strength of the actual material of which the AM part is made, and how consistent those properties are. This will be discussed in a later section.

Part Certification

Unlike system certification, that may only happen a few times in the lifecycle of a product family (airplane type in the example above), part certifications happen hundreds, or even thousands of times, in a single year for a product. This certification, which is common across many industries and manufacturing processes, entails the manufacturer of a part or a subsystem certifying that the part or subsystem being delivered meets its technical requirements. In the case of an AM part shipped from the part maker to the system builder, a document known as a Certificate of Conformance is either provided with the hardware or delivered electronically to the system builder. This Certificate of Conformance states that the manufacture is not only certifying that the part meets dimensional requirements, but that it was manufactured in accordance with the appropriate process, using the appropriate feedstock, and has passed all other inspections, such as metallurgical, mechanical property, nondestructive testing, hardness, and any other requirements.

Operator Certification

Another type of certification that takes place in AM is the certification of the operators of equipment. This is also not unique to AM, as many critical processes, such as welding, heat treatment, and composite part fabrication require certified operators. Operator certification usually requires a certain amount of classroom and on-the-job training, along with demonstrations of proficiency, such as written and practical (on-machine) examinations. Once an operator has demonstrated the necessary level of proficiency, they are then certified as operators, and allowed to produce production hardware on their own. These certifications are often tracked in a company's manufacturing resource planning (MRP) systems, that will only allow a certified operator to either initiate or electronically sign off a manufacturing operation.

Material Certification

The final level of certification relevant to AM is Material Certification. This has to do with ensuring that the feedstocks used to make the parts (liquids, powders, wires, foils) conform to the relevant specifications. Like part certifications, the **Certificate of Conformance**, which is a document certified by a competent authority that the supplied good or service meets the specifications, may be provided with the feedstock or delivered electronically. In some cases, they may just list the specification or specifications the feedstock conforms to, and in other cases, contain the actual test values and comparison with the specification values. While material is often certified to a public specification, such as an ASTM, SAE Aerospace Material Specification (AMS), or Military Specification, in the case of AM, many Original Equipment Manufacturers (OEMs, e.g. General Electric, Airbus, Toyota, Wabtec, Stryker) have their own proprietary specifications. In this case, a single lot of material may be certified to multiple specifications

Development of Design Values

Key to certifying a system made from engineered materials is knowing the properties of those materials. If the stiffnesses of the materials are not known, then one cannot be confident of the load paths or the stresses in the parts. If the strength properties of the materials are not known, one cannot be confident that the parts will be able to withstand the loads or stresses they are subjected to. If the thermal properties of the materials are not known, one cannot be confident of the operating temperature of that part and the surrounding parts, and their ability to withstand the temperatures without static, fatigue, creep, or excessive oxidation failure. Thus, in order to certify a system, it is necessary to know with confidence the properties of the materials that the parts are made from.

This knowledge of properties includes the following:

1. Knowing the strength that a significant amount of the population of a material will have
2. Knowing the physical properties of a material
3. Understanding the relationships between material composition, processing, and strength
4. Knowing the impact of environmental conditions on the material properties

The first of these often requires the development of what might be called "minimum" properties. They are minimum properties because it is a statistical characterization describing what can be expected to be achieve a very high percentage of the time, so therefore the process should always be able to deliver higher properties ensuring the part's success. One can imagine that if a design used median properties, it could be expected that as much as half of the parts used would have insufficient strength to meet service needs. In most industries, that would be considered a deficient design, and the system would not be certified. Therefore, many industries use minimum material properties in determining a design. Because knowing the true minimum properties of a material would require testing all of it, industries have developed methodologies for determining the minimum properties used for design.

One of the most widely used methods is the aerospace industry standard known as Metallic Materials Properties Development and Standardization (MMPDS), currently in its 14th version. The methods used in this standard have been developed over several decades with participation by the global aerospace industry and its regulators. It contains a chapter of over 200 pages that lays out the methodology, requirements, and the means of presenting the data. The types of Design Mechanical and Physical properties published in this are listed below.

- A-Basis Values – This is the value that 99% of the material will be stronger than with 95% confidence
- B-Basis Values – This is the value that 90% of the material will be stronger than with 90% confidence

- S-Basis Values – This is the minimum value that a specification will allow but does not have the statistical basis of A-Basis or B-Basis values

The criticality of the part will often determine the need for A-Basis, B-Basis, or S-Basis values. Because there are no published design properties for AM metals in MMPDS, we will use examples from wrought metals to illustrate these properties. The figure below contains the table of properties for 2024-T351 aluminum alloy plate, made to the Society of Automotive Engineering (SAE) Aerospace Material Specification (AMS) 4050.

Table 3.2.4.0(b_2). Design Mechanical and Physical Properties of 2024 Aluminum Alloy Sheet and Plate

Specification	AMS 4037 and AMS-QQ-A-250/4[a]											
Form	Plate											
Temper	T351											
Thickness, in.	0.250-0.499		0.500-1.000		1.001-1.500		1.501-2.000		2.001-3.000		3.001-4.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:												
F_{tu}, ksi:												
L	64	66	63	65	62	64	62	64	60	62	57	59
LT	64	66	63	65	62	64	62	64	60[d]	62[d]	57[d]	59[d]
ST	...	...	...	...	...	...	...	...	52[b]	54[b]	49[b]	51[b]
F_{ty}, ksi:												
L	48	50	48	50	47	50	47	49	46	48	43	46
LT	42	44	42	44	42	44	42	44	42	44	41	43
ST	...	...	...	...	...	...	...	...	38[b]	40[b]	38[b]	39[b]
F_{cy}, ksi:												
L	39	41	39	41	39	40	38	40	37	39	35	37
LT	45	47	45	47	44	46	44	46	43	45	41	43
ST	...	...	...	...	...	...	...	...	46	48	44	47
F_{su}, ksi (L & LT)	38	39	37	38	37	38	37	38	35	37	34	35
F_{bru}[c], ksi:												
L & LT (e/D = 1.5)	97	100	95	98	94	97	94	97	91	94	86	89
L & LT (e/D = 2.0)	119	122	117	120	115	119	115	119	111	115	106	109
F_{bry}[c], ksi:												
L & LT (e/D = 1.5)	72	76	72	76	72	76	72	76	72	76	70	74
L & LT (e/D = 2.0)	86	90	86	90	86	90	86	90	86	90	84	88
e, percent (S-Basis):												
LT	12	...	8	...	7	...	6	...	4	...	4	...
E, 10^3 ksi	10.7											
E_c, 10^3 ksi	10.9											
G, 10^3 ksi	4.0											
μ	0.33											
Physical Properties:												
ω, lb/in.	0.100											
C, K, and α	See Figure 3.2.4.0											

Last Revised: Apr 2009, MMPDS-04CN1, Item 07-41. Design allowables were last confirmed in Item 07-41, MMPDS-04CN1.

a Mechanical properties were established under MIL-QQ-a-250/4..

b Caution: This specific alloy, temper, and product form exhibits poor stress corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

c Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

d The following rounded T_{99} and T_{90} values represent production capacity at the time the table was last confirmed; F_{tu} LT for 2-3 inches T_{99} = 63 ksi, T_{90} = 64 ksi; for 3-4 inches T_{99} = 60 ksi, T_{90} = 62 ksi.

Figure 5.3 MMPDS Design Mechanical and Physical Properties for 2024-T351 Aluminum Alloy Plate

The MMPDS table contains values for the following:

- Tensile (Ftu)
- Yield Tensile (Fty)
- Compression Yield (Fcy)
- Shear Ultimate (Fsu)
- Bearing Ultimate (Fbu)
- Bearing Yield (Fby)

Note that the properties are different for different directions, illustrating that the specific material, like most engineered materials, is anisotropic. It also has S-basis values for elongation. Finally note that the physical properties (moduli, Poisson's ratio, density, heat capacity, thermal conductivity, and thermal expansion) provided are not minimum properties, but averages. This is because unlike strength properties, where bigger is better, and having a statistically derived minimum value provides design confidence; higher or lower physical properties may not be any better, hence the use of average properties. Note that in some very specialized applications, it may be necessary to have statistically based physical properties.

There are different sets of columns for different thicknesses. In the case of wrought aluminum alloy plate made to industry standards, there is an inverse relationship between strength and thickness. Additionally, these properties are achieved in material that has received this specific thermo-mechanical treatment (solution annealed, quenched, stretched, and overaged). In the case of a developing technology like AM, the understanding of these variables is a work in progress.

While the over 200 pages in MMPDS lays out the methodology, requirements, and the means of presenting the data is well established for wrought materials, the methods for AM materials still being developed. One of the primary questions for AM is establishing the range of part geometries and processing parameters to include in a data set for determining the design values. Until such methods are standardized and validated, design authorities are independently developing methods. Depending on the circumstances, different approaches are being used, examples of which are below.

- Part Specific Design Values – This entails building a large number of the same part, excising test coupons from them, and deriving the properties based on the test results and applying the proper statistics.
- Part Family Design Values – This can be developed from the start or can be an extension of Part Specific Design Values, and entails building replicates of a number of parts that are closely related in terms of geometry and processing parameters, and deriving the properties based on the test results and statistics. If done as an extension of Part Specific Design Values, it would usually involve building and testing parts similar to the original one and verifying consistency of properties.
- Feature Based Design Values – This is very much like those shown earlier for 2024-T351 plate (thickness). The key challenge in developing these for AM is determining if there is any good relationship with features exist, and how to demonstrate that. Would the appropriate ones be feature thickness, overall cross-sectional area, layer thickness, or some much more arcane definition? Additionally, the appropriate feature for one material or process may not be appropriate for another one.

Recall the property list above. Item four, knowing the impact of environmental conditions on the material properties, means that it is also necessary to understand environmental effects on material properties. For example, temperature has an effect on materials, such as impacting the temperature on tensile strength. So, if an AM part is to be used in elevated temperature conditions, it will be necessary to have an understanding of these effects. MMPDS may also include data tables or graphs/curves pertaining to environmental impacts such as temperature.

Depending on the application, it may also be necessary to understand the performance of a material under cyclic loading (fatigue) conditions. S-N curves show fatigue values, and can be applied to a variety of material applications, such as a notched or unnotched item. In the case of fatigue (sometimes referred to as durability), the wide scatter often makes it difficult or impossible to determine a statistically based minimum value. In that case, an average curve may be developed and used for analysis, but the certification requirements may require that the part be designed to last many (2 or more) lifetimes than predicted. Depending on the fatigue environment encountered, it may be necessary to develop a unique curve for that ratio.

In some critical applications (safety-of-flight aircraft parts, pressure vessels, underwater oil valves), it is also necessary to know the damage tolerance of a material. This requires knowing how quickly a crack will grow, and how long it can be before catastrophic failure occurs. These are based on properties known as crack growth resistance and fracture toughness. These properties (usually a minimum for toughness, and average values for crack growth), along with the assumptions of an initial crack size, which is related to the NDT methods used and the service environment; need to be known with some confidence to certify a system that has damage tolerance requirements.

While most of the properties of interest are mechanical and physical properties, in some cases, product-specific properties are required. Examples of these are:

- Flame, smoke, and toxicity for materials used in aircraft cabins and passenger rail cars to prevent small fires from killing the passengers or preventing them from escaping.
- Chemical-specific corrosion properties in chemical plants.
- Ignition temperatures in automotive braking systems.

5.2 Nondestructive Testing (NDT)

Learning Objectives

By the end of this section, students will be able to:

- Describe basic nondestructive testing (NDT) technologies.
- Describe process control, process monitoring, and in-situ NDT.
- Understand how NDT methods relate to certification and qualification.
- Understand nondestructive testing methods and how they relate to certification.

Most of the parts and materials used in the world are made using robust, repeatable processes with minimal post-fabrication inspections. In industries where the consequences of failure can be high (aerospace, turbomachinery, nuclear, medical, oil and gas, high-value costly to replace automotive), parts are often subjected to **nondestructive testing**, which is process of inspecting components or assemblies for discontinuities, or differences in characteristics without destroying the serviceability of the parts, to see if they contain any defects that would cause failure while in service. Thus, the use of NDT to ensure freedom from defects that could cause in-service failure is integral to the certification of many systems.

While more detailed definitions exist, for the purposes of this book, a **defect** is a discontinuity that may compromise the ability of a part to meet design intent. While it can be expected that the above industries will continue to use NDT for AM parts, the lack of long-term service history may cause other industries, such as automotive, to consider the use of NDT until manufacturing and service history provides the data needed to eliminate it. One unique aspect of AM is that since the parts are built in layers, the opportunity presents itself to inspect the part as it is built, known as In-Situ AM. Related to this is the ability to gather and analyze significant amounts of data while a part is being built, which provides unprecedented ability to perform Process Monitoring or Process Control while the part is being built.

Post-build NDT, often referred to as conventional NDT, is divided into volumetric and surface methods. Volumetric methods look for discontinuities in the interior of a part or material, while surface methods look for discontinuities on the surface of a part. Each of these methods have their own attributes, with surface methods generally considered more critical. Surface discontinuities tend to have a greater impact on performance than subsurface ones due to higher stress concentrations and the potential for crevice corrosion. It can be imagined one day, that in-situ NDT of AM may address both volumetric and surface inspections. In the following paragraphs, each of the inspection technologies will be briefly described with relation to AM, followed by an example.

Radiographic Inspection

This original method of NDT is almost exclusively used for volumetric inspections and dates back to the days of Roentgen. It can be used for the full range of AM materials, and works by passing X-rays (although some systems use Gamma rays or neutrons) through a part and onto a detector. Cracks and pores are found because they have less matter to absorb the X-rays so more hit the detector. Inclusions (undesirable foreign material) are found because they either absorb more X-rays (higher density) or fewer X-rays (lower density). General practice is that when more X-rays hit the detector, the image is darker, and when fewer hit the detector, the image is brighter. It can be inferred that for a discontinuity to be detected, it must be oriented so that it has some thickness in the direction of the X-ray beam. This means that planar discontinuities, such as cracks, may be difficult to detect, unless one knows their preferred orientation.

While photographic film was the preferred detector until the 1980s, more and more industries are now using digital detectors to capture the image. These offer significant benefits in terms of time, sensitivity, and ability to analyze the image. The most sophisticated, and expensive, radiographic method is known as computed tomography (CT). In this method, the part is rotated while being continually exposed to the X-rays and the detector continually collects the data. The data is then processed to generate a 3D reconstruction of the part. In addition to being used to detect and characterize discontinuities, CT can also generate a solid model for comparison with the actual design. This extra capability can be quite useful in AM to determine if a complex part with internal passages meets dimensional requirements where conventional metrology would not be able to inspect.

For the purposes of this discussion, we will say the discontinuities of interest are pores, inclusions, and cracks. Additionally, it is necessary to know whether internal passages are the correct distance from the surface of the part. A series of radiographic shots, as shown below, could be used to look for pores and cracks, with a typical sensitivity being 2% of material thickness (thus if the part is 50mm thick, pores above 1mm across could be detected), and to provide some information on the cooling channels. The use of CT, however, would provide the ability to determine the actual geometry of the cooling channels and allow a digital comparison with the original model the part was built to. One aspect of AM where complexity can be a hindrance is in performing radiographic inspections. Parts with a large number for small features can have lots of noise around the edges of the features, making it difficult to interpret the radiographic results.

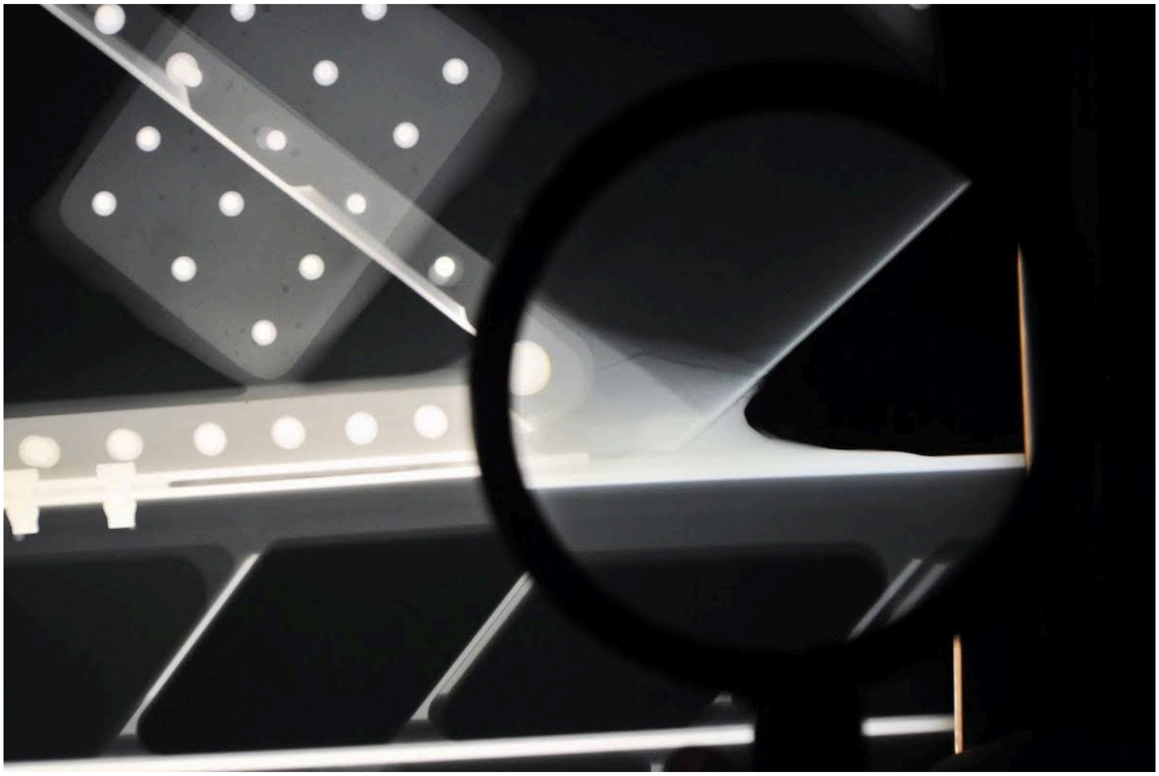


Figure 5.4 A nondestructive aircraft technician holds up a magnifying glass in front of a radiographic image of an aircraft component in an effort to detect cracks or other defects. (credit: U.S. Air Force photo/Senior Airman Chris Willis on DVIDS, Public Domain

Ultrasonic Inspection

One version of ultrasonic inspection, called surface wave inspection, is used as a surface or near-surface inspection. This entails introducing a surface wave (called a Raleigh wave) into a part and then listening for it to reflect back off of a discontinuity. Because surface wave inspection is relatively rare in industry, and would be so for AM, we will focus on the use of ultrasonic as a volumetric inspection method. Ultrasonic inspection is effective in materials that transmit sound, such as metals and composites. It is less effective in porous ceramics, neat polymers, or elastomers. Volumetric ultrasonic inspection works much like sonar on a ship. A pulse, generally between 1MHz and 20MHz, is sent out from a transducer.

1. In the most common mode, called pulse-echo, the transducer, then listens for the pulse. If it reflects off an internal discontinuity, the size and location can then be inferred by looking at the signal.
2. Another approach, called pitch-catch, uses a second transducer that listens for the signal reflecting off of the discontinuity. This can be a benefit over the first for some geometries.
3. A third approach, called through-transmission, uses a second transducer that records the volume (amplitude) of the signal transmitted through the part.

While the first is used in metals and composites, and the second mainly in metals (especially welds), through-transmission is most commonly used for the inspection of composites. Inspection of flat shapes will use general service probes, while more complicated shapes may use customized probes other devices (called shoes) to introduce the sound into the part. The most complicated shapes often require building custom phased array ultrasonic probes, which contain an array of transducers specifically designed for the inspected geometry. All of these methods are best for finding discontinuities that are oriented perpendicular to the direction of sound. Thus, radiography (good at finding discontinuities parallel to the beam direction) and ultrasonic inspection can be very complimentary, which is why they are often used together in the inspection of welds.

Figure 5.5 A non destructive inspection technician uses an ultrasonic flaw detector to analyze a damaged aircraft panel. (credit: U.S. Air Force photo/Senior Airman Andrea Posey on DVIDS, Public Domain)

The primary challenges in performing ultrasonic inspection of AM parts are due to geometric complexity and surface roughness. Because the sound needs to be introduced into and received out of the part, the geometry needs to be relatively simple to allow both access for the transducer and the ability to have some area of contact. Additionally, a predictable back surface is needed. Finally, the wave needs room to propagate, so thin or narrow features are difficult to inspect. In conventional manufacturing, most ultrasonic inspections are performed on simple shapes, such as rectangular plates or round bars. The rough or irregular surfaces of many AM parts also make inspection difficult, as a smooth, consistent surface is needed to introduce the sound into the part.

Eddy-Current Inspection

Eddy-current inspection is primarily a surface inspection method, although discontinuities within 1mm of the surface can be detected with the correct set-up. Eddy-current uses an electromagnetic coil (generally between 10Hz and 4Mhz, depending on material and application) to induce eddy-currents in the part. Thus, only conductive materials can be inspected. The presence of a physical discontinuity will disturb the eddy-currents, which is picked up the test equipment. Eddy-current testing requires a reasonably smooth surface, so the rough surfaces of AM parts can be a significant hinderance. It can also be very labor-intensive. As a result, it is often relegated to inspecting small areas, where a production discontinuity or fatigue crack is suspected.

Magnetic Particle Inspection

Like Eddy-current, magnetic particle inspection can detect surface and near-surface (also up to ~1mm deep) discontinuities. A prerequisite for this inspection method is that the material in question be reasonably ferromagnetic (alloy steels or PH stainless steels). Magnetic particle inspection works by inducing a magnetic field in the part and applying magnetic particulate matter to highlight areas where the magnetic field is disturbed. These are areas of potential cracks, laps, etc. Needless to say, the rough surfaces and undercuts in many AM parts would generate many false positive indications, so magnetic particle inspection would be limited to smooth surfaces.

Penetrant Inspection

Due to the ability to use a common inspection procedure, applicability to all nonporous materials, and quick examination time, penetrant inspection is the most common surface inspection method in industry. A discontinuity must be open to the surface in order for penetrant inspection to work, as the method entails using capillary action to draw the penetrant into the discontinuity, which then bleeds back out after the excess penetrant is removed and a developer is applied. Like magnetic particle and eddy-current inspection, linear discontinuities around 1.5mm and above are typically detected with high-sensitivity fluorescent penetrant materials. Also, like magnetic particle and eddy-current inspection, the ability to inspect is significantly compromised by rough surfaces. Additionally, surfaces must be free of grease and oils. Finally, for the high-sensitivity penetrants, machines parts with yield strengths under 1500MPa require a pre-penetrant etch to remove any smeared metal. The combination of these often means penetrant inspection requires cleaning and acid or alkaline etch tanks, which is why the inspection is often performed by specialist chemical processing contractors.

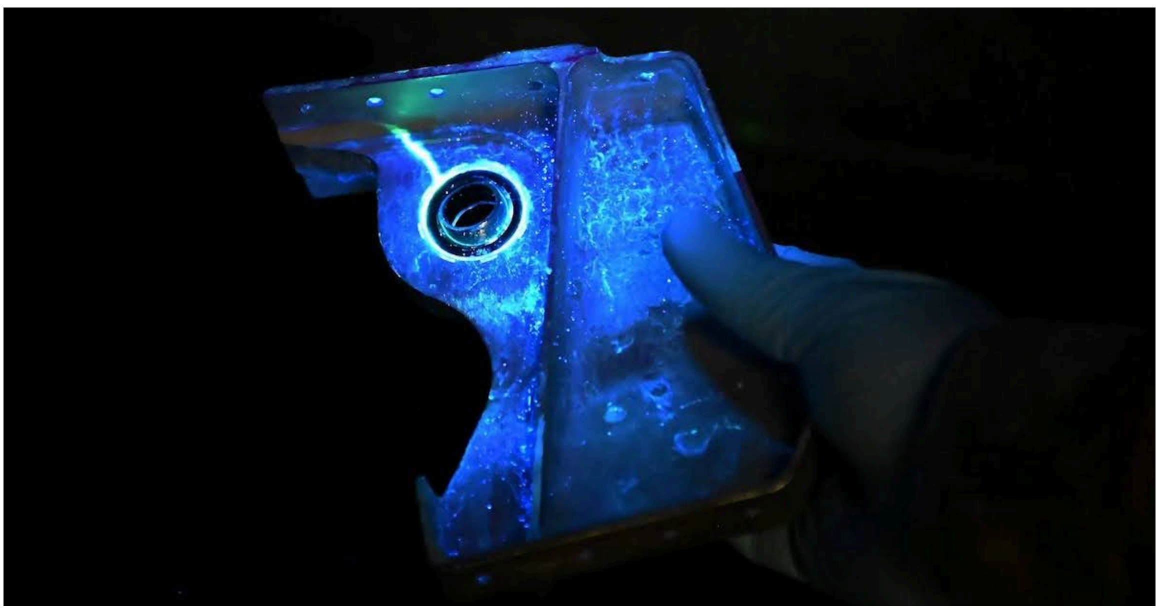


Figure 5.6 An inspector finds a crack in a bulkhead from a jet aircraft. This two-hour inspection had four steps: soaking in a penetrant solution, rinsing, then soaking in emulsifier, drying, and finally examining the part under a high-intensity UVB black light. (U.S. Air National Guard photo by Senior Airman Emily Copeland on DVIDS, Public Domain)

Resonance Inspection

This method treats each part like a tuning fork, although in many cases the sound is outside of the audible range. The part is loosely held and tapped in a controlled method. The sound coming off the part will have a characteristic resonance frequency that is detected with a specialized microphone and analyzed. Changes in the resonance frequency may be the result of either discontinuities or discrepant geometry. Because it is quick to perform, resonance inspection can be used as the primary inspection to screen parts as acceptable or questionable, with the questionable part inspected using another method for final disposition.

Thermographic Inspection

Thermographic inspection involves imaging an area with an infrared camera to look for differences in temperature. The inspection can be either passive (using background thermal energy to look for hot or cold spots) or active (applying heat via flash lamps or the like and looking for hot or cold spots). Outside of AM, thermographic inspection is often used to inspect areas where a coating may be bonded onto a surface to check for unbonded areas. This also takes advantage of one of its advantages, which is being noncontact and able to inspect large areas quickly. Within AM, it is being developed and implemented for process monitoring and in-situ NDT.

Process Monitoring, Process Control, and In-Situ NDT

Because of the difficulty of inspecting AM parts post-build, and the opportunity to inspect parts while they are being built, process monitoring, process control, and In-Situ NDT are being implemented and developed. We will start with defining the three terms:

- **Process Monitoring** – Monitoring the inputs and responses of a process while it is being performed to see that it is operating within limits.
- **Process Control** – Using data from process monitoring to change the inputs to a process to keep it within desired limits.
- **In-Situ NDT** - Inspections performed while a part is being made using AM.

Because AM is an inherently digital process, and because the machines produce large amounts of data, Process Monitoring is the most widely applied of the three. Ideally, Process Monitoring is performed while the process is active, although it can be applied post-built as part of an accept/evaluate/reject decision tree. A wide range of process parameters can be monitored. These include input parameters (laser input power, recoater voltage, arc current, gas flow rate, etc.) or output parameters (melt puddle size, bed surface temperature, laser energy, etc.). The key is reliably determining how the parameters correlate with either an acceptable part, a rejectable part, or a suspect part that requires further evaluation, which is made more challenging in that the definition may be geometry dependent. Making this determination is being helped by the use of a range of data analytics and machine learning tools that are now available.

Process Control will often use the same sensors and data as Process Monitoring. The difference is that the AM machine uses the results of the sensing and analysis to determine if a process is going out of the desired limits and makes changes to the input parameters to keep it within its desired limits. Needless to say, this must be done while the process is active so the changes can be made as part of a closed loop. While not as widely used as Process Monitoring, Process Control is beginning to appear on newer-generation AM machines with increasingly sophisticated sensors and analysis methods.

Making parts without discontinuities is always the goal. Depending on the industry and the part requirements such as, the criticality of the part and the level of confidence in the process, NDT may still be required. In AM, the best time to perform this may be while the part is being built, either to achieve desired level of sensitivity and reliability, minimize NDT cost, or to avoid continuing to add value to a part that is not acceptable. In-Situ NDT may look very much like Process Monitoring and use the same sensors and analysis methods. The difference, however, is that the output of the analysis is a determination that a region of a part contains or does not contain an unacceptable discontinuity and its approximate size.

The decision to use Process Monitoring, Process Control, In-Situ NDT, or Post-Build NDT or some combination of the four, and the methods to be used requires the input of a combination of disciplines and needs to be integrated into the overall design and build of the system as part of the overall certification of that system.

Integration of NDT with Design and Analysis

Key to the effective use of NDT is knowing the size of discontinuities that can be detected. Ideally, the NDT methods used to inspect a part can detect discontinuities that are smaller than those that will cause a part to not meet design intent; that is, smaller than the applicable defect size. One measure of this is knowing the smallest possible discontinuity a method can detect on a part, often referred to as the minimum detectable defect size, Because of the complexities of part geometry, discontinuity geometry, operator skill, etc., however, having an absolute size for what can be detected in a part is rarely possible. Thus, the term Probability of Detection (PoD) is used to refer to the size of discontinuity that can be detected with a good chance of success. A typical definition of success is being able to find 90% of the discontinuities above a certain size with 95% confidence. Depending on the material, part geometry, type of discontinuity and NDT method, parts with either actual or simulated discontinuities in the locations of interest and of a range of sizes will undergo NDT multiple times to statistically determine that value.

The final stage in integrating NDT with design and analysis is determining the effects of defects (EoD). That is, how do different discontinuities of different sizes impact the performance of a material. This type of testing is often done when a new material or process is introduced, or it is used for the first time in a new application, especially one that is loaded in fatigue or where damage tolerance is needed.

EoD testing often requires the following:

- Building test parts with intentional discontinuities
- Performing NDT on the parts to see if the discontinuities are detectable and to characterize their apparent size
- Testing the parts to failure to see the impact on either the static strength, fatigue life, or fracture stress
- Correlating the size estimated by NDT, actual size, and impact on performance

When this is completed successfully, the results are analyzed and the size of discontinuity that needs to be detected is determined. Ideally, this size is larger than the size that can be detected with confidence. If not, changes to the design and/or materials and processes need to be made. In the case of AM, many industries are just beginning studies to determine both the detectable sizes and the effects of defects.

Summary

Certifying a system containing AM parts from engineering materials requires an understanding of the properties of the material as a function of composition, processing, and environmental effects on the part and the material it is made from. As we now begin to cover qualification, it is important to keep in mind that the primary goal of qualification is demonstrating that the production system (factory, personnel, AM machines, post-processing, feedstock, and quality assurance measures) is capable of repeatedly and reliably producing AM parts whose properties are consistent with those used to design the system.

Certification ensures a component meets specified requirements, which are defined according to industry, material, regulatory agencies, and other factors. The process begins with defining system requirements by stakeholders (e.g., customers, users, and regulators) and proceeds through design, manufacturing, testing, and certification phases. Certification includes system, part, operator, and material certifications.

System certification involves extensive testing (e.g., flight tests for aircraft) and analysis to validate performance. For parts like AM components, both material strength and design efficiency must be assessed. Part certification is more frequent, verifying compliance with technical and manufacturing standards through a Certificate of Conformance.

Operator certification ensures skilled personnel produce quality parts, requiring training and proficiency evaluations. Material certification ensures feedstocks meet technical specifications, with standards varying from public to proprietary requirements.

Certifying systems with engineered materials requires comprehensive property knowledge, including strength, reliability, and environmental effects. Methodologies like MMPDS provide statistical design values for materials, critical for safety and performance.

Nondestructive testing (NDT), essential in high-stakes industries, includes methods like radiography, ultrasonics, and eddy-current inspection, identifying defects without damaging components. Emerging technologies like in-situ NDT integrate real-time monitoring during AM processes, enhancing defect detection and system reliability. Combining design, analysis, and NDT ensures robust certification practices, especially in evolving fields like AM.

Review Questions

1. Which of the following certifications would one expect to see performed the least?
   a. Material Certification
   b. Part Certification
   c. System Certification
   d. Operator Certification

2. Which of the following would one expect to be the lowest for a given material?
   a. A-Basis Design Values
   b. B-Basis Design Values
   c. Average Properties

3. Which of the following NDT methods is limited to discontinuities open to the surface?
   a. Radiographic
   b. Ultrasonic
   c. Magnetic Particle
   d. Penetrant
   e. Eddy-Current

Key Terms

5.1 Certification

Certification, Certificate of Conformance, Criticality, Design Values, Qualification

5.2 Nondestructive Testing (NDT)

Nondestructive Testing, Process Control, Process Monitoring, In-Situ NDT, Effects of Defects, Probability of Detection

6 ADDITIVE MANUFACTURING QUALIFICATION

Figure 6.1 Qualification involves evaluating a manufacturer's ability to undertake each step in the part or system creation process. This becomes even more complex when two or more processes are involved in the creation of a part. This hybrid additive manufacturing system combines 3D printing with compression molding. It is capable of producing parts made of one material as well as building multiple materials, such as interconnected metals and polymers. But before such builds are done at production scale and pace, the machine, the build processes, the personnel, and the testing approaches all must be evaluated and qualified as effective and up to standard. (credit: Modification of "Additive Manufacturing Compression Molding System" by Oak Ridge National Laboratory/Flickr, CC BY 2.0).

Chapter Outline

Introduction

Like certification, qualification can apply to a wide variety of activities, ranging from a very high level (a factory is qualified to make AM hardware) to a very low level (a part is qualified for production). While each of these qualifications apply to different aspects of producing AM hardware, in the end, each of them points to the ability to repeatedly make hardware that meets the engineering requirements and will perform as expected in service.

6.1 Qualification

Learning Objectives

By the end of this section, students will be able to:

- Differentiate the levels of qualification (part, supplier, machine), how they apply to different industries, and how qualification can be achieved.
- Apply qualification to its role in facilities and processes beyond the printer.
- Conceptually connect qualification to certification and design.

A simple example of the relationship between certification and qualification would be the design of a rope swing. Let's say that the rope has to withstand a 10,000 N load. The engineer specifies a 10mm diameter nylon rope and hangs a 15,000 N weight from it (10,000 N x a safety factor of 1.5) from the rope as part of the *certification* process. Needing a reliable supply of rope, the rope swing company goes to a variety of rope manufacturers with a specification requiring 10mm diameter nylon rope that can withstand 15,000 N without failing. The rope manufacturers submit to the swing maker the results of tests on their 10mm ropes showing that their rope can withstand 15,000 N without failing. At this point, the swing maker qualifies several rope manufacturers as suppliers, and adds them to a qualified producer list (QPL). In brief terms:

- The swing maker *certifies* that their rope swing design is fit for service. The design that is certified specifies the kind of rope that can be used;
- The swing maker *qualifies* rope manufacturers as suppliers of conforming rope.
- Extending it further: the rope manufacturers *qualify* suppliers of nylon strand that conforms to the rope manufacturer's specification to be used for making 10mm diameter rope.

To bring this into a common AM application – aircraft manufacturing – the analogy would be:

- The swing maker is analogous to the the system builder – the airplane manufacturer.
- The rope maker is analogous to the AM part maker.
- The nylon strand supplier is analogous to the powder production facility.

In the AM application above, to ensure proper, effective, safe, and efficient production, the airplane manufacturer needs to qualify the part supplier, and the part supplier needs to qualify the powder production facility.

Facility Qualification

Facility is the highest level of qualification and is usually the result of some of the other qualification types. Facility qualification also indicates that the facility (or the overall company) has the proper business, manufacturing, training, and other quality processes integrated throughout the operations. This qualification often involves the coordination of different organizations such as the following:

- Facility Quality and Management – Organization that will be using the machine to make parts
- Part Customer – Organization that will be receiving parts made on the machine
- Industry Group or 3rd Party Organization – Organization that represents the part customer, as part of a larger industry organization. Examples of these are NADCAP, Lloyd's Registry, etc.
- Regulatory Agency – Governmental body or industry group

A qualified AM facility must be able to demonstrate a few key systemic, organizational, and process-oriented capacities, including having an overall quality management system, approved AM-related processes and equipment, and relevant non-AM-related processes and equipment. These three areas are described in more detail below.

Overall Quality Management System: This often requires that the facility operates in accordance with an industry-approved specification, such as ISO-9000, AS-9100 (aerospace), or ISO-13485 (medical).

Typical parts of the overall quality management system are:

- Understanding customer and contract requirements
- Organized and documented leadership roles and responsibilities
- Involvement of employees, which includes personnel training and qualification
- Control of business, manufacturing, and other processes. This includes control of materials, designs (build files) software, machines, work instructions (build programs), operators, inspectors, etc.
- Closed-loop improvement processes – Monitoring production and making improvements in a controlled fashion, or taking timely corrective action when things go wrong
- Data-based decision making
- Management of relationships with suppliers and subcontractors

Approved AM-Related Processes and Equipment: Prior to receiving a facility qualification, it is usually necessary for the AM-related processes and equipment to be qualified. Examples of these qualifications include feedstock handling and tracking, qualification of at least one AM machine, and qualifications of operators for the machines.

Non-AM-Related Processes and Equipment: This can apply to processes outside of the actual print operations. In some cases, these processes are performed within the facility, or they may be performed in sister facilities or subcontractors, which have been approved.

Examples of these processes and equipment that may require approval are:

- Heat treatment
- Machining and other post-processes
- Nondestructive testing

- Mechanical and material testing
- Dimensional inspection

A qualified AM facility consists of qualified personnel, equipment, and processes working together in an integrated fashion to reliably produce AM hardware that meets requirements and is consistently being improved in a controlled fashion.

Machine Qualification

A qualified AM machine is one that can reliably produce AM parts that meet requirements. As the AM industry matures, machine qualification is coalescing on a staged approach that closely aligns with medical equipment qualification. The stages differ in the propose of the testing, feedstock used during the testing, types of testing being done, the pass/fail criteria, and who is involved in the qualification testing, and determining a machine to be qualified.

The different types of organizations involved may include the following:

- Machine Builder – Organization that designs and builds the machine
- User – Organization (Facility) that will be using the machine to make parts
- Part Customer – Organization that will be receiving parts made on the machine
- Industry Group or 3rd Party Organization – Organization that represents the part customer, as part of a larger industry accreditation organization; examples of these are Nadcap and Lloyd's Registry
- Regulatory Agency – Governmental body or industry group

Factory Acceptance Testing (FAT): Factory acceptance testing is usually conducted at the site at which the machine is built and performed by employees of the machine builder, to determine whether a hardware and software of the product satisfies the requirements. Since FAT occurs before the machine is accepted by the user, it is sometimes considered outside the realm of qualification, but either way, it is considered a prerequisite to the other qualification stages. FAT is also good practice as it provides data to a default or baseline known point. FAT essentially consists of the machine builder verifying that the machine operates as intended. The involved parties are the machine builder and the user. In the case of smaller machines (e.g. 250mm class Laser Powder Bed Fusion machines), this testing takes place at the factory where the machine was built. In the case of large Direct Energy Deposition or Material Extrusion machines where the machine is assembled for the first time in the user's facility, this would take place at the user's facility.

FAT consists of a number of operational tests to verify compliance with the machine specification. Some of these tests will check the performance of individual sub-systems, including the items below.

- Testing the optical train on a L-PBF machine by scanning the laser over the build area that has a series of detectors installed to measure beam profile, placement accuracy, consistency, and power.
- Translating the deposition head on a DED or ME machine over the full build volume to verify accuracy and repeatability over that volume.
- Measuring the protective gas flow on a machine to verify the lack of dead spots in coverage
- Measuring the heating tip temperature on a ME machine.
- Testing the powder recoating system over a range of powder sizes and layer thicknesses to verify range of operation.
- Verifying operation of the feedstock handling system by checking material feed rates or dosing rates.

While the feedstock used for the actual tests may be a standard material specified by the machine builder, it is more commonly that material the user intends to put in the machine in production. This is not only to avoid potential contamination issues, but to have a continuity of material type from FAT through Installation Qualification, Operational Qualification, and Part Qualification. After these tests have been successfully completed, FAT will often culminate with making a series of test parts that validate the performance of the machine over a range of geometries and location within the build volume. These geometries are generally determined by the machine builder as ones that provide the best information on the performance of the machine in the shortest amount of time and cost. Post-build dimensional inspection is the most common, with radiographic, CT scanning, and surface roughness measurements often employed. Additionally, the log files that were generated during the builds are analyzed for any anomalies. After successful completion of FAT, the machine is then disassembled to the extent necessary and shipped to the user's facility.

Installation Qualification (IQ): IQ Is a process that verifies that all aspects of facility, utilities and equipment that affect product quality adhere to the specification, and that the equipment has been properly delivered and correctly installed. IQ, sometimes known as Site Acceptance Testing (SAT), almost always takes place at the user's facility, after the machine has been received, installed, and re-assembled. In the case of machines that are only assembled at the user's facility, IQ and FAT may be performed simultaneously to reduce time and cost. In many cases, the first stage of IQ is repeating all of the FAT testing to ensure that the newly re-assembled machine performs the same as it did at the factory. A SAT may include the FAT initially but then increase in scope to the user's definition if they possess or add capability to the standard machine and thus becomes the default condition for the user which is then different from the original factory.

IQ will often consist of additional tests required by the machine user. In the case where final payment on the machine is contingent on passing IQ, the machine builder will also be involved in designing the tests and determining pass/fail criteria. Depending on the industry, the part customer or a 3rd party may also be involved. While some of these acceptance tests are subsystem diagnostic type tests, they will usually include building test parts that are representative of the geometries that the user is intending to make with the machine. The intended production feedstock is almost always used for this testing, for the aforementioned reasons. Figure F07_02_iq shows an example IQ component. In addition to the tests performed for FAT, additional tests sometimes include chemistry, microstructural, dissection, and mechanical property tests. Depending on the testing performed, post-processing may be necessary. Mechanical testing at this stage would generally require exceeding specification minimums.

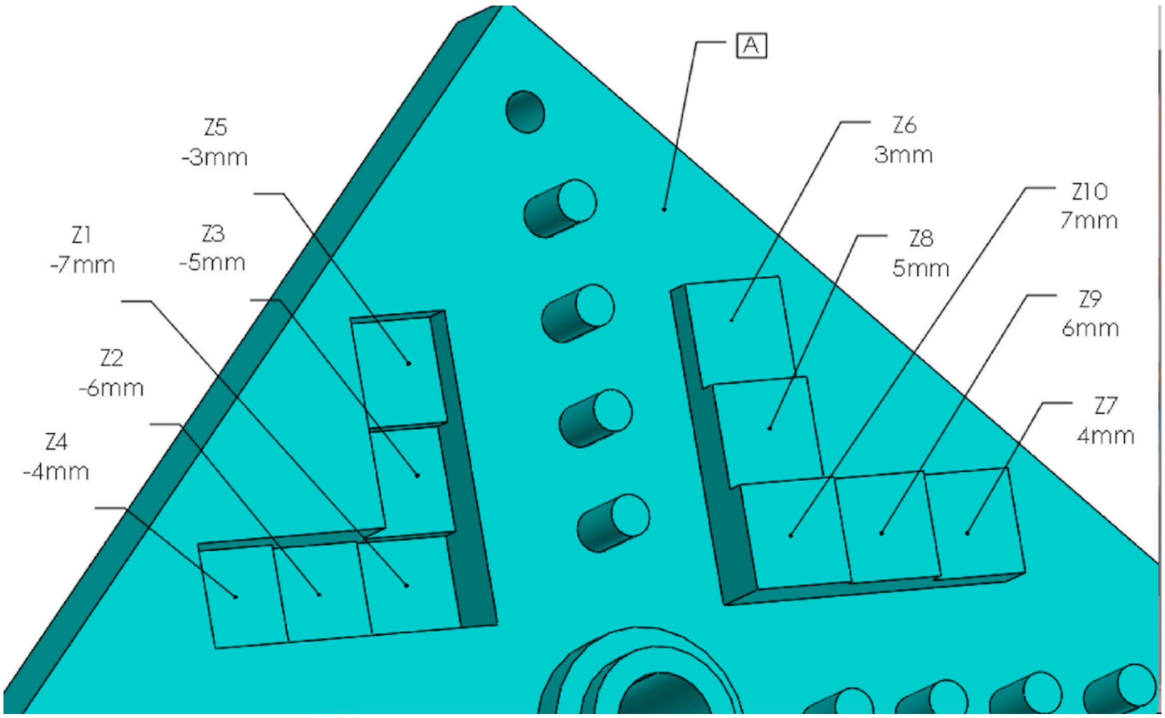


Figure 6.2 Installation Qualification test part example from the US National Institute of Standards and Technology. (credit: Modification of Figure 3 in "Gary Mac, Hammond Pearce, Ramesh Karri, Nikhil Gupta. "Uncertainty quantification in dimensions dataset of additive manufactured NIST standard test artifact." Data in Brief, Volume 38, 2021, 107286. CC BY 4.0)

Operational Qualification (OQ) – OQ is series of tests which ensure that equipment and its sub-systems will operate within their specified limits consistently. This 3rd stage of machine qualification almost always involves the user and the part customer or 3rd party in defining the qualification tests and the pass/fail criteria. They may even collaborate in performing the actual testing, such as the part customer performing the actual chemical, microstructural and mechanical tests. This is generally the earliest instance for a regulatory body to get involved, although usually in a review capacity. Another prerequisite for OQ is that the basic processes for building and post-processing parts is locked down and documented in what is often referred to as a process control document (PCD).

The requirements for OQ are generally found in the specification used by the part customer to procure production hardware. While in most cases, the specification used for OQ are proprietary to the part customer, the general push is to move to industry-standard specifications. Examples of this are AWS D20.1 (Specification for Fabrication of Metal Components using Additive Manufacturing) and AMS 7032 (Additive Manufacturing Machine Qualification). The specification will either include or reference a specification that contains the full range of qualification tests, along with the relevant pass/fail criteria.

OQ will use the feedstock intended for production, as the end result is the approval to use the machine to make production hardware to a specification that includes the feedstock and final part material. Feedstock from a qualified source is also generally required. Full post-processing may need to be performed to properly perform certain tests like chemistry, microstructure, and mechanical properties. These will also need to be performed by post-processors who have the necessary approvals from the part customer or 3rd party.

Because the objective of OQ is to demonstrate that the machine and feedstock combination are capable of repeatedly making hardware that conforms to specification, the following are often part of an OQ:

Test material comes from the full volume of the machine that will be used for production: While this is potentially the full build volume of the machine, in many cases, certain parts of the build volume, will not be used to make production hardware. In this case, test material would not come from these regions, and the qualification documents would state which areas of the build volume are excluded. An example of this is shown in Figure 6.3.**Qualification Volume** is the portion of the build volume qualified to make the specified hardware.

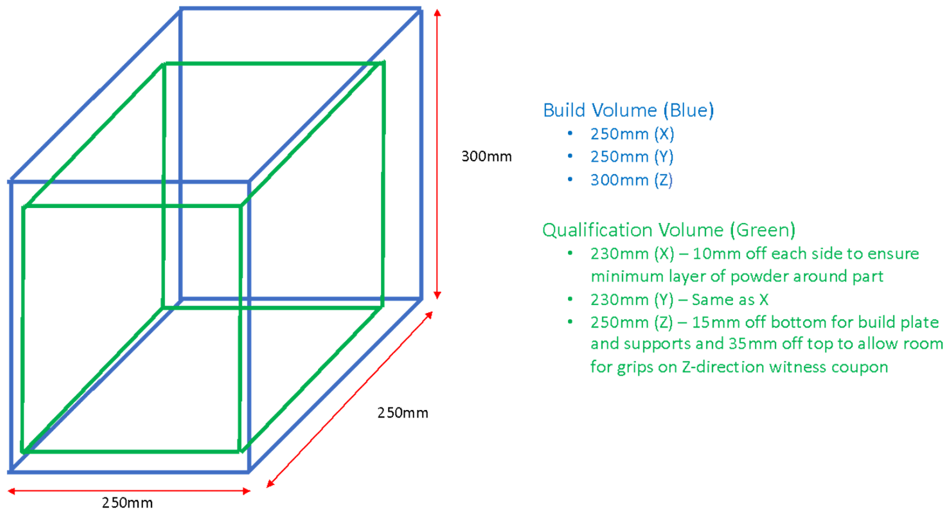


Figure 6.3 Relationship Between Build Volume and Qualification Volume

Multiple lots of material: While some specifications allow all of the test material to come from a single build, others will require 2 or more builds. These builds may allow the same feedstock lots, or they may require different feedstock lots. Producers consider the same options for post-processing operations. The objective is to show that the machine can produce conforming material multiple times. The specification may even require that the builds be non-consecutive or that the feedstock contain a range of chemistry within the range allowed by the feedstock specification. In the case of this example, chemistry and microstructure tests will be done on material in the grip areas of the specimens, but additional coupons or excess material could also be used. (A coupon is a small piece of material that is used as a representative of the entire build for the purposes of testing. It is common in AM and other areas of fabrication.) It should be noted that designing the test builds for qualification to meet all of the coupon size, orientation, and location requirements can be quite challenging. Making spare coupons is recommended because it is possible to have a “bad” test that would then invalidate the qualification by having insufficient tests.

Machine performance during builds meets specification requirements: This means that the machine being qualified performs as expected during the qualification builds, without any anomalies that would require the build to be stopped or the parts to be rejected, such as a loss of shielding gas or input energy.

Hardware meets specification requirements: This means that the parts and coupons built during the qualification builds meet all of the specification requirements for chemistry, microstructure, dimensions, NDT, minimum mechanical properties, and so on.

Consistent mechanical properties: While the specifications for many engineering materials require that their mechanical properties meet the minimums in the specification, newer ones are beginning to require that the population of the material used for qualification match or be more consistent that that used in generating the design values. The reason is to show that not only does the material meet minimum properties, but that the process/machine is sufficiently in control to prevent drift over the production run that could result in the part having low properties that are not detected in lot acceptance testing. While only a few AM specifications currently require this, it may become more common as AM moves to more critical applications.

An example of this is shown in Table 6.1. Note the bottom three rows of the table, which contain the mean, standard deviation, and mean – 3 standard deviations. The high scatter in the X-Direction testing (41 MPa standard deviation, versus 20 MPa for the design value population) means that the potential minimum values for the process (899 UTS and 849 YS) falls below that of the design value population, even though the actual values are all above the specification minimum. There are many methods to compare data sets to see if they are the same population, some of which are described in MMPDS. In this example, the high scatter in UTS strongly suggests that the process is different from that used to develop the design values, and the machine would fail OQ if consistency were one of the criteria.

Data Set	Direction	X direction			Y direction			Z direction		
Design Value Population	Property	UTS (MPa)	YS (MPa)	Elongation (%)	UTS (MPa)	YS (MPa)	Elongation (%)	UTS (MPa)	YS (MPa)	Elongation (%)
	Mean	1050	1000	14	1050	1000	14	1050	1000	15
	Standard Deviation	20	20	1	20	20	1	20	20	1
	Specification Minimum	930	860	10	930	860	10	930	860	10
	Test 1-1	1090	1090	11.0	1085	1090	11.0	1090	1030	12.0
	Test 1-2	1065	1065	11.5	1080	1065	11.0	1090	1030	12.5
	Test 1-3	1040	990	12.0	1075	990	12.0	1040	1010	13.0
	Test 1-4	1015	965	12.5	1065	965	12.5	1015	1000	13.5
Build Lot 2 Feedstock Lot 2	Test 2-1	1010	1030	12.0	1020	1030	12.0	1020	1030	12.0
	Test 2-2	1000	1020	12.5	1010	1020	12.5	1010	1025	12.5
	Test 2-3	990	1015	13.0	1000	1015	13.0	1000	1010	13.0
	Test 2-4	980	990	13.5	990	990	13.5	990	1005	13.5
Build Lot 3	Test 3-1	1070	1030	11.0	1075	1030	11.0	1070	1020	11.0
	Test 3-2	1065	1025	11.5	1070	1025	11.5	1065	1010	11.5
	Test 3-3	1060	1010	12.0	1065	1010	12.0	1060	1000	12.0
	Test 3-4	1055	1005	12.5	1060	1005	12.5	1055	990	12.5
Qualification statistics	Mean	1023	973	13.0	1023	1039	13.0	1029	969	13.0
	Standard Deviation	41	41	1.0	41	36	1.0	31	31	1.0

Table 6.1

Part Qualification

While prototyping, risk reduction, and pre-production development for a part may be performed prior to machine qualification, part qualification may only take place on a machine that has been qualified, except in instances where the engineering authority allows simultaneous machine and part qualification. In part qualification, the user is demonstrating that the combination of the feedstock, machine, general build process (as documented in the PCD), and the part-unique processes produces a part that not only conforms to the general part specification, but also to the Engineering requirements for the part. This part qualification can consist of 3 to 5 activities:

Build File and Build: After the qualification part or parts are built, the log file for that build, like the builds for OQ, are reviewed and analyzed for any anomalies that would normally have caused the build to be halted or the parts rejected.

Engineering Lot and Part Acceptance: Once the build has been deemed to be acceptable, the qualification part or parts are subjected to the post-processing, lot acceptance testing (chemistry, witness tensile coupons, etc.) and part acceptance testing (dimensional and NDT). In the case where final part machining would prevent destructive coupon testing, that post-processing may be omitted.

First Article Testing: In the general case, first article testing refers to any testing that is performed on a first article or articles that would not be performed on production articles. For the purposes of this, it will refer to additional dimensional and NDT. Examples of first article testing are:

- While part acceptance testing may require dimensional inspection of key interface and other critical dimensions, first article testing may consist of making a 3-D point cloud of the whole part and comparing it to the model. This could also include detailed surface roughness measurements.
- While part acceptance may require film radiographic inspection of the part, first article testing may also include CT scanning the part. This can also be used to generate a part model to compare to the Engineering model.

Destructive Testing: As has been practiced in the forging and casting industries for decades, or even centuries, one or more of the first articles may be destructively tested. Examples of this type of testing are:

- Excising mechanical test coupons from the part to verify that the mechanical properties of the material in the part meets specification requirements. In most cases, the only requirement is to meet specification minimums, but for parts that are critical or have low design margins, it may be required that sufficient coupons may be tested to compare the mean values and property scatter. Depending on the part and the number of coupons needed, it may be necessary to destructively test multiple parts. Additionally, the properties of the coupons excised from the part should be compared with any witness mechanical test coupons used for lot acceptance. This is shown in the table below. In this example, two parts were destructively tested, with 6 X-direction, 2 Y-direction, and 4 Z-direction coupons excised from the parts. In addition, 2 X-direction and 2-Z-direction tests were performed from the lot witness coupon. In the case of this data set, all of the tensile values are higher than the specification minimum, and the UTS and YS values are higher than the Design Value Population Mean. While the number of tests are too small for a true statistical comparison, it is apparent that the part properties are consistent or better than the Design Value Population. Finally, the values from the part are higher than those from the witness coupon, which indicates that the witness coupon will provide an early indicator if the process drifts out of control and the overall properties get lower.

Data Set	Direction	X direction			Y direction			Z direction		
Design Value Population	Property	UTS (MPa)	YS (MPa)	Elongation (%)	UTS (MPa)	YS (MPa)	Elongation (%)	UTS (MPa)	YS (MPa)	Elongation (%)
	Mean	1050	1000	14	1050	1000	14	1050	1000	15
	Standard Deviation	20	20	1	20	20	1	20	20	1
	Specification Minimum	930	860	10	930	860	10	930	860	10
Destruct Part 1	Test 1-1	1090	1090	11.0	1085	1090	11.0	1090	1030	12.0
	Test 1-2	1065	1065	11.5	1080	1065	11.5	1090	1030	12.5
	Test 1-3	1040	990	12.0				1040	1010	13.0
	Test 1-4	1015	965	12.5						

Table 6.2

Data Set	Direction	X direction			Y direction			Z direction		
Destruct Part 2	Test 2-1	1030	1010	12.0	1020	1030	12.0	1020	1030	14.0
	Test 2-2	1000	1020	12.5	1010	1020	12.5	1010	1025	14.5
	Test 2-3	990	1015	13.0				1000	1010	15.0
	Test 2-4	980	990	13.5						
Witness Coupons	Witness 1	1040	990	12.0	1023	1039	13.0	1085	1035	13.0
	Witness 2	1035	985	12.5	41	36	1.0	1080	1030	13.5

Table 6.2

- Excising macrostructure (approximately 10x-50x magnification) and microstructure (>50x magnification) coupons to make sure the material in the part matches what would be expected. For all materials, this would be looking for porosity, lack of fusion, laps, inclusions, etc. that are too small to be detected with NDT or visual methods. In the case of metals, this would include grain size, orientation, and the presence of strengthening or deleterious phases. In the case of composites, it would be reinforcement content, size, orientation, and distribution.
- Perform dimensional inspection of features that cannot be accessed in normal production or with nondestructive first article testing, such as the roughness of internal cavities or the dimensions and straightness of micro-trusses. These can be compared with engineering assumptions.

If multiple parts are made in the same build or lot, a decision needs to be made to perform first article testing of one, some, or all parts, and the extent of the testing. A common approach would be to perform the additional dimensional and NDT tests on all the parts, but only perform destructive testing on either one or two of the parts, or parts in the extremes of the build volume.

Part or System Component Qualification Testing: The most involved, and often most expensive form of first article testing is performing a component qualification test on the entire part. This can consist of testing the part individually or as part of a subsystem or system. They type of testing can be static, fatigue or even impact/fracture testing. In the case of a subsystem or system test, the part is installed in a test system, is usually highly instrumented, and the entire subsystem or system is subjected to qualification testing. An example of that could be the testing of an AM manifold for a hydraulic system.

In the case of an individual component test, an elaborate fixture for introducing the loads into the part is designed and built. The part is highly instrumented and installed into the fixture, like that shown in Figure 2, and the part is subjected to the load or loads that the design authority has determined is appropriate for the qualification test. Because of the time and expense of such testing, it is often done either for the initial qualification of a material/process combination or design concept, with the results of the test used to support qualification of future parts without component testing.

Process Qualification / Validation

The previous paragraphs described a qualification structure where machines are qualified, and then each individual part is qualified. While this approach is appropriate in many cases, it can be quite costly and time-consuming, especially when a machine or cell of identical machines is making a large number of similar parts. An alternate approach, commonly known in the medical industry as Process Qualification (PQ) or Process Validation (PV), and referred to in other industries as a Part Family approach.

Consider the manufacture of implants for hip or shoulder replacements. The shape of the typical implant stem is basically the same: A ball-like structure is connected to a curved stem, which attaches to the femur (in a hip replacement) or the humorous (in a shoulder replacement). From there, however, there is a good degree of variance: Surgeons need stems of various lengths, thicknesses, and with different surface details (ribbing, texture) for the purposes of attachment. As a medical replacement part, it can be imagined that a manufacturer would need multiple machines to meet the production rate on most of the parts, which will be discussed later. The desirability of performing PQ on this family of parts is apparent. Instead of qualifying each part individually, the manufacturer could develop a common process (location and orientation in the build chamber, build parameters, post-build thermal processing, finishing), and qualify by testing the extremes and the middle of the process windows. As new variants are added, a lower level of qualification (potentially just NDT, dimensional, and a single destruct article) may be needed.

Figure 6.4 A shoulder implant, featuring the familiar shape of the ball at one end, which is inserted into the shoulder's ball-and-socket joint, and the stem that is implanted in the upper arm bone. Hip implants have a somewhat similar shape. Both types of implants must be manufactured in a range of sizes and lengths to accommodate the wide array of sizes of people's bodies and bone structures. But each size must maintain the same level of quality, strength, and material makeup to ensure long-term effectiveness and no adverse reactions. (credit: Modification of "humerous endoprothessis-36" by Raimond Spekking/Wikimedia Commons, CC BY-SA 2.0)

Personnel Qualification

Intrinsic to having a facility qualified, or to have an expectation of success on a machine or part qualification, is having qualified personnel. Like many other industries, such as welding, personnel qualification consists of the operator or operators undergoing a series of classroom (increasingly virtual or web-based) and practical training on the equipment they will be qualified on. A certain number of on-the-job hours running the equipment under the supervision may also be required. After completing training, they will then have a series of oral, written, and practical (on-machine) examinations. After successfully passing these examinations, the operator certified to operate the equipment. In some instances, especially for critical parts or ones that require skilled manual operations, an additional level of qualification for that part may also be necessary. Like many of the skilled trades, AM levels of qualification could look like:

- Apprentice – Able to operate equipment under supervision of a Journeyman or Master. Generally, not qualified for critical parts.
- Journey-level – Able to operate equipment without supervision. May supervise apprentices. Could be qualified for critical parts.
- Master level – Able to operate equipment without supervision and supervise apprentices. Qualified for critical parts. Responsible for other aspects of an AM facility, such as approving build files, signing off on maintenance, administering qualification of Apprentices and Journey-level.

Some industries, professional groups, and higher education institutions have been reconsidering the use of "master" to indicate authority over other people, due to the term's deep association with slavery. Nearly all states, certifying bodies, and college systems have decided to continue using the term, but those involved in the field should consider the implications of its use and be conscious of the context and connotations of the word.

Some skilled workers, such as plumbers and electricians, are certified in reaching these levels through state-specific evaluation and experience standards. (In other words, to progress from journey level to master level requires specific evidence of experience.) Others, such as machinists, often do not have such formalized levels, but workers can still showcase their experience and qualifications through evidence and resumes. AM may fall into the latter, less formalized category, but the field is growing significantly and there will be plenty of opportunities for career progression.

Feedstock Qualification

Without feedstock that reliably meets specification, any manufacturing process will be hard-pressed to repeatably produce hardware that meets requirements, hence the need to qualify feedstock. The use of a qualified feedstock is almost always a requirement for OQ, Part Qualification, or PQ. The specification the covers printing and processing the AM parts will generally require the use of feedstock qualified to a specification. ASTM and SAE (AMS Series) are issuing a series of feedstock specifications for many of the commonly used powders, wires, and filaments. Where a public specification does not exist, or where different controls are needed, organization will issue their own proprietary specifications.

Feedstock specifications contain requirements for items such as the following:

- Classifications – Sub-categories
- Chemistry – Intentional Constituents
- Chemistry – Unintentional Constituents or Contaminants
- Method of Manufacture
- Product Form and Size – Powder size distribution, wire/filament diameter, foil thickness
- Physical Properties – Density, Flow Rate, etc
- Types and Frequency of Testing
- Packaging, Safety, Handling, Labeling, etc.

Many of these specifications also contain qualification requirements or call out another specification that covers qualification. Qualifying a feedstock to a specification generally requires sampling a certain number of feedstock lots (often 3 or more) and testing them against the requirements in the specification. If all of the lots pass, then a feedstock supplier will be considered qualified. Additionally, each lot of material that is produced will be individually qualified to meet the specification. A powder lot that passes the qualification tests, can then be certified to meet the specification, as mentioned above.

Each company and industry has its own approach to who can be qualified against a feedstock specification. Industries that produce more critical hardware (aerospace, medical) will often only qualify the factory/plant where the feedstock is made from a precursor (monomer for polymers, bar stock for wire or powder, etc.). For critical parts, the facility that produces the precursor and its precursors (e.g. ingot or sponge for titanium powder) may need to be qualified. In other industries and applications, a distributor (facility that procures feedstock and re-sells to users) may be qualified.

Qualification of Additional Facilities, Machines, Personnel, and Feedstock Sources

The simplest and lowest-cost method of qualifying an additional feedstock source is to perform the same qualification tests (3 lots, etc) that were done for the original source. In some cases, however, the engineering authority may want to expand upon that qualification, which would include the building and testing of hardware. This may be driven by the criticality of the part. Another reason, especially in an emerging industry like AM, is to ensure that what is nominally the same feedstock from a different source also performs the same in processing. The extent of this additional qualification can range from building and testing and IQ test part, to one or more OQ builds and testing, to repeating the qualification testing for each part.

Like additional feedstock sources, there is a broad range for qualification of additional machines. This range is also highly influenced by the similarity of the additional machines to the initial machines. The range of similarity can be expressed by the categorizations listed below.

- Identical – Same model number with exact same hardware, firmware, and software
- Very Similar – Same model number but slight differences in hardware, firmware, or software that do not influence the operation of the machine. Examples of this would be a larger spool for filament, or different software for uploading the build log file to memory.
- Similar – Same model number but differences in hardware, firmware, or software that could influence the operation of the machine. Examples of this would be a larger heater tip for improved thermal stability, or a redesigned galvanometer that has higher reliability.
- Not Similar – Same model number but differences in hardware, firmware, or software that will influence the operation of the machine. Examples of this would be a different laser, process control software, etc.
- Different Machine – Different model number and design.

While all of the machines would receive a full IQ, OQ or PQ could range from a full repeat of the OQ for the first machine (definite for a different machine, with a demonstration of equivalent material property values and scatter), to something abbreviated, such as a single build and a check of the material properties against the specification (Identical or Very Similar). Likewise, part qualification could range from full component and/or destructive testing (different machine) to first article testing without a destruct (similar or very similar) to part acceptance testing only (identical). Additionally, the criticality of the part will play a role, with more critical parts requiring more intensive qualification.

6.2 Production Acceptance Testing

Learning Objectives

By the end of this section, students will be able to:

- Describe the types of hardware-accepted testing that are employed in industry.
- Differentiate between lot and part acceptance testing.
- Describe statistical process control and conceptually connect it to lot and part acceptance.

Everything thus far addressed in this chapter has gotten the AM part to the verge of production. Once a part has been qualified, and the system on which part is installed is certified, production may now begin. It should be noted that in some instances where certification can take a year or more, such as aircraft, parts may go into production before the aircraft is fully certified for delivery and use. While parts are in production, they will undergo both lot and part acceptance tests to not only ensure that the parts meet requirements, but often that the feedstock and processes used to make them are in control.

Lot Acceptance Testing

Lot acceptance testing refers to testing that is performed on a group (or lot) of parts to show that the processing the parts received meets specification. There is a range of definitions for a lot in AM, such as the following:

- All of the parts in a single build in any process that go through key post-processing operations, such as thermal treatment, together.
- A series of parts in DED that use the same lot of feedstock, the chamber atmosphere is never broken, and go through key post-processing operations together.
- A series of parts in BJP that made in multiple consecutive builds, and undergo de-binding, sintering, and key post-processing operations together
- A series of parts in VP that use the same lot of resin and are made consecutively

Note that each lot could theoretically consist of identical, opposite-hand, similar, or even different parts. What is being checked in lot acceptance is that the process met requirements. So, one type of lot acceptance would be a check of the build file and process monitoring that there were no unacceptable process events, such as energy source failure, recoater failure, contaminated atmosphere, and so on. While another type of lot acceptance could be a check of witness material in the build to verify that nominally acceptable material was produced. These types of tests consist of mechanical (mainly tensile) tests, micrographic (mainly in metals) chemistry tests, etc. Since AM builds parts in layers, careful thought must be put to the location of the witness coupons to ensure they are representative of the build process.

As occasionally practiced in other industries, destructive lot acceptance testing is sometimes performed in AM. This would be driven by a combination of part criticality, and overall maturity of the process. Destructive lot acceptance testing would generally consist of selecting one or more parts from the lot and performing destructive testing on it, in a similar or less extensive manner than destructive part testing for qualification. Different schemes may be used to select the part to be tested, with some requiring the same location in the lot, and others requiring a random location.

Failure of one or more of these tests can result in the entire lot being rejected, require the need for additional testing to demonstrate lot or part acceptability, or being analyzed by engineering authority to determine if any of the parts are acceptable either as-is or with rework.

Part Acceptance Testing

Part acceptance testing verifies that the part meets key requirements. It is generally performed on each and every part, although schemes for sampling (where some parts might not be qualified) do exist. Some examples of part acceptance testing include the following:

- Dimensional tests of key dimensions
- Nondestructive testing of both the part volume and/or the part surfaces
- Hardness testing to ensure proper response to thermal treatments

Failure of one or more of these tests can result in the part being rejected, indicate a need for additional testing, or require analysis by an engineering authority to determine if the part is acceptable as-is or with rework.

Statistical Process Control

Modern quality management systems will often utilize statistical process control (SPC), sometimes referred to as statistical quality control (SQC). SPC consist of recording data from either the process or the product and checking it against limits to determine if a process is in control. The goal is to use this tracking to get advance warning that a process is getting out of control before it happens and begins making unacceptable hardware. As a digital and data-rich technology, AM is ideally suited for this.

Examples of process variables and outputs that could be tracked include the following:

- Tensile properties of the witness coupons
- Key dimensions of the part
- Atmosphere gas consumption during build
- Laser output power
- Peak tip temperature in ME or peak current in an arc DED process

Having an in-depth understanding of the key variables in the process can help a product team decide what inputs and outputs to monitor, with the default option being to monitor all and let advanced data analytics software to make that determination. The former is preferred, as the latter can generate numerous false warnings (crying wolf) that distract the product team from other tasks.

6.3 Fixed Designs and Processes, Change Management, and the Future of Certification and Qualification

Learning Objectives

By the end of this section, students will be able to:

- Understand the importance of a fixed process.
- Understand the importance of having a disciplined change management process in AM.
- Understand how Certification and Qualification for AM will evolve as more experience and confidence is gained in the technology.

The design, manufacture, and use of AM parts should follow fixed design, fixed (also known as locked down) process and change management protocols used in modern industrial practice. This is in spite of the fact that by being a digital process that rarely requires tooling, it can be very easy from a practical standpoint to change either the design or the process. In essence, once a design or process is fixed (or locked down), any changes to the design or process need to be approved by the relevant engineering authority to ensure that the previously attained part qualification and system certifications are invalidated.

The approach for change management is much like that used for qualification of additional machines. Depending on the type of change, the amount of re-qualification can range from a minimal amount (first article testing without a destruct) to a full repeat of part qualification (design or process change) to repeat of machine and part qualification (process change). Standard practice in organizations using AM is to initially require that all changes be brought to a change control board (CCB) to decide what requalification is necessary. As the organization develops a history of change management, standard practices are then developed to more quickly determine and plan the re-qualification steps. A good indication of the need for some form of requalification can be gained from reviewing the key process variables. AMS 7003 (Laser Powder Bed Fusion Process) lists 34 key process variables. A change in any of these could potentially trigger a requalification.

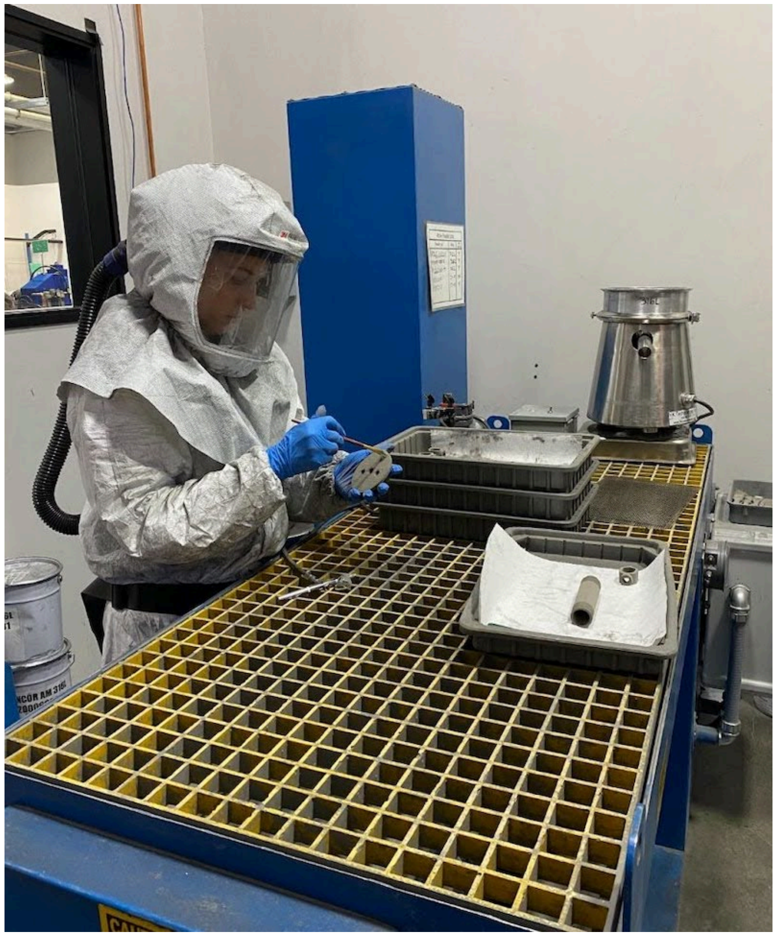


Figure 6.5 A green part is formed by metal powder held together with a binding agent. In decaking the part, the technician is removing any fine or residual powder from the part before it goes through the binder removal, or debinding, process. Qualification would ensure that the tools, process, and the technician themself is capable of producing the part repeatedly. If any element of the qualified process were to change, including a change in personnel or a new sequence or location of the steps, requalification may be required. (credit: Morgan Blackstock on DVIDS, Public Domain)

Another type of change that can happen is maintenance or movement of the AM or post-processing machines. In the case of a minor maintenance action machine could be nearly identical to itself before the maintenance, which would often just require a simple IQ. In the case of a major maintenance action, the machine could be considered not similar, which would require IQ, OQ/PQ and part requalification. This would be similar if the machine is moved to a different location. In most cases, an IQ would be all that is required, unless the IQ fails, and a maintenance action is required. Like design or product change management, the initial requalification requirements for maintenance actions have a high level of oversight until history and standard practices are developed. In the case of intermittent production, or if a machine is idle for a period of time, some industries will require an IQ prior to resuming production, with a reduced OQ/PQ or part requalification potentially required as well.

Future Changes in Certification and Qualification

As a rapidly evolving technology, AM will continue to develop and mature. Along with the general maturation of the technology, certification and qualification will continue to mature to evolve as well. At this time, most organizations qualifying AM parts on systems that require certification are being very careful in their approaches. The primary changes in the future for certification and qualification will be to streamline those processes.

Because it is generally independent of the exact materials and processes used, certification will see fewer changes in the future. The primary change to certification will be a better understanding of material/process/property relationships that will enable a transition of design values from part-specific to part-family to feature-based. Advances in Integrated Computational Materials Engineering (ICME) combined with advancements in process simulation and part design/analysis codes will give designers and analysts the ability to predict properties based on the part design. While the design value tables may be multi-dimensional, versus the 2-dimensional format, it can be imagined that these could be simplified if the potential performance impact of lower design values is minimal.

Additional changes may include exploiting the same ICME advancements and developing the ability to more quickly generate design values as faster or more precise AM technologies are introduced. Also, we may transition NDT from post-build to in-situ, which may align with the future ability to undertake repairs during the build. This capability, along with the ability to predict maximum undetectable defect size will enable better analysis of critical components. Overall, we should we improved knowledge of the performance of AM-unique geometries to reduce the amount of full-scale component and system testing.

Changes in qualification will be based on obtaining a better understanding of the key process variables and the impact on part performance.

Qualifications changes may exhibit themselves in the following ways:

- A more extensive, but more automated IQ, that will be able to make a better determination of the status and health of a machine than is currently possible.
- A reduction in the number of builds and tests needed for OP or PQ, particularly due to improved IQ.
- Improved characterization and better definition of feedstock requirements to eliminate the need for any feedstock qualification save acceptance testing.
- Advances in process monitoring, process control, and in-situ NDT to eliminate the need for destructive testing for part qualification.
- Lot and part acceptance based on process monitoring and in-situ NDT of the build, along with process monitoring of key post-processes, such as thermal treatments.
- Integration of process monitoring with post-build evaluations as part of an integrated SPC program.

Summary

Qualification in additive manufacturing (AM) ensures that machines, facilities, personnel, and feedstock meet stringent requirements for consistent, reliable production. It aligns closely with certification but focuses on production readiness. Qualification involves several levels:

1. Qualification: Verifies that an organization has comprehensive quality systems, approved AM processes, and related equipment. It encompasses training, materials control, and post-processing.
2. Machine Qualification: Includes factory acceptance testing (FAT), installation qualification (IQ), and operational qualification (OQ). FAT tests machine functionality before delivery. IQ confirms proper installation, while OQ ensures consistent part production within specified limits.
3. Part Qualification: Demonstrates that a machine-feedstock-process combination meets engineering and production specifications. It involves build file analysis, acceptance testing, and often destructive testing of first articles.
4. Process Qualification (PQ): Common in medical and high-volume industries, PQ qualifies part families by testing process extremes, reducing individual part qualification needs.
5. Personnel Qualification: Ensures operators are trained and tested for competence, with defined roles.
6. Future advancements aim to streamline qualification through automation, better process control, and integrated statistical process control (SPC). Improvements in ICME, in-situ NDT, and predictive modeling will reduce destructive testing, allowing faster, more efficient qualification and production acceptance. Certification will evolve to enable part-family and feature-based design values, enhancing flexibility while maintaining safety and reliability.

Future advancements aim to streamline qualification through automation, better process control, and integrated statistical process control (SPC). Improvements in ICME, in-situ NDT, and predictive modeling will reduce destructive testing, allowing faster, more efficient qualification and production acceptance. Certification will evolve to enable part-family and feature-based design values, enhancing flexibility while maintaining safety and reliability.

Review Questions

1. Which of the following would not be expected for qualification of a wire/plasma DED facility?
   a. Quality management system
   b. Wire feedstock source qualification
   c. Wire/Plasma machine qualification
   d. NDT lab

2. Which of the following is out of order for qualification?
   a. Installation qualification
   b. Operational qualification
   c. Part qualification
   d. Factory acceptance testing

3. Which is not a feature of operational qualification?
   a. Multiple feedstock lots of the specified material
   b. Encompassing a defined portion of build volume
   c. Multiple machine operators
   d. Multiple coupon orientations
   e. Material properties

4. Which is generally the most involved and expensive form of part qualification?
   a. Lot acceptance testing
   b. First article testing
   c. Component testing
   d. Destructive testing

5. Which of the following is false?
   a. A given feedstock can be qualified to multiple overlapping specifications
   b. All industries only allow feedstock manufacturing facilities to be qualified
   c. Feedstock qualification often requires analysis of multiple lots
   d. Feedstock qualification can involve a full range of properties beyond chemistry

6. Which of the following is not an example of lot acceptance testing?

a. Checking the chemistry of a witness coupon
b. Tensile testing in the X and Z directions
c. Review of build and heat treat data to ensure conformity to specification
d. Radiographic inspection of every part in the build

Key Terms

6.1 Qualification

Factory Acceptance Test , Installation qualification, Operational Qualification, Part Qualification, Qualification Volume

6.2 Production Acceptance Testing

Lot Acceptance, Part Acceptance, Statistical Process Control

6.3 Fixed Designs and Processes, Change Management, and the Future of Certification and Qualification

Fixed Process, Change Management

7 THE ADDITIVE MANUFACTURING DIGITAL THREAD

Figure 7.1 The digital thread refers to the data that is associated with and required for the design, materials selection, build planning, build, post-processing, and quality assurance processes in additive manufacturing. The digital thread becomes very complex and may have compatibility issues as machines of different types and origin are integrated into one process, as is the case in this hybrid manufacturing system. (credit: Modification of “hybrid manufacturing system” by Oak Ridge National Laboratory/Flickr, CC BY 2.0)

Chapter Outline

Introduction

The digital thread has come to represent a series of concepts throughout the manufacturing industry. Specific to additive manufacturing, it represents the accumulation of data that is generated at various steps of the 3D printing workflow. This not only includes the production of the part from an individual printer, but also the information that is generated at related steps including customer orders, design information, material details, and post-processing. The digital thread can be quite overwhelming and challenging to navigate given the fact that printing modalities and software solutions are continuing to evolve.

7.1 Digital Trends Throughout Manufacturing

Learning Objectives

By the end of this section, students will be able to:

- Understand the importance and role of the digital thread in both conventional and additive manufacturing.
- Describe the end-to-end digital requirements for additive manufacturing.

Additive manufacturing is a small piece of the overall manufacturing and production landscape. Within any manufacturing environment there will be multiple machines that in conjunction with the operators work together to produce physical goods. The interaction between machines, the facility, and the employees generate terabytes of data daily and insights through leveraging the digital thread have been transforming the manufacturing industry for many years.

One of the principal trends moving the pace of development forward is that computing power, wireless connectivity, and the internet have allowed sensors and integration platforms to become less expensive. Functionally, the primary driver of any manufacturing organization is producing a physical product in a safe and efficient manner that allows the firm to make a profit. The systems within a manufacturing environment are oftentimes highly complex and rely on the integration of information from several processes and people over a sustained amount of time. Even the most optimized and high-tech manufacturing floor is rife with areas where sensors or increased data analysis could lead to efficiency gains that can influence the bottom line. Framing these questions and hypotheses is a central tenet to the digital thread because just capturing data at different points in the manufacturing process does not inherently add value. There needs to be some action or response tied to the outcome of this information. Listed below are some example hypotheses that manufacturing companies have sought to examine with increased digital connectivity:

- How efficiently are my machines operating?
- Are there machine optimizations that should be made to increase sustainability and decrease energy usage?
- Where are the errors in my manufacturing process occurring and can we fix or predict them?
- Can I predict when my machine is going to break down or when I have to replace a tool?

Because the pace of development with sensors and wireless connectivity has accelerated more rapidly than most manufacturing plants have updated their machines, there are operational challenges to implementing digital strategies into an organization. Newer CNC equipment may have sensors already built in that allow easy downloading of analytics but older generation machines still perform their functional role very well but are not connected to any other parts of the plant. Now there are retrofit kits that enable users to install sensors on their legacy equipment in less than one hour. The functionality of the sensors varies, but users can typically select parameters that give them visibility into the machine status, heat generated from the machine, and operational statistics.

Perisense offers low-cost retro-fit sensors that help inform production decisions on manufacturing lines. The sensors keep track of runtime, part count, process repeatability, and maintenance indicators.

The challenge of digital connectivity may start with the data that one might be trying to capture. For example, a data component might be some error or inconsistency in the build. However, there is an increasing disconnect between how long it takes to acquire the data and the window of time that the information is relevant or actionable. If the error data is discovered after the build, the entire build may be disqualified, wasting expensive material and time.

In conventional manufacturing similar gaps persists, especially as it refers to quality assurance. Presumably most organizations have some quality metrics in place to ensure that the parts that are being produced fulfill the customer requirements. Most of these metric systems are able to pick out an individual part or batch of parts that are out of spec once the full part is built. Digital tools based on the machine can now identify problems earlier on in the part manufacturing process. Signal irregularities or even electrical disturbances can be gleaned from mundane machine sensors and relayed back to computer systems that aim to keep a long-term cumulative view of the machine performance.

Key Digital Requirements for Additive Manufacturing

Additive manufacturing has many unique features that enable it to impact a wide variety of industrial applications. Fundamentally, the process is rooted in a digital ecosystem; no printing can take place without some sort of digital file as an input. The necessity of digital inputs avoids a major hurdle that faces other forming technologies where a 2-D drawing may suffice without any digital record. This has major implications for building a full-fledged digital thread capability within the process workflow but arguably just as important, it requires those that engage with the technology have at least some familiarity with operating in a digital ecosystem. The breadth of manufacturing sophistication and workforce training is something that should not be overlooked. Even 30 years into its existence, the AM industry faces limits on widespread adoption and operator/engineer training.

Throughout this chapter, the AM digital thread will be evaluated at each step of the process workflow. As it pertains to the concept of the digital thread, we will try to maintain a consistent nomenclature; however, the nature of the additive manufacturing industry is that the acceleration of development and advances is ever increasing. The table below outlines the high-level concepts that will form the foundation of this chapter. We will cover five main sections of the digital thread: Design, File Processing, Simulation, Build Monitoring, and Quality Assurance. Within each of these sections, the methods that have been employed to retrieve data from the manufacturing ecosystem along with how end users can leverage the information to make meaningful advances in their business will be discussed.

Design	File Processing	Simulation	Build Monitoring	Quality Assurance
Production of the digital files for use in 3D printing including higher order operations	Transfer and dissemination of design files to the printer destination. This includes formatting individuals into a complete build with multiple components and designating printer settings	Digital simulation of the functional part, process simulation, and analysis of the final part, as well as part processing aspects such as support structures	Data generated from the printing and operation the machinery including yield/ efficiency data, part production metrics, and quality reports	Data generated from various workflow steps, including materials processing and post-processing, which contribute to a complete view of the resulting parts.

Table 7.1

When considering which 3D printing workflow components have a significant digital component, the obvious component is the fundamental design input – the STL and related files. However, several other elements have a significant digital footprint, including the following:

- Parts selection
- Materials profile
- Machine characteristics and requirements
- Post-processing steps and data
- Testing and inspection

By using digital inputs, parts selection can be automated to assist with the evaluation of whether a part makes sense for a given AM printing system. Contained within the data of a digital part are things like geometry and part dimensions. As one progresses through the workflow the material inputs become another element of construction. Data can be generated on the type and caliber of material along with information that results in a more complete view of the operations in the facility such as usage and price.

Next, the machine and process data provide a window into the actual operations that go into constructing the part. The exact **data stream** coming from this step will be highly variable depending on the type of process modality. Similar to traditional manufacturing, most early model 3D printers have limited ability to track and export build information to a coherent platform. Most of the time this information ends up residing in the machine and unconnected from other information generated in the full workflow. Aspects of the machine and process data that can be currently captured include build height, timing, cost as well as more fundamental machine performance details generated from data from embedded sensors. Many printers now have the ability to take a picture of each layer or provide user feedback on critical parameters such as the environmental conditions inside the build chamber.

Once the parts are removed from the machine, there are a number of steps necessary to deem a production part completed. This could include support material removal, heat treatment, machining, or finishing. Most of these steps are conventional manufacturing processes that historically do not have a great deal of interconnectedness to digital documentation. Nevertheless, several printer modalities have very specific post-processing requirements and equipment that are being integrated into extensions of the printers themselves. This assists in the ability of the users to document a full digital transcript of all the activities that take place following the printing process. The reason that these steps become critical is two fold. First, since many of the processes can have a major impact on the final part properties, it is important that the end customer has visibility into the end-to-end process. Second, throughout the post-processing procedures there may be multiple employees or facilities handling each part. By documenting each part of that workflow errors can be minimized and long-term traceability preserved.

Figure 7.2 Operators and manufacturers may not consider post-processing steps, such as sintering as shown here, to have a significant digital component. However, some printers, processes, and end-users may require a detailed transcript of the precise conditions of sintering in order to undertake further steps. (credit: U.S. Marine Corps photo by Cpl. Jamin M. Powell on DVIDS, Public Domain)

The final stage of the AM digital workflow process is testing and inspection of the parts. There are multiple approaches to validating components and this is typically driven by the industry requirements. Many inspection methods are digital in nature whether it be dimensional analysis or material testing. Again, similar to traditional machine tools, the digital outputs may live on independent servers or platforms that are not obviously connected to a centralized repository. With all that in mind, the breadth of the 3D printing digital thread is expansive and is not uniform across even the same printing modalities.

The Challenges of the Digital Thread for Additive Manufacturing

The AM digital thread is by no means mature. While certain technologies are well established, most manufacturing, logistics, and related organizations would admit that the technology as a whole remains a new entity for manufacturing. There are three primary challenges to adoption of the digital thread in the additive manufacturing sector:

- Stability of the AM Process and Technologies
- Cost for Implementing End to End Solutions
- Workforce that Can Build, Interact and Leverage the Digital Thread

Stability of the AM Process and Technologies

3D printers can be considered a platform technology that enables a wide range of applications for many industries. There are dozens of printer manufacturers accounting for thousands installations globally. The relative newness of the technology and the intensive research and development underway means that significant incremental improvements or capability expansions are represented by new machines and processes. As a result, many facilities may have multiple printer modalities. Each system may have a unique workflow with different part production and processing requirements. In an ideal world, these inputs would be centralized on a data stream where information could be connected from part to part. There are software tools that are starting to connect some of the machines to gain intelligence; however it is a significant challenge to adapt to such a wide array of technologies, materials and vendor platforms and do so in a way that makes sense for multiple industries.

Costs for Implementing End-to-End Solutions

One of the biggest factors that has pushed the concept of the digital thread throughout a broad user base is the cost reductions for sensors, data storage, and high-quality internet connectivity. This set of parameters makes it possible for even the smallest manufacturer to add low cost solutions to their facility such as cameras or temperature sensors. Ultimately, this is a positive thing, but in many cases, additional data streams become unique islands of information that may not be connected to any other part of the manufacturing process. In order for the full concept of the digital thread to be realized, a significant amount of infrastructure needs to be put into place including either cloud or local databases, security protocols, and methodologies for maintaining the systems. Even more importantly, it may require manufacturing facilities to recruit different types of employees to manage these processes. Expertise in data science, machine learning, computer science, and artificial intelligence may be required alongside a fundamental understanding of how the mechanical and material aspects of the production processes work.

Cost is measured not only by money but also by time for implementation. Depending on what sorts of legacy IT systems are in place at a given facility, it may take some time for facilities that are trying to modernize to integrate new platforms. This transfer becomes one of the biggest barriers to success and can push out time scales significantly. Finally, printing technology and the digital thread are not static. Things will continue to evolve and organizations can be slow in deciding when is the right time to make an investment that can pay real dividends but also not be obsolete in a few short years.

Workforce that can Build, Interact, and Leverage the Digital Thread

Assuming an organization can build a platform that enables widespread data analytics on their manufacturing processes, success is not immediately guaranteed. Data is useless unless it has some contextual grounding. Certainly, interesting insights can be gained developing machine metrics but the higher order benefits of the digital thread will come from a close collaboration and translation of real life activities on the factory floor from employees partnered with new information that is coming from the digital thread. There is a risk that having too much information being generated during the manufacturing processes can be harmful or so confusing that the tools ultimately become ignored. In many ways, the reliance on just numbers to provide top-down insight on an additive manufacturing operation is likely not going to be successful. The hope of most organizations is that the digital thread augments a workforce that together can become more efficient. This may mean that the tools will have to be designed with the existing workforce in mind and additional training would be required to make the digital thread approaches worthwhile.

Long-Term Implications for Additive Manufacturing

As 3D printing technologies continue to evolve there will be many more platforms and even fundamentally new technologies that will continue to add tools to the manufacturers’ tool belt. It is likely that more capabilities that were once segmented (such as post-processing, digital inputs) would be more integrated into the machines themselves so that users starting new will have an easier time getting deploying a digital thread strategy. Ultimately, the potential for building a robust digital strategy around 3D printing is extremely powerful. The process is driven by digital designs that can be transferred around the world (or even out of this world) with the click of a button and can make supply chains much more robust through distributed manufacturing.

The other hope for more digital engagement with the manual workflow of 3D printing is that the technology will become more repeatable and stable. This has enormous implications for enabling business models for 3D printing, whether it is customized part production or building a digital warehouse of files to support repair or replacement parts. These promises are still more fantasy than reality for the average manufacturer; to implement them, the operators, engineers, and customers will need to be engaged at a level to ground the possibilities in practical reality.

7.2 The Digital Thread in Design for Additive Manufacturing

Learning Objectives

By the end of this section, students will be able to:

- Describe the opportunities presented by software solutions in part selection and management.
- Understand the impact of design choices on the digital thread.

The foundational step of any 3D printing operation is the creation of a digital design file. We covered the full process of design for additive manufacturing in detail in an earlier chapter. As we break down each step of the additive manufacturing workflow, we are going to discuss how each of these parts generate digital information that can be strung together as part of a global digital thread strategy.

Digital design tools are not new for manufacturing. In fact, they have been around for the better part of several decades. What is different for AM is that they are a requirement for starting the process. A two-dimensional drawing, even if it is fully developed, will not suffice in the workflow process. Therefore, any user needs to be able to access a CAD tool to build a 3D model. This often becomes a hurdle for organizations who are building their additive manufacturing strategy because many or even most of their parts are generated for conventional manufacturing processes with 2-D drawings. Even if the part is a good business case for 3D printing (perhaps a low volume repair part or some high value component), the first step is building the model in three dimensions.

Throughout this chapter, we are going to be touching on two main aspects of how design interacts with the AM digital thread. The first is through the creation of these digital files and the types of digital tools are required to do that. The second area that we will be discussing is how the design approach influences all aspects of the 3D printing process and ways that companies are trying to build tools specifically for 3D printing modalities.

Digital Design Creation

There are many different software tools available that allow a designer or engineer to construct a part in three dimensions. Typically, these approaches live in the realm of parameter-based modeling where a solid model is developed and once it is ready for export to the 3D printer the file is converted to a triangle mesh. There are certainly other types of modeling based on scanning (point clouds) and more surface based modeling approaches that can be utilized in 3D printing, however for the most part the majority of 3D printing files start in the region of solid modeling.

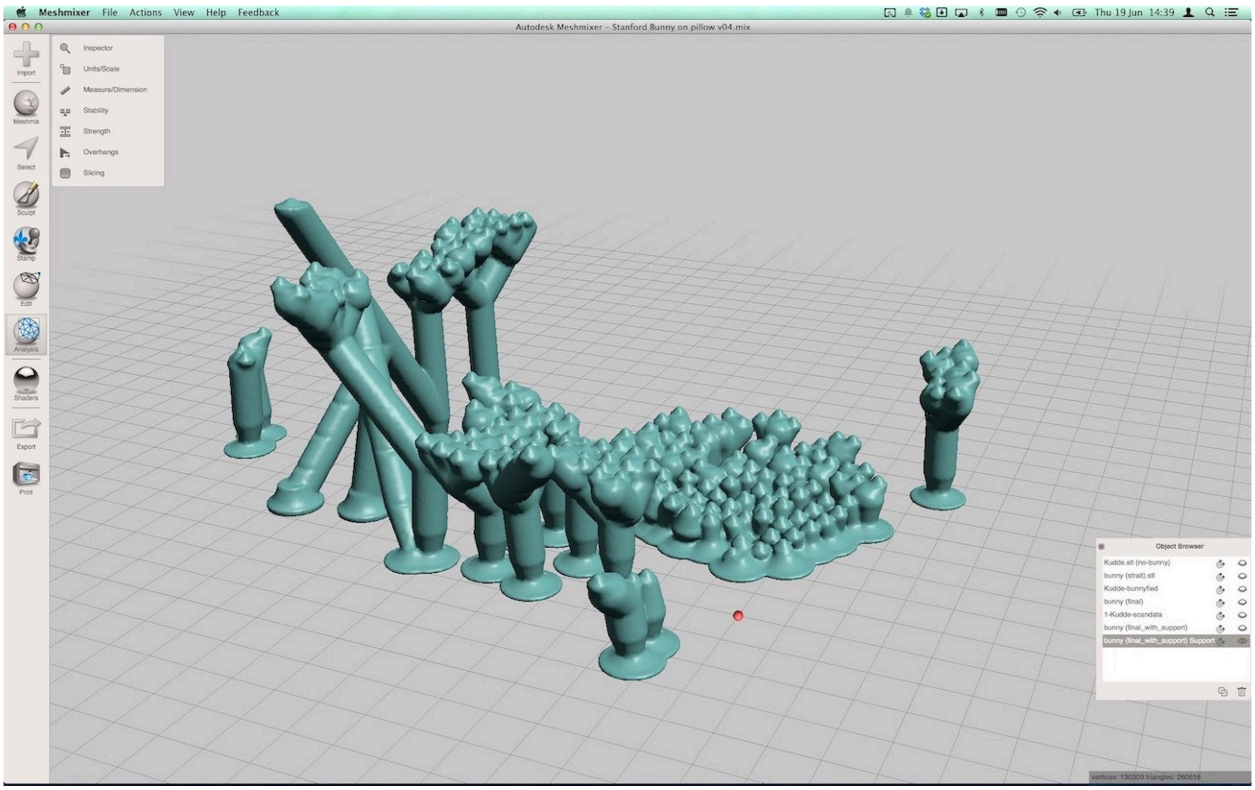


Figure 7.3 This model was made by 3D scanning an object with an ASUS XTION depth camera, then importing the scan data into an Autodesk software where it was made into a solid and captured as an STL file. (credit: Creative Tools/Flickr, CC BY 2.0)

Because the vast majority of traditionally manufactured parts are not 3D printed, the legacy CAD and solid modeling companies have a wide range of software options that can be adapted to 3D printing. Some of the most common industry stalwarts are SolidWorks (Dassault Systemes), Onshape, PTC, Autodesk, and Siemens NX. There are also numerous free or low cost CAD software systems on the market. The primary function as it relates to 3D printing for these tools is the creation of the digital model. However, the CAD design process is actually a very small portion of the capabilities of these software tools. Most CAD systems have the ability to create complex assemblies, do different levels of part or process simulation, and manage bill of materials.

Many of the traditional CAD systems also have embedded workflows that are dedicated to specific industry applications. For instance, in the dental or medical space, imaging equipment is often used to create digital designs to assist with surgery or medical implants themselves. In these cases, point cloud data from various scanning platforms needs to be converted to STL but at the same time patient data and prescription information should be documented alongside this information. These types of workflows are where the current landscape in 3D printing is often limited because operators start to have multiple files that connect to the same patient. Manufacturers must then come up with a system to continue to manage that information as it goes into the printer and a subsequent database, ultimately landing back with the customer or patient.

Something to keep in mind as we think about the digital thread is the way in which designs are built and disseminated amongst a team. In some cases, part designs are managed by a single individual that is enabled by their own single software platform. In many other cases there tends to be a sharing of CAD or design files between numerous people in an organization. This is often one of the big reasons that individual companies will tend to have a company wide policy of only using one brand of design software as it can be challenging to move design files between different CAD platforms.

There is also a trend to deploy cloud-based CAD design tools that further enable collaboration within an organization. The principle advantage of having a cloud-based solution is that software tends to become obsolete over time without routine updates. Cloud-based systems are updated at a more regular basis, often with a subscription model for the user.

It is important to always keep in mind that 3D printing is one of many tools in the manufacturer's toolbelt, and that the use of the technology does not always guarantee improved outcomes on every dimension. We have discussed in earlier chapters the ability of 3D printers to produce parts that are highly complex with design features like internal passageways that may not be easily replicated in conventional manufacturing. The addition of these features may allow for lightweight parts that can improve overall performance. Typically, a complex structure may only be a portion of the overall part geometry, but can still cause challenges within existing CAD files because the geometry file becomes larger. Long term, it is also a consideration as most designs are not static. Users should consider how and who might be able to edit a part in the future for improvement or including advanced features.

We have been discussing the basic tools for creating the digital files required for 3D printing. As you think about the application of the technology within an organization, a part design is not something that just materializes one day and is complete. Instead, any design file goes through numerous iterations through the prototyping process before it is finalized for production. The current STL file format does not offer an embedded iteration history in the file. A user can use an internal naming convention on the specific file to signify changes, but this is certainly a limitation of the file type. From a digital thread perspective, this does introduce potential version control issues into the process of production printing. In order for full traceability to be documented, there needs to be at minimum a process to ensure that a file is locked at a particular version signifying date and time of the last change. Not only is this important for internal organizations, but is important for organizations that are outsourcing their printing to service bureaus or contract manufacturers because there are limited controls to who can make changes to a design once they have the digital files.

Part Selection and Management

We have covered throughout this text the mechanics of designing parts for AMalong with software tools that enable that process. Up until this point, we have neglected a discussion on the ways to digitize the selection of what parts should be 3D printed. We already know that there are good and bad part choices when it comes to the technology, but as the technology becomes more improved, the hope is that the combination of geometry, materials, cost, and performance of 3D printed parts becomes more comparable to traditional technologies.

There are basic screening techniques that can be applied to help organizations decide what is a good candidate for 3D printing. Organizations must consider the digital design information such as part dimensions and features. They must also gather and assess costing and material requirements, which are critical elements of the 3D printing digital thread and ultimately help inform the pathway of production for many parts.

Figure 7.4 An engine cylinder head cast from a 3D printed mold. Deciding on whether such a critical part could be produced through AM – even indirectly – is a complex process that can more deeply associated with digitally supported decision making. (credit: Modification of "Automotive cylinder head cast from aluminum cerium alloy in a 3D printed mold" by Oak Ridge National Laboratory/Flickr, CC BY 2.0)

At the moment, the process of selecting suitable parts and design spaces for AM components is mostly a manual process. The process is relatively slow, and requires a team with expertise in the 3D printing technology space to evaluate all the potential options. Emerging digital decision approaches have been commercialized to streamline that process. For example, Castor is an automated part screening software that informs manufacturers when it is beneficial to use additive manufacturing.

Design Implications that Impact the Digital Thread

We have emphasized the importance of contextualizing your 3D printing designs within the entire process workflow. Many of the elements involved in design approaches require a strong partnership between the user and the software tools to enable a successful thread of information. There are efforts to enhance the connection nodes between design variables with underlying file types like 3MF. However, the adoption rate of new fundamental approaches to replace files like STL will undoubtedly take time to iron out of the system.

In the meantime, users should focus on best practices to engage the operators and technicians of the equipment to leverage the most appropriate software relevant to their industry. This may sound obvious, but some organizations may not need the most expensive or advanced design tools with all the latest features because they may only use a small subset of their capabilities. As with most applied elements of the manufacturing sector, a thorough understanding of the critical workflow elements, led by those who operate the equipment, typically gleans the most insight.

The 3D printing sector should not be thought of as a static entity. There is a constant updating of processes and procedures in relation to the overall organization, facilities, and machinery. In some ways, the job of the user is never done in finding a way to optimize the process of structuring designs both for functionality in the real world but also in a digital sense to optimize the process for their construction. Part design is not only the foundation of the overarching 3D printing process, it is also the foundation upon which the 3D printing digital thread is built. The software platforms that are utilized in the beginning of the workflow to create a part underpin what decisions can be made with the digital thread later on in the process of part production.

In some cases, all design tools will reside within a single operational platform. In other cases, the software tools used to perform one aspect of the design process may be incomplete for a future step, and we need to connect that information to another software platform. These connection points are what make the digital thread so “bumpy.” We rely on operators and engineers to know what data is meaningful to keep across the timeline of the part. But the body of knowledge is not always transferable to every printing platform, new material, or design need. Many organizations go through a painful growth stage where the nuances of each machine are mapped out over a period of several months or even years to identify what signals are strong and impactful for the process.

Design factors that influence final parts and the digital thread include:

- Software platform
- Design approach (CAD, surface modeling, etc.)
- Build orientation
- Printer
- Materials
- Collaboration requirements
- Intellectual property considerations

The creation of the digital file is only the first step in the printing workflow. As we build upon the subsequent steps we will continue to discuss how the data generated can influence the outcome of each 3D P\printed build but hopefully provide you with the tools to consider how best to construct your own AM digital thread that is most relevant to your industry and organization.

7.3 Processing a file for 3D printing

Learning Objectives

By the end of this section, students will be able to:

- Describe and prioritize the impact of the digital thread in file processing.
- Explore various software solutions for AM file management.
- Identify opportunities and impacts of AM-based distributed manufacturing on the digital thread.
- Understand the basic intellectual property and information security considerations of additive manufacturing.

The previous section highlighted the process of producing 3D printing ready files and the data concepts that go into their production. As we move into the next part of the workflow, we want to focus more precisely on the connection that the file has to the broader 3D printing process and business model for the organization. While 3D printing has a heritage in prototyping, the fact remains that the push for most organizations, involved directly or indirectly with the industry, is for production. This means that the volumes of parts are going to be potentially higher (meaning more data loads) and higher stakes for data management throughout the lifecycle of the parts. For instance, medical device parts would require a lifelong traceability story that connects the part with the manufacturer and ultimately the patient. Also, those that are operating manufacturing facilities for 3D printing will certainly have multiple projects, customers, and part requirements. These elements need to be documented correctly to maintain operational stability but also to more fully understand the business of 3D printing. Data points such as printer up time, material usage, and reject rate are important for users to assess how well their operations are functioning.

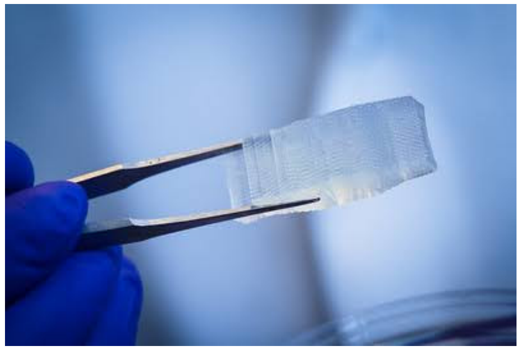


Figure 7.5 This 3D printed implant has been developed to treat spinal cord injuries. Nerves would grow across the soft, textured surface to repair a break or gap in the spinal cord, healing injuries that are often difficult to treat. Because of the precision in size, shape, and materials, and because the part will "live" inside a person permanently, every aspect of the design, build, and post-build process must be deeply documented and traceable. (credit: Modification of "Chen_spinal_cord_implant-03109-8MP" by UC San Diego Jacobs School of Engineering/Flickr, CC BY 2.0).

3D printing Job Management

One of the biggest advantages of 3D printing is the fact that no tooling is required to build an individual part. Conceptually, you are able to produce a set of parts every build that is produced on a given printer. This has many implications including the ability to customize components for several customers in a single job or do small batch production in a cost effective manner. However, as you start to think about the combinations of parts, build data, cost, material usage, and customers, it gets overwhelming quite quickly. As the industry moved along the transition from prototyping to production, many companies had built solutions by hand in spreadsheet software to document some of these values. However, more machines and builds makes some of these basic approaches challenging.

One of the first steps for many production manufacturing operations is building in a tool to connect their printer usage and the cost of operations. This step is often required as part of basic operations for many companies because the upfront investment in equipment is on the order of several hundred thousand or even millions of dollars. The most common approach is to build a cost model for each printer that calculates the cost of each part in the build based on a set of variables such as material, recycling rate, build geometry, number of parts in the machine, machine cost, time, post-processing, and finishing requirements. Building an exact cost model can be quite challenging and even more complex at the organizational level because there may be several types of printers involved in the production process. The outputs from these cost models typically have two functions. One is to provide insight for the printer operator on how much usage the organization is getting out of the machine as well as to guide things like personnel required or material ordering. The other critical use is the understanding of how much to charge a customer.

A good way to understand how some of these models work is by exploring the websites of service bureaus around the industry. These companies enable their customers to submit a digital design online and will print the part for a fee. There are large service bureaus that have multiple printers, materials, and technologies in which you can select the appropriate fit for your part. Pricing will often differ based on those selections along with the lead time required.

AM is not a one-size-fits-all solution for every physical part. It is better to consider AM as one of several manufacturing processes. With that in mind, the cataloguing and management of parts and inventory already has a digital environment built around it. Database companies such as SAP, Oracle, Microsoft, Salesforce, JobBOSS, and IBM have created products that allow for end-to-end supply chain management for organizations to track customer orders and manufacturing. Many of those products were built prior to widespread AM integration into that industry or application, so the integration between these legacy platforms and the information generated during the AM process and customer requisitions was not always connected. It is also the case that the methods of production that are unique to AM don't always align with traditional manufacturing tools or could quickly overwhelm the systems. The other challenge has been that there is limited software integration between the printers themselves and management software tools requiring manual entry of data.

There are several companies in the additive manufacturing industry that have built solutions to address these problems.

The companies are listed below along with links to their websites showing a more complete view of their feature set. Fundamentally, these companies are aiming to add another link in the additive manufacturing digital thread to connect the full story of the digital design with the business of operating a facility where manufacturing is taking place.

Company	Relation to digital thread	Application or use case
Link3D	Link3D helps organizations scale their manufacturing process and automate their workflows.	EOS North America performs benchmark studies for its customers to gauge how additive manufacturing can be used in a distributed manufacturing model. In an effort to enhance this process, EOS looked to Link3D's AMES and Additive Workflow Software. The software helps speed up order turnaround time, maximize machine utilization, and allows for all engineers to gain access to the supply chain. EOS has also used Link3D's Build Simulation software to provide quotes for clients.
3YOURMIND	3YOURMIND optimizes end-to-end AM processes and provides the tools for efficient scheduling and tracking.	Erpro 3D Factory has utilized 3YOURMIND to streamline their production of high quantity products, such as 17 million mascara brushes they produce for Chanel. Erpo was able to consolidate their various tracking systems into a single tool, helping reduce potential for human error that can arise with the complexity of organizing so many parts.
SAP	SAP enables collaboration, streamlining the entire process of part certification	US manufacturer Jabil has been using SAP to support its supply chain and manufacturing operations
Materialise	Materialise Stremics is a software system that helps to automate, centralize, and streamline the additive manufacturing workflow.	Nissan Motor Company uses 3D printing to prototype and experiment with new vehicle shapes. However, due to the print bed limitations, larger parts need to broken down into smaller, separate prints. The process of manually dividing parts into subparts was time consuming and inefficient. Using Materialise Magics, Nissan was able to reduce the time required for this process by over 50%. Magics comes with a feature that allows for the easy splitting of a part at a specified location, along with the ability to automatically create positioning pins, reducing the final assembly time.

Table 7.2

Distributed Manufacturing

The concept of **distributed manufacturing** states that a single product can be made in parallel from multiple manufacturing sites that are closer to the end customer. Thinking about this in the context of AM, we come to the definition of a single digital file being able to be manufactured at multiple locations on similar or the same equipment. This is in contrast to most conventional manufacturing approaches where a part is mass-produced at a singular location, then shipped to multiple customer or warehouse locations. The advantage of AMin this equation is that by having a series of locations that are able to produce 3D-printed products on demand is that supply chain challenges offered by traditional approaches such as high inventory costs and over producing products becomes more manageable. The model for 3D printing allows for a more nimble approach to manufacturing that could result in the product being closer to the end customer and leaves companies with flexibility to better manage their stream of product. From a digital thread perspective, this fully relies on the ability to transfer data between multiple organizations in a consistent manner without compromising the quality of the product.

Some companies such as Fast Radius and UPS have teamed up to apply this model in a real-life context by having printing facilities near regional air distribution centers that give companies the ability to print a part during the day and ship it to anywhere in the US overnight. Ultimately this success of this model would require end-to-end connectivity with the digital design, printer, and material information but just as important is the communication between all the parties involved to manage quality along these dimensions to incorporate the approach into a sound business model.

Figure 7.6 A Stratasys F900 3D printer manufactures a replacement part for an aircraft fuel mixing chamber on site at

the airfield. Large aircraft rely on thousands of parts, and airlines and other organizations have can have significant logistical challenges to keep them in stock at every possible location they may be needed. Shipping them takes time and money, so distributed manufacturing is an efficient and effective means of repair. (credit: U.S. Air Force photo by Staff Sgt. Marquis Russel on DVIDS, Public Domain).

Security and IP Considerations

The digital nature of the AM process has many positives that enable the flexibility in production approaches, rapid collaboration, and the ability to produce parts without costly tooling. However, one of the implications of this flexibility is the reliance on digital files that on the surface do not have much in the way of intelligence built into them. A standard CAD, STEP, or STL file may dictate geometric requirements, but other details such as materials, quantity, and who (or who is not) authorized to print the file are not controlled as a default. Compared to traditional manufacturing, this has profound implications for manufacturers as they think about AM as an end-to-end solution for production and how it relates to the security of their product designs as well as **intellectual property**.

From a design security standpoint, we have to take a step back to understand the different models that organizations may use to produce 3D printed products. The first approach may be to have an internal 3D printing production capability that allows them to control the full process from start to finish. In this scenario, the main security considerations remain internal to the employees and systems of the organization. An alternative approach to fully internalized AM is the scenario where the printing is done externally at a contract manufacturer. This tends to organize itself in which the parent organization develops and owns the engineering designs and shares these digital files with a manufacturer. Users should make sure that they fully define the extent of these relationships and how much leeway the final manufacturer has in building the parts. For example, defining the full extent of the production process is very important. Aspects such as build orientation, printer, and material parameters should be well defined and documented in any relationship. It should also be made clear that there are strict limitations on production of the parts to the amount ordered.

This brings us to a second and important consideration for the digital thread: intellectual property (IP). The wider availability of AM technologies, due to lowered costs and increased quality, has increased access to the machines and materials. The ability to produce an individual design is available to far more people and organizations. This means that control of the digital designs, especially those with critical IP design data, opens up new risks for manufacturers. One risk is that someone or a competitor may copy a design and produce it on their own 3D printing system. Additionally, someone may take a design and produce it in such a way that was not intended. For example, a part could be counterfeited or produced on a subpar printing process; if subsequently delivered to a customer, the lower-quality, knock-off part if it could cause injury or equipment damage. In such a case, it is not always clear where the liability or fault lies: Is it the design owner, the material supplier, or machine operator/manufacturer? While these are all serious concerns, there are companies such as Identify3D who are looking to enhance the security of the 3D printing file process.

An alternative risk is the one posed by the technology capabilities itself. For example, 3D scanners were developed in part to capture the geometry of existing parts. When used within an organization, there is no IP risk. However, the same devices can be used to copy other designs and completed products in order to counterfeit them or repurpose the design. To counter some of these efforts, companies can use novel materials or create elements that show authenticity. For example, the geometric flexibility of 3D printing allows also unique markings to be made on the inside/outside of the part in such a way that it cannot be easily scanned or replicated. With other types of IP theft, such as copying the materials mix, companies may protect information and issue non-disclosure agreements among their employees, contractors, and suppliers. There are even practices of inserting tracer materials to show the authenticity of a build.

7.4 Simulation

Learning Objectives

By the end of this section, students will be able to:

- Describe the use cases of simulation and their impact on the digital thread.
- Differentiate between part simulation, build simulation, and other simulation types.
- Understand the importance and several means of build monitoring.

Part simulation is a part of the additive manufacturing workflow that has been becoming increasingly more prevalent. Visualizing and analyzing the structural properties of a part is an integral step in producing high-quality, effective components with the hope to reduce iterations and failed builds. We discussed simulation approaches in earlier chapters and the aim of this section is to tie in the technical approaches we've covered with the digital thread structure. There are two main facets of simulation that will be considered for this context including part simulation and build/process simulation. Ultimately, these two approaches are heavily reliant on one another as well as the full context of the printing of a part.

Part simulation

Part simulation consists of evaluating a part's mechanical performance when subjected to a variety of different conditions. The simulated introduction of different physical loads, temperatures, deformations, etc can help identify the structural integrity of the various geometries that make up a part. These processes are incredibly useful in finalizing the design of a part that will be efficient in terms of material usage (and therefore cost) as well as mechanically sound enough to withstand its intended use. An additional aspect of part simulation is design optimization. Many simulation softwares geared towards additive manufacturing include the capability to optimize a part's design for 3D printing. Design optimized parts take advantage of unique capabilities of 3D printing, utilizing geometries that would not be possible with traditional manufacturing. The two main types of part optimization we will go over are lattice creation and generative design. Both of these design optimization techniques result in parts that require less material to print, while maintaining the same physical properties of the original design.

Lattice creation

Lattice structures are design configurations based on a repeated unit cell which can be a hexagonal, honeycomb, or other geometric pattern. Integrating lattice structures into a part's design can help reduce the part's mass, and therefore weight without compromising the structural integrity of the design. Many software programs are capable of automatically generating them into an existing part. Companies like Altair, Autodesk, and nTopology provide software that automatically integrate optimized lattice structures into your part designs, with options to change parameters such as the unit cell geometry or lattice density.

Generative design

The second type of part optimization, generative design, achieves similar results to lattice structures in that it helps reduce a part's weight without compromising strength. The generative design process is iterative, meaning that the simulation tool will attempt to meet a set of defined constraints through many different design options. The generative design software will identify the most integral geometries of a part and keep them as intact as possible, while removing any unnecessary mass that serves little to no purpose in terms of structural strength. Also similar to lattice structures, generative designs are unique to additive manufacturing and would be impossible to produce using traditional manufacturing methods.

Build Simulation

Build simulation is another part of the additive manufacturing workflow and is used to visualize and obtain insight of the 3D printing process of a part. Build simulations can be used to predict the layer-by-layer results of a 3D printing process under specified machine parameters and can help ensure that 3D printing jobs will not fail. Mitigating possible print failures is a key aspect of maintaining the efficiency and cost effectiveness of an additive manufacturing operation.

Process optimization: Simulating part builds helps identify all of the possible reasons for print failure, and will allow you to ensure that parts are printed at the best possible quality. Process simulation software will allow you to set the different parameters for the 3D printing process, and visualize how they will affect the final printed part.

Build speed: Nearly all AM build simulation software will indicate the time in which it takes the specified printer to produce a part. This information is valuable not only for identifying the turnaround time on individual parts, but also for ensuring efficient machine utilization. Additionally, the mechanical properties of printed parts is affected by the orientation in which it was printed. Different orientations can result in different print times, as an orientation that requires more support will generally take longer than a print that does not. Build speed is a key element to track in an additive manufacturing production line, as it plays a notable role in optimizing machine uptime and ensuring that production is as efficient as possible.

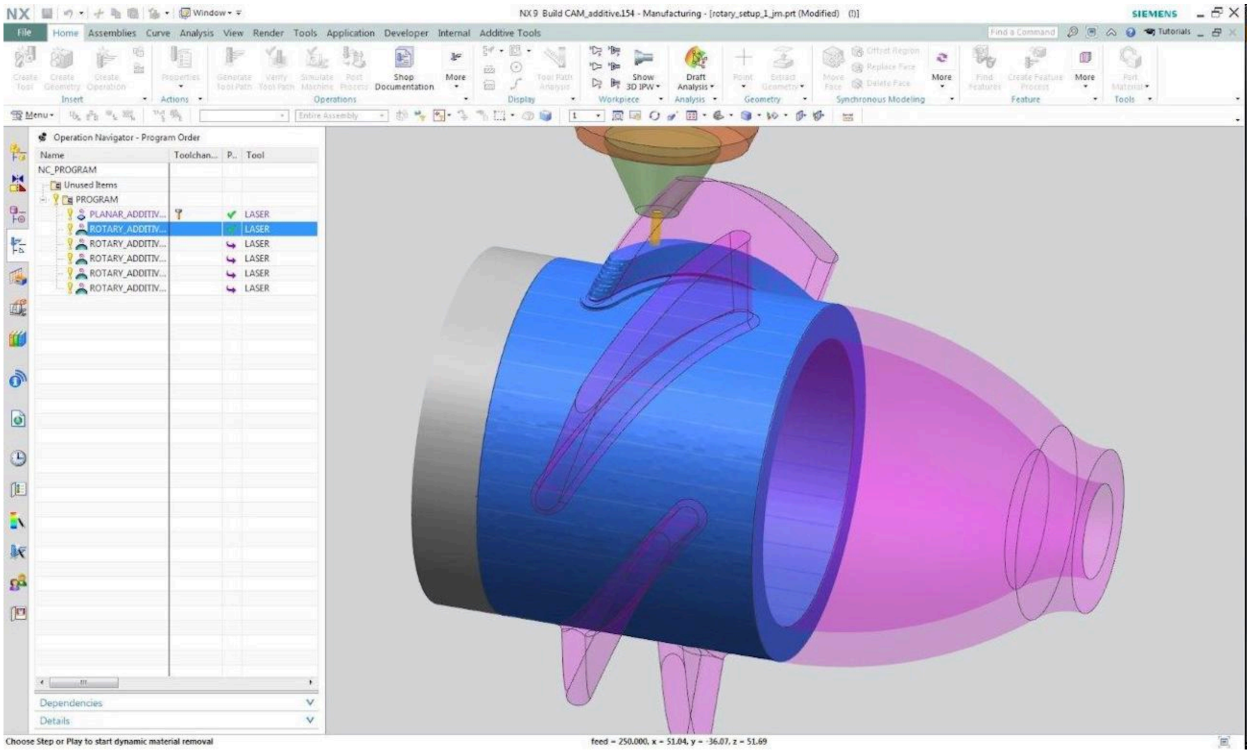


Figure 7.7 This Siemens software can drive multiple printer heads along five axes, and incorporate multiple types of manufacturing in one design. Simulation is an important component prior to the build to understand sequence, timing, and overall process. (credit: "NX Cam Hybrid Additive Manufacturing" by Siemens PLS Software/Flickr, CC BY-ND 2.0)

Part optimization: The insights gained from process simulation can also be used to identify important mechanical properties of the part to be printed. Part deformation is one of the key factors you are able to simulate, and provides an accurate representation of how a 3D printed part will deform after being printed. Additionally, the temperature gradient of a printed part can be simulated to help identify areas where mechanical properties may be affected. Since this simulation can be quicker than the full deformation simulation, it is useful for locating places where deformation may occur.

Support Structures: Support structures, generally, are needed when a part has overhanging features that are not supported by anything below them. These structures are usually printed at different settings (density, infill, etc) than the actual part, and are constructed so that they are easily removed from the final printed part. Most build simulation software will automatically generate supports based on the overhanging features of the part. The need for supports also varies from printer to printer, with some machines being capable of printing larger degree overhangs without any support structures. It is important to determine your printer's capabilities before including support structures in your prints. This can be done with a number of "overhang tests" that can be found online. While including support structures will increase a part's build time, and results in additional post-processing steps, it may be necessary to ensure that a part is properly printed.

Company	Relation to Digital Thread	Application or Use Case
Dassault Systemes	Dassault Systeme's SIMULIA Portfolio offers software that can simulate structural mechanics, computational fluid dynamics, and electromagnetic fields.	Eviation Aircraft set out to create a nine-passenger, 100% electric-powered aircraft that could reach a cruising speed of 280 miles per hour. Utilizing Dassault Systemes's software, Eviation was able to simulate the aerodynamic behavior of their design, and identify the dynamic and static loads that would occur during flight. The cloud capabilities of the software allowed the easy sharing of ideas and collaboration across different disciplines.
nTopology	nToplogy's platform provides the tools to effectively lightweight part design, as well as automatically optimize the topology of the part's geometry.	Cobra Aero, a US-based UAV designer, wanted to find a way to design and manufacture lighter engines in order to decrease drag on their UAVs and increase flying efficiency. Utilizing the nTop platform, Cobra Aero was able to introduce an internal lattice structure to their air-cooled engine cylinder, replacing the external fin structure which they used previously. In testing, the new design was more efficient at cooling in every possible case.

Table 7.3

Build Monitoring

As we continue to build out a model of the digital thread that for the AM workflow the area that arguably has the most data (in terms of pure memory required) is monitoring of each layer in the build. Any 3D printing process is built on the concept of consolidating layers upon other layers to build a fully dense part. Most printing processes have a layer thickness somewhere in the range of 40-150 microns which translates to potentially thousands of build layers per part. This ultimately becomes the single biggest area for variability for a 3D Printed part. From a 3D printing digital thread perspective there are a few concepts that we will cover.

The first area is simply being able to document process details about each build during the process of construction as well as compiling data from each individual layer. Depending on the printer modality there are different levels of detail that can and should be monitored during the process. In nearly all printers some elements of the machine operation should be documented (temperature, layer thickness, inert gas flow, energy inputs). For most machines, the operator has some levers to pull on this when they start the build. Lower cost printers generally do not have much in the way of sensors that can output to an accessible software data stream. This leaves the user in a trusting position to make sure that the part is constructed in a way that meets the requirements. As the industry targets more applications in the production environment, the demand from customers is that machine manufacturers allow access to a variety of sensors within the machines to enable full build visibility.

Some examples of build monitoring platforms are shown in the following table. EOS and Renishaw enable build monitoring data through their DMLS Platforms. 3D Systems Examines the Build Process of Polymer Laser Sintering

Company	Relation to Digital Thread	Application or Use Case
EOS	EOSTATE is a modular solution for end-to-end build monitoring of all production and quality-relevant data in industrial 3D printing.	MTU Aero Engines has been using EOSTATE for process development and quality assurance in the additive series production of borescope bosses for Airbus A320neo engines. This has allowed them to completely eliminate any downstream quality assurance procedures.
Renishaw	Renishaw's InifniAM enables near real-time insight into ongoing builds and allows for the in depth analyses of completed builds.	IMR, a Dublin-based manufacturing company that has been working with a variety of clients to explore the capabilities of 3D printing medical devices. Spinal implants was a device that was identified that could benefit from being additively manufactured. Metal AM would allow for the integration of lattice structures into the implant's design. Using Renishaw's RenAM 500M metal 3D printer, IMR was able to confirm that their AM spinal implants had mechanical properties greater than those of their traditionally manufactured counterparts.
3D Systems	3D Systems offers DMP Monitoring, a real-time process monitoring tool that allows the user to see, analyze, and fine-tune their metal additive manufacturing processes.	Node-Audio manufactures high-fidelity speakers with a distinct cabinet design that distinguishes itself from the rest of the hi-fi speakers on the market. Using a 3D Systems SLS printer and 3D audio simulation software, Node-Audio was able to design speakers that produced sound similar to that of a live experience.

Table 7.4

The second area that is important to consider due to the layer upon layer process is that any error in a single layer could potentially be catastrophic to the build process or render the part not usable. So while we have been talking about many aspects of the digital thread being historic in nature (recording data that has occurred) there is another forward-looking application: Manufacturers can use information during the build process to prevent or solve for error-prone directions in building a part. While this is an opportunity, it has a significant data load. Even a simple thermal scan of each layer of a build will result in terabytes of data that needs to be stored and analyzed. To do that at scale for multiple machines on every build is extremely challenging. However, there are tools that are being developed to quickly analyze this information use it to solve for issues in the build.

Ultimately, all of this information could be documented and transferred for every part that is generated, allowing manufacturers and product companies to have a before, during, and after set of data for the construction of the component with the hope of providing a robust quality summary.

7.5 The Digital Thread in AM Quality Assurance, Post-Processing, and Standards Alignment

Learning Objectives

By the end of this section, students will be able to:

- Describe the importance and impact of quality assurance on the additive manufacturing digital thread.
- Identify post-processing steps and decisions that impact the additive manufacturing digital thread.
- Discuss the was in which industry and related standards and external requirements impact the digital thread.

One of the most exciting opportunities for the implementation of the digital thread into real world production applications in the 3D printing sector is for quality assurance. A digital data approach, as described above, can provide a deeper perspective on the end-to-end process of part development, which quality assurance personnel and software could incorporate into their efforts.

With this opportunity, there also challenges, such as the following:

- Many variables, no consistent framework. Currently there are over 100 variables that need to be resolved, documented and stored for each production AM Part.
- No centralized data source. Companies are having to build bespoke tools to track and store this information or are allowing teams to stand up siloed solutions, which may or may not map to industry standards.
- Knowledge transfer and data retention is fragmented. Teams warehouse their own data and documentation is inconsistent – when people leave, so does the information.

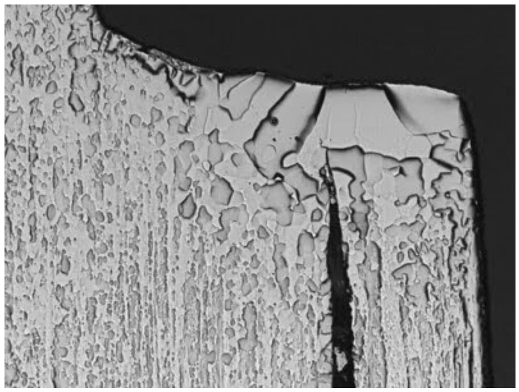


Figure 7.8 This highly magnified view of a weld reveals a gap in the form of the darker region to the right of the center. Quality assurance personnel (or software) would need to assess whether or not this gap constitutes a risk, and whether it requires repair or a complete rebuild. Ideally, that quality assurance data – including the size and location of the gap itself – would be captured in the digital thread. (credit: Modification of "Art of Science 2023" by Oak Ridge National Laboratory/Flickr, CC-BY 2.0)

If we examine the full 3D printing workflow, we see that there are a number of entries that should be documented in order to maintain a traceability record on each component.

Design	Material	Process	Post-Process	Inspection
• File Name • File Format • Build Orientation • Desired Surface Finish	• Feedstock Material • Material Vendor • Powder Blend • Batch Number • Production Method • Particle Size Distribution • Melting Temperature	• Machine ID • Model • Serial Number • Configuration Date • Recoater Configuration • Build Plate Material • Preheat Temperature • Purge Gas • Ventilation Flow Rate • Oxygen/ Temperature Limit • Layer Thickness • Build Date • Operator	• Material Used (Amount) • Restart Criteria • Post-Processing Steps • Date of Post-Processing • Post-Processing Technician	• Non-Destructive Test Methods • Tensile Strength • Tensile Modulus • Yield Strength • Elongation at Break • Date of Inspection

Table 7.5

Organizations seek to address this issue and keep track of these variables. For example, TRACEam is a software tool that allows users to document and input all their production 3D printing data into a single platform, tied directly to the machine workflow that is most relevant.

One of the greatest challenges with quality management for additive manufacturing approaches is the fact that each individual user of the technology may need or want to be presented with different data. This could be driven by a specific printer but also the user's industry. For instance, the qualification requirements for the medical device industry differ greatly from that of aerospace or automotive. There are a handful of standards that are listed in the literature that provide a benchmark for these data sets and many can be found in the documents listed below:

Standard	Primary Focus
ANSI/AMSC	Roadmap for AM standards
ASTM Material Test Standards	Numerous standards materials testing and characterization
ASTM F42	AM specific testing procedures for limited subjects
FAA	Memo released covering the Engineering Considerations for Powder Bed Fusion Additively Manufactured Parts
SAE AMS 9001	Ni Base 625 Alloy for Add Mfg Machines
FDA	Technical Considerations for Additive Manufactured Medical Devices
NASA	Em20 MSFC Technical Standard Specification For Control And Qualification Of Laser Powder Bed Fusion Metallurgical Processes
NIST	Technical Note 1801

Table 7.6

Another element of quality management is the warehousing of information that is pertinent to the materials and processes of the applications in the industry. There are several areas where this information is being stored for users to analyze and apply in their digital data ecosystems:

The Digital Thread in Post-Processing

Post-processing varies by the printing modality, and may include heat treatment or surface treatment of parts. The quality requirements most often documented are simple completed/non-completed. For some organizations, there are broader (and more expensive) end-to-end ecosystems where a series of machines for material and part inspection are all connected in the same software platform. This allows a single part to be transferred inside an existing database connected to a set of machines.

Let's work through an example for metal powder bed fusion. When a part is ready for production, a material needs to be selected. If this part is going to be produced to fit a specific standard or industry requirement, most likely there will be some documentation of the material characteristics of the feedstock going into the machine. In some cases, the material vendor shares a written Certificate of Conformance with the entity that is printing the part. This will include characterization details such as material composition, particle size distribution, and morphology details.

For those organizations going beyond this specification, they may need to do additional screening on their in house equipment such as particle size analyzers, SEMs, flow meters, or DSC's. Each of these tests typically take place on external test equipment (which is designed for all types of materials, not only AM materials), and the data can be outputted to a spreadsheet or test report. Even at this early stage, the team has created a substantial amount of data that may not be directly tied into an organization's digital thread. (Think of it like an island within the workflow.) Next, the material is processed in the machine and goes through a variety of thermal change before consolidating in its final shape. The machine and process data is another island of information.

Finally, a third island of data is created during post-processing and inspection of the part once it is removed from the machine. This could take the form of part scanning like CMM or even CT Scanning to offer users a validated inspection record.

In other words, the data can be analyzed after the fact but in-situ changes or trends are much more difficult to process because the amount of data that is connected in a standard additive manufacturing is a combination of data islands and operator intuition.

An additional hurdle in quality management of 3D printed parts is the difficulty of achieving process repeatability and part-to-part reproducibility. The multitude of different process parameters, along with inconsistencies in buld-to-build job management, can make it difficult to 3D print identical parts across multiple build cycles.

Trends and Consolidation in the Quality Management Digital Thread

Inspection equipment of manufactured parts is becoming more digitized, which allows manufacturers and organizations to leverage machine learning and artificial intelligence. Since part inspection is not unique to the AM production process, the companies in the space have been looking to improve these tools for all manners of manufacturing. Some have taken the approach to build a suite of hardware and software systems that can talk to one another in a similar ecosystem. Others have approached the problem by applying lower cost scanning tools and matching them up with high powered data analysis tools.

With inspection, one of the fundamental challenges is deciding what to inspect and to what degree. Part complexity, material, and size all come into play when thinking about approaches. Alongside our discussion of the digital thread is a conversation about automation. There are certainly inefficiencies in most current 3D printing workflows requiring heavy manual inputs, and part inspection is often one that relies the most heavily on this integration with the user.

Overall, when considering the digital thread for quality management, manufacturers must think about the balance between how much data is being manually *captured* versus automatically captured, and, perhaps more importantly, how much is being *analyzed* by operators and engineers versus being automatically analyzed.

Applications of Standards in the 3D printing Digital Thread

Based upon the rapid pace of change throughout the sector, the addition of standards to benchmark and ground approaches to the technology has lagged behind. Most of the standards that have been generated in the industry have been rightly focused on the process and materials. The American Society for Testing and Materials has a working group dedicated specifically to additive manufacturing (ASTM F42). Collaborations between them and the international community, embodied by the International Organization for Standards (ISO), have produced a series of detailed documents to help guide users along their AM development cycle. Many of these standards do provide details on elements of vocabulary and structure for a consistent language across the various platforms but very few report on specific standards relative to the digital elements of 3D printing.

In addition to the AMMD system architecture, the NIST team along with a series of collaborators have created a common dictionary to help users, machine producers, and software companies across the industry develop new tools to increase capabilities among the AM digital thread.

As with many elements of the 3D printing sector, analogous efforts have been taking place in technologies such as machining for a number of years as well. The MTConnect platform is a device information model that helps organizations and teams define a series of structures within their machines that can be outputted to a common data structure. This is an effective tool for some aspects of manufacturing; however given the range of data streams that could be tapped for AM, the variable set can become much wider than a technology like machining. This has led to an approach by many machine manufacturers of 3D printing equipment to build their own software connectors (APIs) that can transfer data to partner software platforms. In some ways having a unique API is a competitive advantage for these organizations but the ability for software developers to have widespread interoperability is highly limited with this approach.

Approaches to integrating the Digital Thread in an Organization

The opportunities presented by the potential of an end-to-end digital AM thread are enormous. We have discussed how the fundamental inputs (a 3D Digital CAD) start the process of 3D printing, and that through the workflow there are a number of interactions that reside both in the digital as well as the physical realm. As we think about how this ecosystem will have an impact on the additive manufacturing sector, it is useful to think about this question from three different perspectives: the printing machine manufacturer, the operator processes and support equipment, and the end user.

The first is within the 3D printing machine manufacturer space. There are dozens of different machine manufacturers producing equipment for different materials, end uses, and customers. Most equipment manufacturers are focused on providing their customers with a stable platform that delivers parts on a repeatable basis. Historically, because many of the platforms were targeted towards the prototyping market, the necessity to have additional software integrations outputting machine analytics or costing was not really necessary. It was also the case that most printer manufacturers were not considering how the technology could relay data from other parts of the 3D printing workflow. That is slowly changing, and the ability to connect machines is coming down in price. WIth that said, the structure and format of these data flows remain at the early stages of usefulness. Efforts such as the MTconnect platform alongside third-party vendors in the AM software space are building that digital functionality space along with efforts from NIST and other standards organizations to structure the data for the end users.

The second perspective is from the standpoint of support equipment and steps involved in the 3D printing workflow. There remain a number of steps that are not machine-centric and often rely on actions of people involved in the operations. This includes aspects such as those associated with the material and material characterization alongside all the post-processing and inspection elements that come with any build. These aspects are starting to get integrated into the digital thread and are critical elements for end-to-end quality assurance for the process.

Finally, the third perspective is based upon the end user. There is a wide range in knowledge regarding AM technology throughout the greater manufacturing environment. Current manufacturers may not have deep experience with the technology, and personnel may not have had AM as a core part of their education or training. Also, there are so many technologies that it is hard for any one person or even one organization to be an expert at every single platform. Often, the adoption and investment in AM equipment and processes comes with high expectations and showing feasibility for a particular application is the first order of business. Ultimately, a mature digital thread that enables users to have an easy way to increase the effectiveness of their operations will help drive more usage and business models for the technology.

Summary

Even though there is still a lot of work to be done when it comes to the 3D printing Digital Thread the long term implications of the potential will continue to drive innovation in the space. The key learnings from this chapter rest fundamentally on being able to assess the digital data being generated at each step of the additive manufacturing workflow and being able to tie this information back to meaningful and beneficial areas for users of the technology. Certainly as you continue on the journey of understanding and applying the lessons of this textbook, keeping in mind the AM digital thread is an important element to further enhance your ability to leverage the technology in a way that is beneficial to your career, business, and customers.

Review Questions

1. What industries could most benefit from a thorough digital thread?
2. What data might be most useful to manufacturers in these industries?
3. How can manufacturers leverage this data not only for their own internal purposes, but as a method of providing value to their customers?
4. Which is the least commonality of all AM processes?
   a. A layer by layer approach
   b. Use of powders
   c. They can be described with describing the layer, energy and material
   d. Starting at the design concept phase
5. Which is not a question used to define any AM process?
   a. How is the layer created?
   b. How is the energy applied?
   c. How is the DfAM applied?
   d. How is the material applied?
6. What layer or layers of a part might be most worth monitoring at higher detail?
7. How can you utilize build monitoring data to inform decisions regarding subsequent prints?

Discussion Questions

8. What industries or companies do you think might most benefit from distributed manufacturing?
9. How might the increased prevalence of personally-owned 3D printers affect a manufacturer's ability to sell replacement parts?
10. How can companies that utilize additive manufacturing best convey to their customers that their 3D printed parts/components are quality checked to the latest standards?
11. How would you manage the quality inspection of a product that contains both additively and traditionally manufactured components?
12. What do you foresee as possible roadblocks to the widespread adoption of uniform AM quality standards?

Key Terms

7.1 Digital Trends Throughout Manufacturing

Data stream

7.3 Processing a file for 3D printing

Distributed manufacturing, Intellectual property

7.4 Simulation

Build monitoring

8

THE BUSINESS OF ADDITIVE MANUFACTURING

Figure 8.1 A 3D printed dwelling can revolutionize the speed and flexibility in home construction, camping, and emergency management. On the other hand, the promise of innovation must also make business sense; if the AM structure costs more to build, process, or maintain than a conventional one, it might not be worth developing at scale. (credit: Modification of "1.0 Hero Mountain Rendering," by Oak Ridge National Laboratory/Flickr, CC BY 2.0).

Chapter Outline

Introduction

Even considering all the various materials, processes, design considerations, and certification/qualification details, the business of AM could be the domain's most challenging aspect. Being able to seize on the disruptive nature of AM in an effective, revenue-positive manner is essentially what will define its success. It is said that innovation isn't innovation until "someone writes a check for it". The bar is quite high here, because not only does it need to be creative or inventive, it doesn't become innovative until people are buying it and using it in commercial practice.

Because AM is disruptive, it can create opportunities in higher performance, lower cost or schedule benefits. We will use these three project management criteria throughout the chapter, also known as the project management triple constraint. In project management teachings, you can choose one, optimize for the second and the third must float. Trying to achieve more than one has rarely proven to be successful.

Thinking about the business of AM will create conversations around how AM should be adopted in a business. What is the role of design led thinking? Do you have the necessary skills? Are you a parts manufacturer today and should you make AM parts or design them and have them made? Are you a consumer of AM parts in assembly? What do you need to know to specify them and integrate them safely?

We will review the business case(s) for AM and offer suggestions on ways to monetize the flexibility created by AM through a deep understanding and appreciation of the cost drivers of AM. The cost drivers create opportunities when truly understood. They also become integral in making a business case for AM, or even choosing the right form of AM for the requirements.

8.1 Managing AM in Your Business

Learning Objectives

By the end of this section, students will be able to:

- Describe what makes AM disruptive.
- Propose ideas to improve the success in implementing AM.
- Understand how functions, roles, responsibilities, and interfaces may need to change to successfully implement AM.

AM is Disruptive, Not Easily Adapted

Additive manufacturing is considered a disruptive technology because it can offer an entirely new way of doing something with potential superior solutions. Innovations such as AM are called disruptive when they displace the original method of operating by offering a method or product that is significantly preferred to the original. One of the best examples of AM disrupting traditional methods is found in the orthodontics industry. In 1997, Invisalign was formed with the idea to dramatically change the braces experience with a teeth-alignment tool that is superior to braces by being removable, discreet, and custom fit for each individual's mouth. AM offers the flexibility to create these unique molds required for mass customization of the alignment tools. Each customer requires several custom molds to accommodate different stages of the alignment process. This would be impractical and extremely expensive using traditional injection molding technologies.

The dental industry is the first big example an industry disrupted by AM, originating from a startup. Startups, inherently small and agile, often bring disruptive technologies to the marketplace first, whereas it is more difficult for larger organizations. Although additive manufacturing can offer better solutions for certain applications, large corporations often struggle to adopt disruptive technologies. These well-established organizations that currently enjoy industry dominance with legacy design and production methods, high certification and qualification requirements, experience barriers adopting AM such as inexperienced staff, resistance to change, and intensive capital requirements to try AM in-house. It's hard to know where to start. Which part of the organization will take on this initiative? What's the right level of staff and investment? What's the strategy for the specific industry with respect to materials, processes, machines, and people? With all these big looming questions, it's easy for an organization to casually explore the technology, maybe make a few trinkets, and move on to shelve AM for another 5-10 years.

Figure 8.2 Dentistry was one of the initial widespread consumer applications of AM, and remains an advanced and

substantial business area. (credit: Modification of "Variety of Dental Resin Material Results from Formlabs Form 2 SLA 3D Printer" by Formlabs Inc./Flickr, CC BY 2.0)

Leading Change, Design-Led Thinking

In order to lead a successful introduction of additive manufacturing into a business, the motivation must be defined. Clearly defining the business benefits and justification will drive adoption more effectively than any corporate initiative. This motivation comes in the form of requirements. For example, the product must be lighter, the design cycle must be faster, the envelope occupied by the part should be smaller, the performance must be improved, etc. AM is a toolset for accomplishing innovative designs that can achieve the requirements in new and sometimes superior ways. With the exception of reducing the consumption of high-cost materials, it is not an alternative production method to be considered at the end of the design cycle for an existing part already tailored for traditional manufacturing. This is a common pitfall in additive adoption and often gives newcomers the impression that AM is expensive, slow, and full of design rule exceptions. The best way to approach an AM project is to let the requirements drive the design, and design for the process from the onset.

Trade It Before You Try It

Now consider that an application has been identified with some great DfAM features and associated business benefits. While it is tempting to dive in with personnel, program plans, and target delivery dates, it is prudent to first conduct a paper trade study to define what actually needs to be true for there to be a value proposition. A trade study is a documented decision-making process to narrow and choose the best solution based on assumptions and desired characteristics. The trade study should also identify key assumptions and associated risk mitigation strategies that prove or disprove those assumptions. One specific risk mitigation strategy explained by The Lean Startup includes creating a series targeted low effort versions of the product and associated low effort tests to quickly verify the assumptions before further investment. This allows a team to collect the maximum amount of validated learning with the least amount of effort. This approach of paper study first, followed by strategic risk reduction plan, will greatly reduce investment uncertainty.

When considering the decision of when to utilize AM, consider the extremely fast pace of change in such a new domain. In a quickly maturing technology like AM, a constraint one year could be an opportunity better the following year. New printers, materials, and processes can improve speed or efficiency by 10-30 percentage points in less than a year's time. With such knowledge, companies can determine when a specific process or decision might be profitable. For example, replacing a conventional part with an AM part might not make sense now (the business case may fail), but it could introduce cost savings as soon as the print speed increases by 10%.

Skills and Capability

Following a successful trade study, the project begins, but even this can be disruptive to the typical organizational factions. Although the traditional groups like design engineering, quality assurance, etc., are all still required just like for any manufacturing process, initially some upskilling for AM will be required for each of these core competencies. Additive manufacturing is a team activity, with a team composed of many personnel – or even teams of personnel – working closely together. Some of the necessary team areas may include design engineering (with DfAM skills), manufacturing process engineering, material science, environmental health and safety, quality assurance, quality control, procurement, operations, program management, and sales or business development. In a typical organization, these functions would be spread across the business, but at least in the early adoption levels of AM, it may be advantageous to form a more agile cross-functional AM team. One reason for this is that for existing manufacturing processes, the different roles, responsibilities, and interactions between the functions has been established; while in the case of AM, it may be necessary to make adjustments in these to better accommodate the new technology.

Let's run through a detailed situational example:

Traditional situation: If a part machined from solid plate is determined to be too porous during penetrant inspection, the part may be scrapped – wasting time and resources – particularly the plate itself. IOn this case, the plate producer is generally responsible for providing a new piece of plate for free, while the machine shop winds up absorbing the wasted machining cost. The machine shop is willing to sign up to this because they know from experience that about 0.1% of parts will be scrapped for porosity, so they build that into their cost.

AM situation: Now consider the part is made using AM. In this case, while it is expected that the AM producer needs to replace any parts (and the underlying materials) that are scrapped, the machine shop may be less willing to absorb the wasted machining time because they don't know how often this may happen. In order to resolve this impasse, it may be necessary for the organization (specifically the procurement personnel) to change the standard contract wording so that the machine shop can be reimbursed for any scrappage due to porosity in the AM part.

The above example delves into different personnel (procurement) and processes (contracts) than we have considered throughout most of this text. That is because, again, the business element brings in nearly every facet of an organization or organizations. As complex and multifaceted as we have seen AM to be, it goes even wider than the groups working on the parts or builds.

Figure 8.3 Maintaining expertise through training and augmenting personnel is citical to sustaining an AM business and maintaining a competitive edge. (credit: Modification of "Composites Innovation Group - summer students working with equipment at the MDF 2" by Oak Ridge National Laboratory/Flickr, CC BY 2.0)

The AM team will look different depending on what part of the application of AM the organization is focused on. A service bureau, for example, will require a team with deep expertise in making and delivering quality parts and will benefit from a strong team of manufacturing process engineers, quality engineers, and customer focused sales / business development personnel. A manufacturer, however, may choose to partner with a service bureau with those skills to make parts and focus instead of design, analysis, and qualification of the AM parts. In this scenario, the manufacturer should train and deploy a team of skilled design engineers with deep, system level product knowledge, armed with DfAM skills, to create new value and product differentiation through AM. In all of these scenarios, the organizational functions are the same as before, but the skillsets to understand and implement AM will need to be trained or hired into those groups.

8.2 Pre-Production to Production: Factors to Consider in a Business Case

Learning Objectives

By the end of this section, students will be able to:

- Determine where an AM application fits in overall AM maturity.
- Apply maturity levels to impacts on the overall product.

There are different business case considerations depending on the type of AM application or reason for doing AM. In chapter 1, the AM Maturity Model was introduced to describe the various AM products and the appropriate learning lessons which accompany it.

The TBGA AM Maturity Model breaks down potential AM products into 5 levels or levels of AM maturity, each level having its own business case considerations. These 5 levels are:

- Level 0: Pre-Production
- Level 1: Production Influence
- Level 2: Substitution
- Level 3: Functional Designs
- Level 4: Multi-Functional

The business value of these levels is further described in the following sections and evaluated with respect to the triple constraint of project management, namely Cost, Schedule and Scope.

Level 0

Level zero is Pre-Production and encompasses using AM prototypes for product development, and short run production until the final manufacturing method is deployed.

Cost: It is possible to impact program costs through applying AM prototyping to condense schedules, but direct product costs are likely unaffected with the use of prototyping alone.

Scope: This level of AM is useful for enhancing the scope by prototyping important scope-enhancing features of the product design, but scope is not directly impacted by prototyping.

Schedule: The primary outcome of using AM for prototypes is condensing schedule. Level zero describes activities such as using AM to make test parts for an assembly, gathering data, or avoiding hard tooling, all of which work towards compressing the development cycle.

Level 1

Level one refers to indirect application of additive, namely tools and fixtures, that can be used to manufacture or assemble other parts.

Cost: Product cost can be affected by application of AM in Level one through improving assembly time, reducing tooling inventory, or improving the cost of poor quality by ensuring a robust, repeatable process. For example, a fixture or tool used on the assembly line that enables faster build time would lower cost.

Scope: Level one parts will not likely benefit from any scope enhancement from the use of AM, since AM is not used for direct production of parts, and therefore cannot affect the final product performance.

Schedule: It is common and relatively easy to find business value applying this level of AM and recognizing savings in schedule, assembly, tooling inventory reduction and cost. This level also includes examples like using AM to produce prototype castings for validation or initial production, enabling overall program schedule improvements.

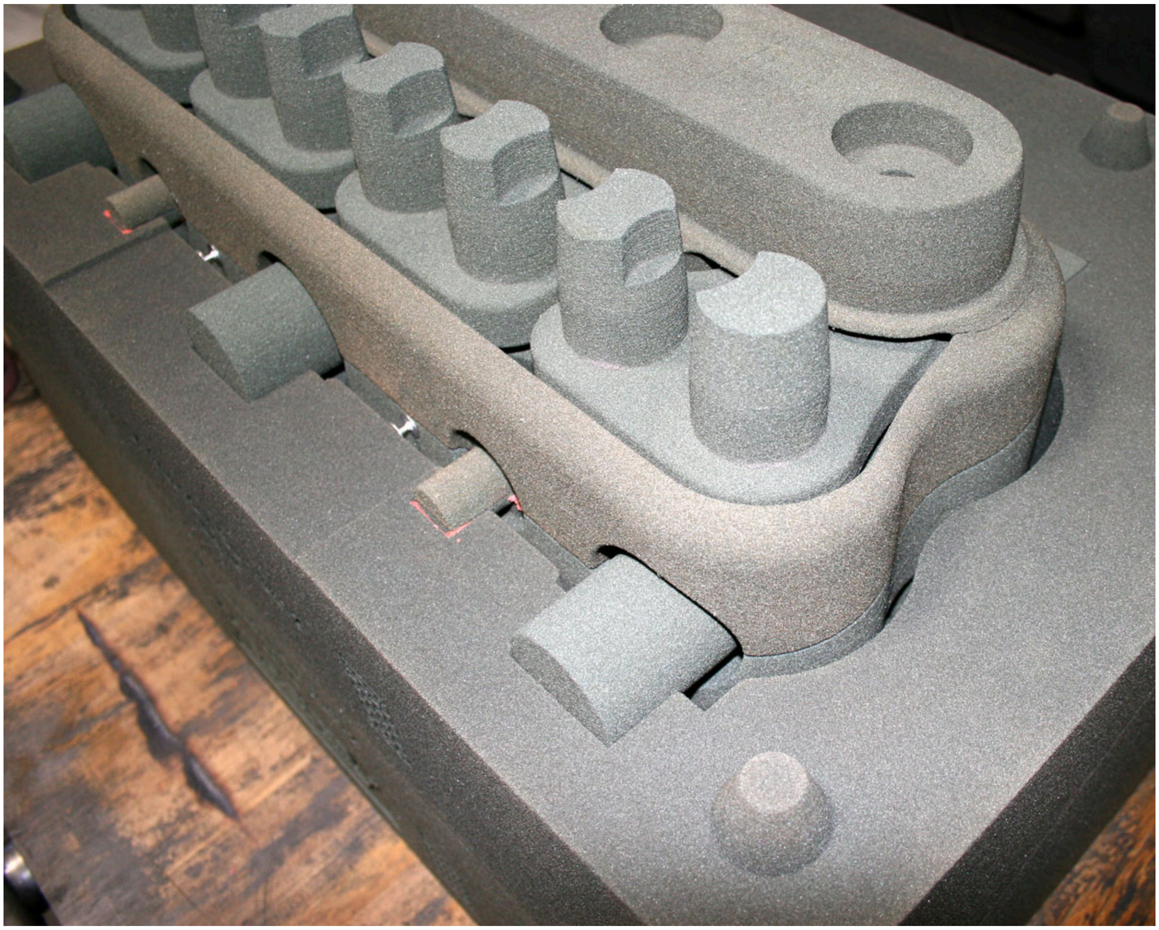


Figure 8.4 This 3D printed engine block mold has a variety of internal structures, passageways, and subcomponents that will be filled with specific alloys. (credit: Modification of Velie Engine Mold Complete Core Package" by O.K. Foundry Company/Flickr, CC BY 2.0)

Level 2

Level two covers making AM production parts that look similar to existing legacy manufacturing designs.

Cost: It is possible to find cost savings in part for part replacement examples in level 3 if the parts are made with complex, multi-step manufacturing processes and/or with expensive materials such titanium.

Spare parts are a good example of a level 3 application where in-kind replacement prolongs the longevity of an expensive asset, which may command a higher price due to its overall business value.

Scope: Since the parts in level 3 are the same as was produced with traditional methods, there is not likely any benefits to scope for the majority of these parts. It is possible that a higher value material will be substituted, which may bring some benefit to mechanical properties.

Schedule: As discussed in chapter 1, this could be useful to deliver spare parts where the original supply chain is no longer viable or practical. Excepting the high-cost material case mentioned before, typically, parts not designed for AM are more expensive (part for part) when made with additive manufacturing vs. their intended manufacturing method. In this case, the business value comes from a condensed schedule, for example eliminating lengthy lead times through delivering low volume spare parts quickly.

Level 3

Level three describes AM parts which take existing part designs and apply the benefits of AM by combining these parts into one.

Cost: This can be financially beneficial by reducing recurring part cost, manufacturing assembly time, potential systems weight savings, creating more robust systems without joints and potential failure points. This also reduces the cost to manage individual part numbers and suppliers which is hard to quantify, but a real cost, nonetheless.

Scope: In this level, the scope of the AM application is paramount and unlocks the value of AM by enabling system level solutions with improved performance and reduction in processes.

Schedule: Part combination does not directly impact schedule, though it is possible to realize some efficiencies by minimizing the number of new parts introduced.

Level 4

Level four, referred to as Multi-Functional or Engineered Capability, although hard to achieve, offers the greatest financial benefits of AM. This maturity level describes parts which can only be made economically through AM methods. These parts take advantage of the design freedom in AM to create system level value such as performance, reliability, and weight.

Cost: These parts are market leading and therefore command a premium price, making cost the largest driving factor to business value.

Scope: In this level, even more than level 3, the scope of the AM application is enhanced by enabling system level solutions with improved performance and reduction in processes.

Schedule: It is difficult to couple schedule efficiencies with game-changing AM applications such as fit in this level. Developing novel AM solutions takes time and will often require significant validation and qualification since these parts are often critical to the product if they bring system level value.

8.3 The Business Case: Definitions and Considerations

Learning Objectives

By the end of this section, students will be able to:

- Describe cost drivers for different types of AM processes.
- Compare the trade-off between different AM processes in terms of size and detail.
- Understand the interactions between design and cost.

Developing the AM Business Case

A critical part of the trade study is developing the AM business case to define and validate what must be true financially to have a successful AM implementation. An AM business case is much the same as any product or part business case and includes considerations such as volume, price point, recurring and non-recurring costs, capital investment, etc. In addition, there is also a heavy AM specific portion of the business case which considers the AM technology and material selections, design considerations, as well as any quality, safety, and regulatory considerations. Some considerations by category would include:

AM Technology: What process did you choose and why? What other processes did you assess? Use the ASTM F42 terms and relevant specifications to describe. How long has this process been used? What are the pros and cons associated with it relevant to the requirements? What development would you recommend overcoming?

Materials: What material form is required to be used? Is there a specification today? What considerations are needed to procure and use the input feedstock. How might the process affect the material as an output consideration (cost, strength)? Will any post treatments be required (HIP, heat treatment, chemical conversion etc.)?

Design Considerations: Illustrate orientation/angles to build and why? Is support structure necessary? Do you have added stock for machining or datums? How would you achieve surface finish requirements? What inspection methods could be used? What tools would assist in design for this AM process? Could additional design time benefit cost and/or weight? Where would you put additional emphasis? What level of the AM Maturity Model would you place this? What additional opportunities for AM implementation exist?

Economics: Would buy the equipment or use a service bureau? What estimate did you make for purchase of equipment and facility? What is the material cost difference and where is the cost savings? Describe the challenges faced when developing an AM business case? What strategies would you implement to face challenges?

Quality and Safety Considerations: What process and material hazards in an AM production environment? What gaps exist with AM Quality and Safety processes to assure production parts meet industry quality and safety standards? What gaps to known industry requirement did you identify? Is the AM process inspectable to the degree necessary? How does the AM design impact the failure mode and impacts of part failure?

AM Cost Model

Although the business case considerations are much the same as any traditional methods, calculating the recurring costs, more specifically, the part costs of an AM part are specific to the AM process and material. To determine the AM part cost, a cost model can be applied. The AM cost model is specific to each AM process and generally is made up of printing costs, material costs, and post-processing costs. A simplified cost model created by Dr. Tim Simpson of Penn State is shown below. This cost model describes the Metal Laser Powder Bed Fusion process for a single laser, but the same type of thought process can be applied to any AM process to generate an equivalent cost model.

User-defined inputs:

1. Material (see Table 8.1)
2. Part Volume (mm^3), including supports
3. Max part height (mm)
4. Machine operating cost ($10-30/hr)
5. Pre-Processing/Post-Processing Cost (30%-40%)

Am Material Data	Ti64	IN718	SS316L	AlSi10Mg
Density (kg/(mm^3)	4.41E-6	8.5E-6	7.9E-6	2.67E-6
Build rate (mm^3/s)	9.0	4.2	2.0	7.4
Layer Height (mm)	0.06	0.04	0.02	0.03
Recoat Time (sec)	9	9	12	12
Powder Cost ($/kg)	$250-500	$120-$180	$70-$100	$70-$90

Table 8.1

Outputs:

$$\text{Material Costs (\$)} = \text{Part Volume} \cdot \text{Material Density} \cdot \text{Powder Cost}$$

$$\text{Build Time (hr)} = \frac{((\text{Part Volume})/(\text{Build Rate}\cdot 80\%))+((\text{Max Part Height})/\text{Layer Height})\cdot(\text{Recoat Time})}{3600}$$

$$\text{Total AM Part Cost (\$)} = \frac{(\text{Build Time})\cdot(\text{Machine Operating Cost})+\text{Material Cost}}{(1-\text{Pre-Processing/Post-Processing Cost }\%)}$$

Starting with material, you must consider that the metallic powder feedstock is 5-10x more expensive per kilogram than the equivalent bar stock of the same material. If you were to consider the cost of material alone, you would have to reduce material by 80-90% to have a good business case for AM with a part-for-part substitution. This is achievable only in rare cases where you have significant processing and associated material waste from the original stock material.

Next the hourly cost of the machine is calculated by estimating the depreciation per hour over some assumed useful life. Typically, this is 5-7 years at 4000-6000 printing hours since this technology is changing so rapidly.

Printing speed is where this cost model should be calibrated to a specific machine to be more accurate, and certainly depends on the number of lasers and even the part geometry as parts with extremely complex or thin wall features can take longer to scan. For a first pass estimate, a single laser build rate is considered around 8-30 cm3/hr. for most single-laser PBF systems. Unfortunately, this is more like an entitlement number, so it can be assumed that you'd achieve on average about 80% of this build rate consistently. To account for this, the build rate is divided by 80% in the cost model formula. Printing time is not only a function of laser speed, but also needs to account for the recoating time where fresh powder is spread over the build box to get ready for the next layer of printing. This is called the recoat time and is typically 6-10 seconds on current Laser PBF machines. The total time spent recoating is based on part height and layer thickness and this per layer recoat time as relayed in the formula above.

The final part of the AM cost model is the post-processing. The next section dives into why the post-processing costs vary by AM process, and they also vary by application since it is very design driven. For this simplified cost model, the post-processing costs can be considered between 30-40% of the total part costs. (We typically use a source such as the Wohler's Report to attain baseline costs.) The total part costs can then be calculated by scaling the AM printing costs + material costs by this 40% markup to account for final post-processing.

While this cost model is specific to Laser Powder Bed Fusion with a single laser, it illustrates how you could build a process specific (even machine specific) cost model for your organization by including factors such as material costs, build time, and post-processing.

AM Technology

One of the first steps in building a business case for AM is selecting the process that will be used for manufacturing. This decision is driven by a thorough analysis of the application and selecting the best AM process to meet the requirements. Just as parts made with additive manufacturing should be intentionally designed for the AM process versus the traditional process. More granularly, AM applications should be designed for the specific AM process selected, and sometimes even the specific machine. Selecting the right 3D printer requires careful study of the requirements and the end to end AM process. At a high level, each of the 7 ASTM classifications has its own considerations and value chain as determined by the process and post-process steps required to realize a fully finished part. These steps in turn feed the business case. Each of the processes introduced in Chapter 2 Core AM Technologies and Supporting Processes have different business case considerations including printing, post-processing, and feedstock.

Laser Powder Bed Fusion is tailored towards small, detailed parts, and can transition from thin to thick sections fairly well. At some point, there is a tradeoff between achievable detailed features and size of the part due to the residual stresses that are built up in a large part.

Binder Jet is capable of detailed features in small parts where sintering effects are less of a concern. It is not ideal for larger parts in general, and there is a space where detailed features may not be achievable alongside thick sections due to sintering distortion and the effects of gravity while the part is going through densification in the vacuum furnace.

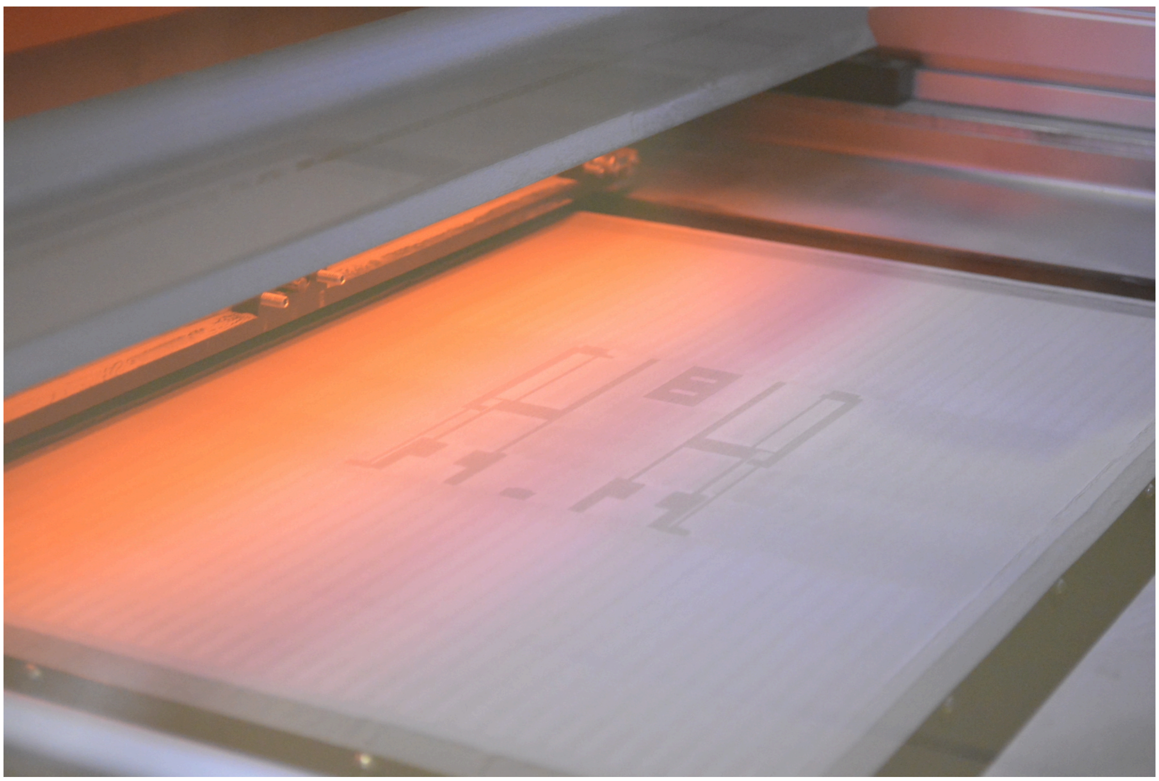


Figure 8.5 An ExOne Binder Jet machine uses a radiant heater to cure a layer of binder deposited into the metal powder bed. (credit: Modification of ExOne Binder Jet machine by Oak Ridge National Laboratory/Flickr, CC BY 2.0)

Sheet Lamination is a hybrid process that only makes sense to select for very detailed parts that take advantage of the in-situ machining element of the process due to its low productivity. The low productivity makes it an impractical process for large or simple parts.

Material Extrusion (direct metal) and DED will also require post-processing to achieve details and are ideal for larger parts. The DED process can make the largest parts since often it works with a robotic arm that is not limited to a defined machine bed size.

There are specific designs which are a best fit for a particular process, and some designs which may overlap into 2 or more processes. These overlapping sections are perhaps the only limited cases where it may be possible to trade off costs of one AM process versus another. However, the most important takeaway is that part design drives the process selection, which in turn has business case implications. The printing cost is driven by the time the part occupies the printer, which is a factor of design and machine productivity. The other cost drivers include feedstock and post-processing, which are both also process specific.

In AM, the material input is typically in the form of powder or filament, except in sheet lamination where it is a thin foil. Powder, wire and foil have additional processing done to them in order to get them into this form, so the price for these materials can be higher than common mill products or bulk plastics. However, it is important to note that the process is doing more of the “work” so the material input for AM is typically the minority cost element.

For most metal AM processes, printing represents the single largest cost element. For the most part, this is the depreciation of the machine represented in a dollar per hour basis. The less time on the printer, the less cost is added.

Lastly, post-processing can be a large cost driver, and more so in some AM technologies versus others.

Laser Powder Bed Fusion

Printing time is the largest cost driver for the Powder Bed Fusion (PBF) process. As mentioned above, part design and productivity are the factors that contribute to the printing costs. Because productivity is mostly influenced by the machine makers, the focus for the AM user should be first on part design. Thoughtful integration of design for additive manufacturing into part design will drastically affect total costs. Other factors that drive printing time for L-PBF include number of lasers and layer thickness. These are further explored later in this chapter, but at a high level more lasers and thicker layer thickness yield higher productivity but must be traded off with cost of equipment to add more lasers and part density for thicker layers.

The other cost drivers of PBF are feedstock and post-processing. PBF feedstock is expensive as compared to traditional manufacturing feedstock and as compared to most other AM technologies. This is due to the process yield and strict size requirements which is further explained in the subsequent section.

Finally, post-processing is also a major cost driver in PBF parts and includes the cost to depowder, stress relieve, remove parts from the build plate, and perform typical machining for interface points and tight tolerances.

Directed Energy Deposition

Directed energy deposition (DED) is a broad range of technology that uses a focused energy source to melt and apply a feedstock material. The various types of DED can have very different economic implications depending on their energy source and feedstock. In this section, the financial considerations of the following DED technologies will be explore further: DED Powder, DED Wire, and DED Cold Spray.

Directed Energy Deposition with powder is one of the highest cost processes second only to Laser PBF. This is likely because they both use a similar laser, have a small puddle size (2mm diameter or less) and create similar productivity. Due to the low productivity and high capital costs of these machines, the printing cost is the biggest cost driver. Post-processing for powder DED always includes stress relief because of the heat input to the part in the welding process. Although this process can create nearly final (near-net) shapes, it’s still often necessary to final-machine these parts for the fully finished part. Finally, the powder feedstock, although still expensive due to its low process yield, is the smallest cost driver for this technology.

Unlike DED with powder, Directed Energy deposition with wire is very efficient at printing. It will always require heat treatment for residual stresses and machining since the large (>4mm diameter) puddle inhibits the ability to produce fine details, making the post-processing the highest cost driver for this technology. Next in line is the feedstock, since wire can be an expensive product form.

Cold spray has a very similar cost breakdown as DED with wire and is very fast and affordable. It does not make near net shapes so additional machining will almost always be required, again making the post-processing the highest cost driver. In some cases, a heat treatment could be necessary as well. The powder cost for cold spray can vary wildly depending on the chemistry or alloy from very inexpensive to more expensive than laser powder bed fusion, specifically in titanium.

Sheet Lamination

Sheet lamination is the third-highest-cost AM process after L-PBF and DED with Powder, again driven by machine productivity. The machine does more, therefore costs more. Sheet lamination has minimal printing costs partly because the print speed is higher but also because the material input is expensive, and the process provides details at the expense of material wastage. The printing and machining are coupled leaving post-processing to traditional metal working and final finishes.

Metal Binder Jetting

Metal binder jetting is also a metal powder bed process but has a very different solution space as compared to other metal AM processes. Not surprisingly, it also has very different cost drivers with post-processing being the main driver followed by feedstock and finally printing costs.

As metal binder jetting is probably one of the fastest methods of AM, it's easy to assume it's also the cheapest. The costliest portion of metal binder jetting however, is actually in the post-processing. The printing process of binder jetting produces a "green state" part, which must be cured and sintered before a finished part is ready for final finishing such as machining or surface finishing. Both curing and sintering are lengthy processes and use additional equipment, and sintering furnaces can be quite expensive.

The second cost driver of metal binder jetting is the feedstock. The powder for metal binder jetting is typically less expensive than other powder bed AM feedstocks such as laser PBF. This is because the binder jet process is built off the legacy Metal Injection Molding process which is mature and used for extremely high-volume applications in automotive and other heavy industries that have driven down feedstock costs over decades.

Finally, the printing cost of metal binder jetting is the lowest cost driver due to this technology's high productivity and lower cost of machines. The machines can be 2x or even lower cost compared to laser PBF machines. This is because they are made up of relatively simple and commoditized hardware such as inkjet printheads instead of lasers. The technology is also inherently faster than laser PBF because and among the fastest of AM processes. Like inkjet printing, there is a consistent layer speed parameter defined that is independent of how much part vs. empty space is on that layer. Binder is jetted only where that layer requires solid material, but the amount of solid material is irrelevant to speed of the jetting pass.

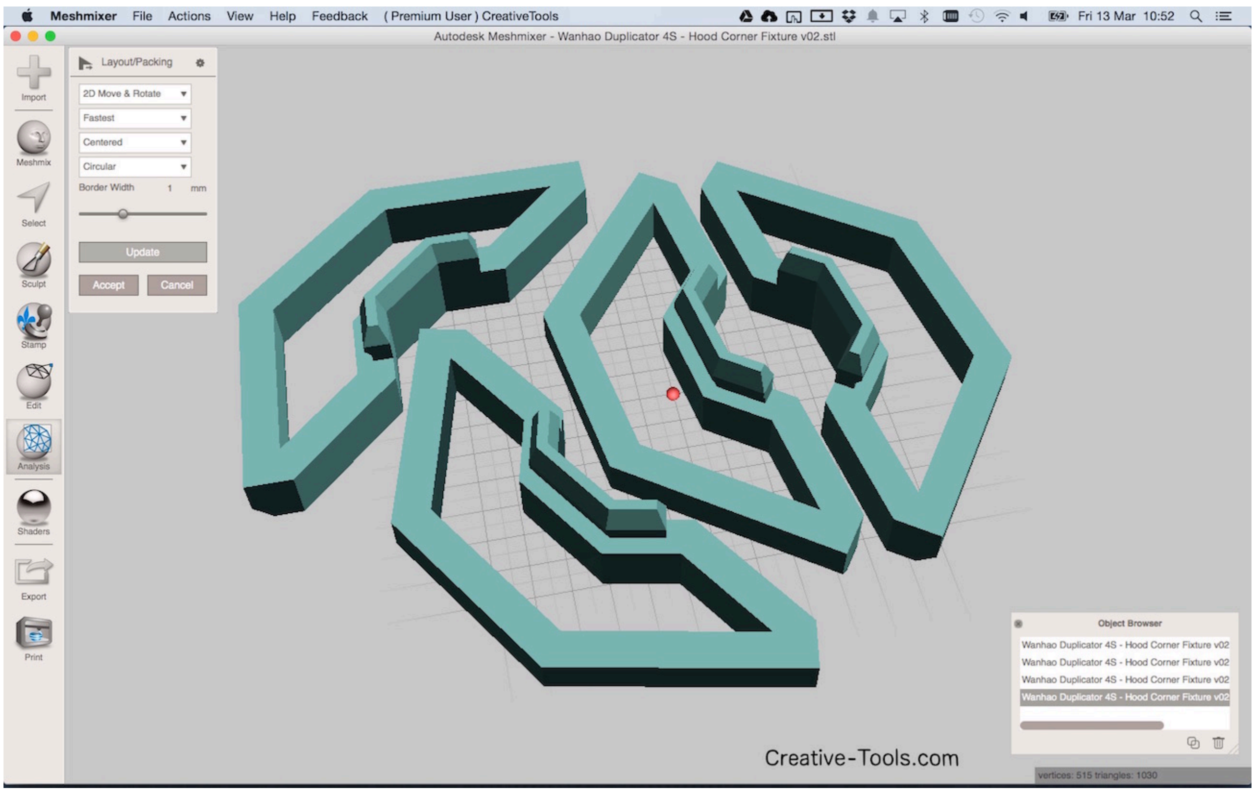


Figure 8.6 Autodesk setup showing 3D nested parts stacked together in the same build box. As you have probably seen in other images, this image is just the start of how complex these nesting approaches can become. (credit: Modification of "Autodesk meshmaker layout packing" by Creative Tools/Flickr, CC BY 2.0)

In addition to efficient nesting, the parts also print faster because they do not require supports for printing. Sometimes supports are required for sintering, which reemphasizes the high cost and difficulty of post-processing binder jet parts. In summary, metal binder jet printing is a fast process which has great potential for relatively niche design space given today's technology maturity, however the full process must be considered to validate the AM business case.

Direct Extrusion

Direct Extrusion is quite fast and not very expensive. It is an efficient method for building with larger amounts of material. For metal extrusion, the feedstock is more like bar stock, therefore readily available and inexpensive. It does require similar post-processing to DED with wire due to its inability to make near-net shapes, which is why the post-processing is the highest cost driver for this technology.

Polymer Material Extrusion

Most of the focus of this section has been on metal 3D printing, but similar concepts and cost drivers apply to the polymer processes. For Polymer Material Extrusion, the most widespread of any of the AM technologies, it is hard to categorize the cost-drivers due to the wide variety of available machines in the market. In general, this is a slow process, so printing time is high, but the printers are often commoditized and cheaper than the other process machines. The feedstock cost also varies widely and can be anything from hobby level, low end plastics, to high strength, flame resistant, polymers made for industrial end use parts. Typically, filaments are a more expensive version of the polymer versus pellets common to the injection molding industry, with some of the larger machines using pellet feedstock for precisely that reason. Finally, post-processing is still required to remove supports, paint or finish surfaces, but it typically is lower cost to finish plastic parts as compared to metal.

Photopolymerization

VAT Photo-polymerization is the oldest and most mature of the AM process technologies, yet still very costly as compared to other AM polymer processes. The original process uses a similar laser tool path tracing method as Laser PBF and has similar low productivity. The machines are also quite expensive, making the printing category a high cost driver. The feedstock is a resin-based polymer and can be an expensive form of the material. The printed parts require washing and post-curing, but after that is complete, the parts produced have excellent surface finish and detailed features eliminating the need for further processing. A more recent iteration of the Photo-polymerization process called Continuous Liquid Interface Production (CLIP) is significantly higher productivity, claiming 25 to 100x faster than the original photo-polymerization methods. It works by continuously curing the 3d parts instead of tracing each 2D layer's blueprint. This method would still have similar feedstock and post-processing considerations but significantly reduced printing costs.

Material Jetting

Material Jetting is the process in which droplets of build material are selectively deposited by a horizontally traversing nozzle onto a build surface where they solidify. The process has a similar setup to binder jetting and shares the same level of productivity and common inkjet industry hardware. The material is the highest cost driver since photopolymerizable resins and molten polymers are an expensive form of polymers as compared to filament or pellets. This technology uniquely allows for varying materials to be deposited during the build, allowing for dissolvable supports (which are always required) or different colors. This benefit minimizes the post-processing steps necessary after the build and makes the post-processing a small contribution to cost. Despite the low cost of post-processing and the processes' high productivity, this form of printing is still among the costliest polymer printing processes.

AM Materials

As mentioned earlier, the form of the feedstock is a driving factor to the business case, but another cost consideration is the actual material selection. Both the feedstock form and the specific material determine the cost of the material and its processing cost. The cost per kilogram of AM material can be shocking compared to more common product forms, but the cost per kilogram cannot be separated from the efficiency of the process to reduce material waste and machining steps. Also, since there are fewer choices of material currently marketed for AM, sometimes it makes sense to choose a superior material versus its incumbent and optimize design (i.e. minimize material). Other financial considerations when selecting a material include the material form, existence of a specification, method of procurement, required post-processing, waste produced, material recyclability, and productivity for the process since some materials print faster than others.

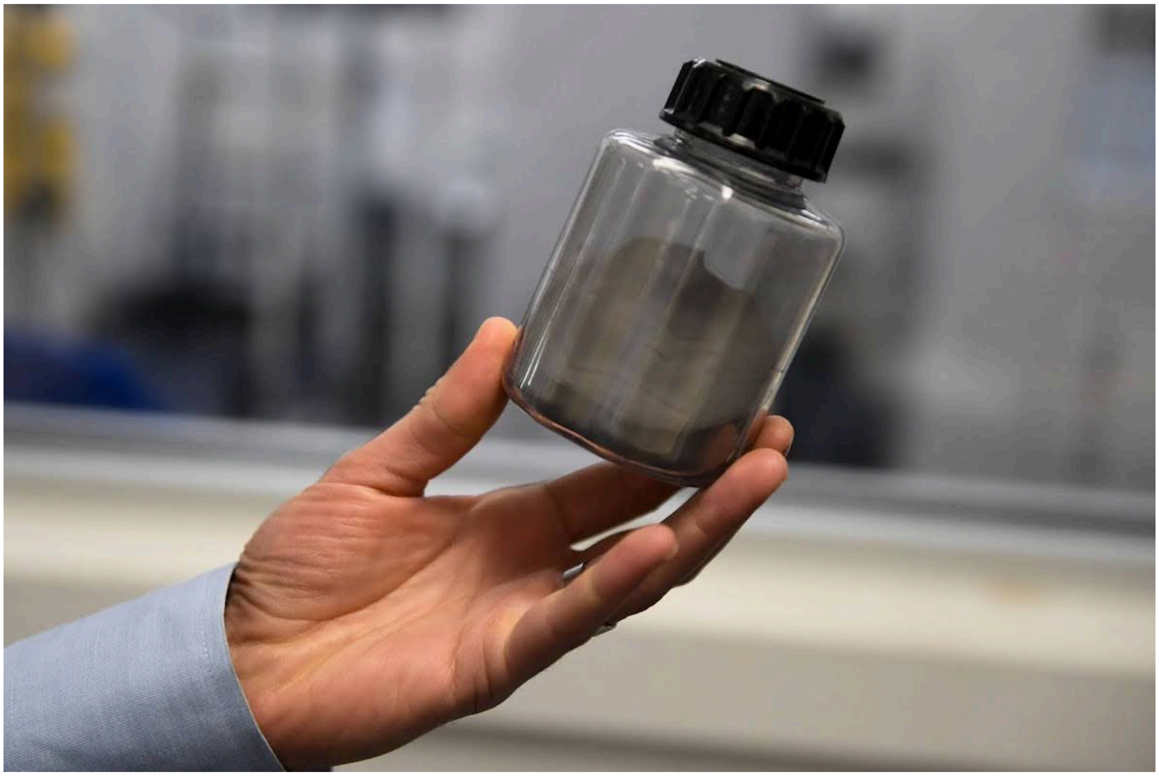


Figure 8.7 Titanium powder, shown here, can be remarkably expensive compared to conventional materials. But the overall cost savings in manufacturing, including transport, can make its use financially viable. (credit: U.S. Navy forward by Zachary Martyn on DVIDS, Public Domain)

AM Design

All these cost drivers originate from the requirements, which govern the design of the part. Cost can be controlled through thoughtful application of design for additive manufacturing methods. Consider a part designed for PBF that is fully self-supported and nests multiple parts neatly into a well-packed build plate.

These roof parts optimize the process cost by eliminating supports completely, avoiding wasted material and associated printing & support removal time. The parts were built to snap off the build plate, eliminating the need for part removal by EDM. Cost is further optimized by the nesting strategy that maximizes the number of parts in one print cycle. Normally in AM, part costs are said to be flat, independent of volume. Although this is mostly true, processes include build set up, turn over, and stress relief cycles that are additional costs, regardless of the number of parts on the build plate.

Regulatory Considerations

A final consideration that should be built into a business case for AM is an evaluation of any regulatory requirements for the part or equipment. Typically, these are similar, if not the same, as what is required for these parts and equipment in any manufacturing method. For example, it is easy to consider in-sourcing parts made today at a supplier or thinking that any in-kind AM machine can create the same parts, but some industries require strict adherence to standards to ensure quality parts and services. Some examples include Good Manufacturing Practice (GMP) followed strictly in the medical field, AS9100 in aerospace, Lloyd’s Register for marine, and NADCAP covering special processes for aerospace, defense and many other industries. Each of these examples carry a cost to achieve and maintain and this cost needs to be considered in the overall AM business case.

8.4 AM Economics

Learning Objectives

By the end of this section, students will be able to:

- Describe the relationship between overall productivity and the balance between the different processes.
- Understand learning curves and how they relate to AM and CM.
- Describe how MfAM, DfAM, complexity, and quantity are interrelated.

Appreciating the economics of additive manufacturing iw core to understanding AM at all. Economics is the study of production and consumption, which helps us to decide when to use and not use AM. While there are scenarios where cost is not the primary driver such as schedule and performance, most of the time, those events ultimately have a cost penalty, or a price premium associated with them. In this section, we will address productivity and examples of what can drive productivity in AM. We will also assess the impact of throughput or volume, what goes into a business case for an AM application and the application of learning curves.

Impact of Productivity

A 3D printer is a tool just like other forms of manufacturing. If the productivity of the tool is low, its usefulness or application will ultimately be limited to items that are not cost sensitive. The Organization for Economic Co-operation and Development (OECD) defines productivity as, "a ratio between the output volume and volume of inputs." It is the measure of how efficient inputs, such as lasers, are being used to produce a level of output, i.e. parts. If adding a second laser increases the cost of the system without increasing its output, it would decrease productivity. It will be through this lens that we will examine the impacts to productivity in some 3D printers and associated processes like metal powder production.

We will examine the productivity of the supply chain, or the process steps required to make the feedstock material through to a finished part. In doing so, we can appreciate the contributions of each step in the productivity of the process. The alternative often is to only examine the productivity of the 3D printer itself. This is an important step to understand, but it is only a step in a multi-step process where to squeeze more productivity out we must look at each process step and how it contributes to or limits the productivity of the process.

Feedstock

For metal PBF, the feedstock is a powder. Traditionally, the metal powder is made via an atomization process whereby the metal is made liquid by heating and the molten droplets fall into a tall chamber. The droplet is broken up by a variety of methods which cause many smaller droplets to form before the they cool and solidify as they fall through the chamber. The output of the process tends to be a spherical powder with a Gaussian distribution of diameters. Not all metal powders are made this way, however, and there are many variations on the concept. Atomization is done via gas atomization, water atomization or plasma atomization which vary in the medium used to break the liquid metal droplet and the raw materials to create the liquid metal. Other forms of powder production exist and have been used in powder metallurgy such as Hydride De-Hydride (HDH) and mechanical methods. In polymeric PBF, the powder can be synthesized or mechanically ground which gives very different characteristics in terms of roundness and size distribution. For our purposes in this chapter, the size distribution will be a particular focus because it drives the yield and therefor productivity that process to make feedstock.

Powder Size Distribution (PSD) is a key factor in any powder production process. This is mostly because the printing process has prescribed a fairly narrow PSD to be used in the process, while atomization produces a fairly wide PSD, regardless of which method is employed. The selection of PSD contributes to surface finish, the ability gets a desirable Packing Factor in the bed, the ability to move the powder and ultimately cost. PSD can contribute to cost in the powder price, the printer performance and the downstream processing so it is a pervasive cost driver. It is also important to point out that size is a factor in the ability to move particles with smaller particles flowing more poorly than larger, which is why roundness or sphericity is often discussed. Spherical particles flow better than non-spherical particles, so when the requirements call for freely flowing, narrow PSD and small particles; having spherical particles helps. Naturally, having fewer smaller particles also helps as well as having particles that can be moved versus having "high flowability" are important specifications. If over specified, the powder costs more than the AM process truly needs to produce a desired output.

AM Process

Within the AM process, the speed of creating a layer and melting the material is critical to productivity. The layer creation step is influenced by the speed at which the powder can be moved into place, the utilization of the powder (i.e. how many times it can be re-used) and the thickness of the layer. In PBF, for example, the scanning step where the laser (or electron beam) is melting the material and thereby creating the part is influenced by the number of lasers and the part thickness. Another nuance is the addition of lasers to create a larger bed size where more parts or larger parts can be made. All of these factors affect the productivity of the printing process. They also then impact the upstream and downstream processing as well.

Thick layer vs Machining

Printing a thicker layer could drive a larger PSD, but also require more machining due to lower resolution. If the part were going to be machined anyway, the bulk of the cost would accumulate in the setup, so machining more can be more productive when printing parts faster.

Using more of the atomization output increases the productivity of atomization and therefore should decrease cost. The thicker layer improves productivity by reducing the input costs and optimizing the downstream costs.

Print Speed

Print speed is often mentioned when discussing productivity or comparing various AM processes. It is important to take this into context as increasing the print speed alone may not increase the speed at which a part can be made and, in some cases, a faster print speed can be more expensive at the part than a slightly slower speed. It is logical to assume with expensive **capital expenditure** (CAPEX) items, like 3D printers, that faster would be better, but this often obfuscates several important factors. There is a difference between the print speed, the effective print speed, and then the actual cost to produce the component. We will discuss:

- **Actual print speed**: Speed at which the printer makes a shape
- **Effective print speed**: The resolved speed of the printing when considering the print time and required steps to make the print useful

Finally, the **final part cost** is the ultimate metric if the productivity of the entire process has been improved or not.

AM is a series of processes, and those processes must be matched or optimized to get the maximum benefit. Inherent in these examples has been the ability to make thicker layers. We will now look specifically at the economic considerations of thicker layers in a series of processes.

Printing thicker layers can be more difficult than it sounds. We've already mentioned that thicker layers can have implications on the powder input. Thicker layers will also impact the processing downstream because of the lower resolution. If the part is extremely detailed, thicker layers may not work but for larger parts or parts without a high degree of detailing, using thicker layers is a means to making more parts faster.

By increasing the layer thickness, we effectively reduce the print time. Going from 30-micron layers to 60-micron layers isn't exactly a 50% improvement, but it is close. Thicker layers only impact the time during printing when the part is being scanned or made. Recoating time is unchanged as is the set up and cool down time.

The figure below shows the resulting calculation to examine the impact of thicker layers on part cost due to reduction in print time. Increasing the layer thickness by 50% leads to a reduction in print time and consequently part cost of approximately 20%.

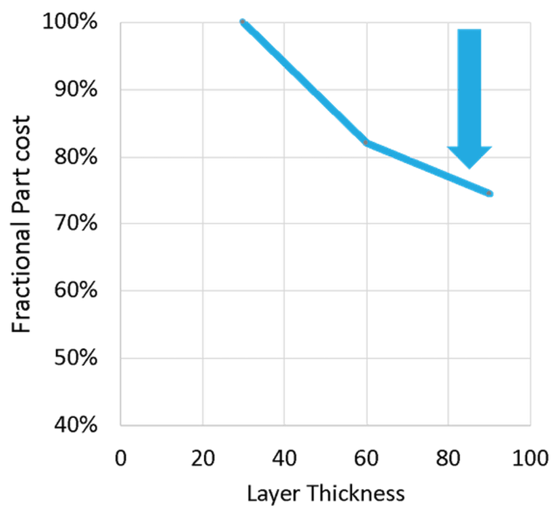


Figure 8.8 The calculated impact of layer thickness on part cost.

The next focus then becomes the cost of the powder because we have shifted our part cost contribution. The figure below shows the new cost implication as escalating the impact of powder as the downstream processing is more or less unchanged.

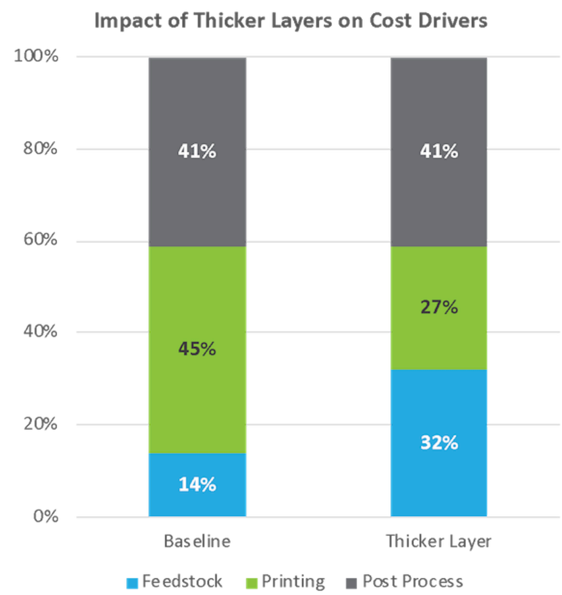


Figure 8.9 Cost driver impact from a 30-micron layer baseline to a 60-micron layer, and same powder PSD and cost/kg.

The Four Lenses of AM and The Business Case

This chapter primarily deals with the financial aspects of AM. After the mechanical approach of adding the material cost plus the equipment time etc. there is the time to appreciate how the situation is improved and optimized. After all, economics is the study of what is the best use of financial resources. In order to provide a holistic view, we will divide this consideration into four domains: Machines, Materials, Digital and People. In these sections we will explore the additional possibilities and potential sources for new performance or savings.

Making a business case considers employing the right AM technology or process, with the right material which meets the design intent which requires people to have experience. AM is sufficiently diverse and within technology types there are many suppliers, brands, makes and models. The material of interest and the design are critical influences on the AM process choice. The process must meet your requirements and those requirements are both technical and financial. Meeting the technical intent but failing to provide some kind of value proposition will not lead to success.

Machines

As the printers or machines are the single biggest factor in the cost of making parts, we will consider them first. With some AM technologies, the printer comes with the peripheral equipment required to finish the part. Polymer PBF, for example, does require some post printing treatments, but due to the maturity of the technology, there are multiple suppliers and automations available. Metal AM, which is less mature by comparison, has a very immature supply chain and is somewhat scattered. We will examine two aspects of machines in a business case: batch vs. series production and operational cost.

In production, the processes must be aligned in a fashion to optimize the part flow. Through this optimization, the producer can get the most from the operational uptime of the equipment. AM can be thought of as a series of batch operations. Batch operations are where a service is performed on a group of parts at the same time, like heat treatment. Several parts are placed in a furnace, and it runs for hours. The cost of running the furnace is the same whether it is full of parts or has one part.

Clearly, we would be wise to optimize the maximum number of parts we need with the chamber size of the printer and the capacity of a furnace. When these are matched well, we can see a benefit close to series production called **batch series**. Batch series simply describes where two batch processes are matched so that they in effect act like series production. Series production is more closely related to the original Ford model of assembly line efficiency. The biggest difference here is that we have a printer which is good at making many different designs so keeping it running may mean making one part in the first week and a different part (same material) the next. This is most commonly referred to as “agile” manufacturing where capital equipment is capable of making many different things as they demand arises.

Calculating Costs to Increase Productivity

Let's consider the case of a fictional company that just bought and installed the fastest binder jet printer available, at a price of $500,000. The CEO is unhappy because their costs are higher than expected, causing the profit margins to be very low. After conducting an audit to map the production process, they discovered that the printer output was fast but did not align to the next two process steps: curing and de-powdering. Consequently, the printer was making 12 parts in 12 hours (1 part per hour) but the remaining steps could only manage to process 12 parts in 16 hours (1.3 parts per hour).

The manufacturing group wanted authorization to buy an additional sintering furnace to handle the part flow. The cost of the sintering furnace was $1,000,000. However, doubling the sintering capacity would result in excess capacity in that step, which would in turn cause the furnace to operate with excess capacity. Again, the printer was purchased for $500,000. So, it was better financially to reduce (throttle) the printer output to 1.3 parts per hour to align to the other processes which were more expensive.

We can see that the role of manufacturing then has to respond to the demands of the market. While on the one hand, AM is agile and a printer can make many parts, on the other, it does not mean that the downstream processes are equivalently agile.

This brings us to the second point, operational cost. Regardless of what we are making, keeping the machines making parts is the most desirable situation. The cost of the capital equipment is high and will be amortized (spread) over a set period. Most AM equipment see the use of seven years for amortization but could be shorter for technologies that are advancing quickly. Spreading costs over seven years is desirable because it reduces the hourly burden of the equipment. Effectively, you divide the capital cost by the amortization period to get your annual cost. By dividing the annual cost by the planned operational hours gives us the $/hr. to use that machine.

The economics or operational effectiveness of AM equipment and the legacy manufacturing equipment are essentially the same. The Accounting of the depreciation of the capital equipment sets in place the hourly cost of using the equipment. The cost of using the equipment then drives how we can design the parts to balance cost and performance.

Beyond the hourly cost of the machines, the next factor is being able to deploy them such that our processes are aligned as much as possible to seek efficiency. Aligning our production so that part flow from the printer to the furnace is an example of **lean manufacturing**. Lean manufacturing is a methodology that focuses on minimizing waste within manufacturing systems while simultaneously maximizing productivity. In some ways, lean and agile manufacturing have opposing requirements, but both promote minimizing waste and focusing on productivity. The difference is perhaps that lean would prefer to make the same widget every day whereas agile responds to the market demand. Agile is then more difficult to predict and therefor harder to manage in manufacturing.

While we have focused on the AM machines, we have also discussed the need to align production capacity with downstream processes. This is more prevalent in metal AM than polymer AM as metals are more exposed to supply chains. The premise of our discussion and examples however are the same. It will be necessary to match the production output of the printer to the stress relief furnace to the HIP vessel to other finishing processes. The ability to do this effectively will drive a decision on what can be done in house more efficiently than outsourcing where you seek market efficiency.

Process-by-Process Discussion: Emphasis on Metals

PBF and DED with powder have the majority of cost in printing and post-processing. Materials, while perhaps more expensive than typical mill products are used so efficiently, most of what you print with you use and remove very little. The AM equipment is expensive, so the depreciation drives the overall cost. Using the printer very productively is key. A key value proposition is making very detailed, very near net shape products either from the platform up or adding on to an existing product form or repair.

Sheet lamination has minimal printing costs partly because the print speed is higher but also because the feedstock (thin gauge sheet) is expensive, and the process provides details at the expense of material wastage. The printing and machining are coupled leaving post-processing to traditional metal working and final finishes.

Binder jetting has more post-processing intensive than other processes because it needs to sinter the part in order to achieve full density. The material cost is somewhat artificially inflated because we have normalized the whole cost to 100%. Materials in BJP are typically less than laser powder bed fusion, for example.

DED with wire is very efficient at printing. It will always require a heat treat for stress relief, perhaps multiple times, and machining due to its inability to make details. Wire can be an expensive product form due to the diameter that is typically required is around 3 mm. Wire is made from bar stock and drawn or swaged down which is a lengthy process.

Direct Extrusion is quite fast and not very expensive, so for putting a lot of material down, it is very efficient. The feedstock is more like bar stock or could be waste material, so readily available and not expensive. It does require similar post-processing to DED + wire due to its inability to make near-net shapes.

Cold spray is very fast and very affordable. It does not make near net shapes so additional machining will most likely be required but the deposition rate can be tailored to produce acceptable surfaces. In some cases, a heat treatment could be necessary as well. The powder cost for cold spray can vary wildly depending on the chemistry or alloy from very inexpensive to more expensive than laser powder bed fusion, specifically in titanium.

Materials

In some instances, the material will help decide the AM process needed. In other cases, where equivalent or superior performance is all that is required, a superior material could be used with better performance and no effect on cost. In some cases, like PBF, the material cost as a percentage is low. In this instance, evaluating alternative materials means getting higher performance at negligible cost impact. Consequently, in Sheet Lamination where the material input is high, further investigation would be required.

Figure 8.10 Each of these canisters contain 10 kilograms, about 22 pounds, of powdered steel, used in the construction process with the EOS M 400 3-D metal printer. Each container is valued at $7,000. The 3-D printer also used soft aluminum or titanium powder to construct hard to find parts or design and build tools specifically for a project at PPB, MDMC. (credit: Marine Corps photo by Keith Hayes on DVIDS, Public Domain)

The choice of material can inflate the importance in processes like BJP and SL because the PSD and thin gage requirements are more expensive in titanium than they would be for example in steel which is more easily rolled to thin gage. However, this choice also drives the point in PBF and DED powder which is that titanium whilst having a high relative $/kg than other materials is <20% of the overall cost.

In consideration of the business case, it would be necessary to consider how the AM feedstock price compares to the legacy form price. This assumes material substitution is not a possibility. If the cost of AM feedstock, being a powder, wire or sheet is multiples higher than the legacy method, it begins to describe how productive the AM process is going to have to be as a first order estimation.

Aluminum Versus Titanium

The price for plate of 7000 series is ~$10/kg and aluminum machines quite easily, an order of magnitude faster than nickel or titanium. Aluminum powder can sell for $70/kg. In this initial look, the productivity of AM is going to have be quite good to provide economic value. If the raw material to final part mass ratio were 11:1 with the legacy approach, we would have 11x$10/kg or $110 of raw material which would need to be machined. If the AM approach had a ratio of 2:1, we would have 2 x $70/kg or $140 of raw material needing to be additively manufactured. With all things being equal, we are starting $30 in the negative before we've employed the manufacturing tool.

The price for Ti 6Al4V plate is ~$45/kg and machines very slowly. Titanium powder can sell for $150/kg. Assuming similar ratios as in the aluminum example, our raw material input comparison is $495 legacy and $300 for AM. Immediately, we are already in a positive situation. The comparison to machining titanium versus AM can be expected to be similar, simply because titanium machines slowly.

Accurately predicting the waste is another consideration. If the powder is converted to part efficiently, as in cold spray, the wasted material is quite low. In powder bed processes like PBF and BJP, powder may be re-used multiple times but for some reactive materials and polymers, the chemistry may dictate a limited number of uses before it must be scrapped. Wire or filament processes are typically very efficient at converting the feedstock into a usable part.

For AM processes that allow nesting of parts, there are details associated with support structures or sacrificial material that is used to improve the survivability of the part. In some cases, like the support structures used in PBF will consume material and then also require work to remove, there is a double effect. In other cases, where a plate is used in the part design, careful selection and placement of the deposition will help minimize the material wastage. Needless to say, when multiple material input forms are used, such as in DED, sacrificing the lower value material is typically preferable.

Digital

The digital component for AM encompasses a large catch-all of activity, as described in the chapter on the digital thread. First, it includes the designing for AM activities as well as the complete workflow associated. Generative design tools, topological optimization (T.O.), simulation tools are all separate components although some integration exists. From an economics point of view, all of these tools must overcome the cost of the tool in order to be productive.

It is easy to find the value in designing for AM, both MfAM and DfAM components. Without this view, it is unlikely for any value to be derived using AM where cost is the ultimate goal. Tools like generative design assist in finding the optimal shape for the given structural or thermal load. We find economic value not only in the higher performance but in the preservation of material as well. Topological optimization can then be used to further optimize the shape but can be used in other ways as well, where traditional CAD tools would be very laborious. Creating repeating or scalable non-solid sections like lattices would be very tedious and time consuming in CAD, whereas it is very efficient with T.O.

Of course, minimizing the design effort for new or re-design for existing applications, have significant economic benefits to the business case. These efforts are required and represent costs that will have to be recovered by the AM production to be of economic benefit.

Analysis and simulation tools are very helpful in achieving early print/build success. The time spent on the simulation tool and operation, however, is significant. So these tools are typically applied where series production is likely, otherwise, employing expensive tools might be more expensive than trial and error for a prototype.

Even with the optimization tools that we have, just as in conventional manufacturing, sometimes it is necessary to move forward with an imperfect solution as the analysis can continue to optimize but with diminishing value. Realizing when you've reached a point of diminishing value can often be difficult for technically driven organizations.

It is worth emphasizing again that designing for AM doesn't stop at the printer. Providing location and data features to the design as it moves through post-processing is a key AM component, and further evidence that AM is a *series* of processes. Consequently, there is significant economic benefit when the design is optimized for the entire value chain, and not just the printer. The printer may not always be the most expensive piece of capital

Figure 8.11 Considering that AM is a series of processes, manufacturers and decision makers must realize that the printer may not be the most expensive part of the process. Here, a line of complex machines is arranged to produce advanced carbon materials. The investment goes far beyond the AM machinery and software. (credit: Modification of "Carbon fiber technology facility" by Oak Ridge National Laboratory/Flickr, CC BY 2.0)

Once the manufacturing processes are complete, capturing and interpreting the data from the build and inspection processes is also of importance. Through a series of dimensional and volumetric inspections, the manufacturer can determine if the part is capable of meeting the final requirements. This is no different than conventional manufacturing. Knowing when to apply non-value-added tasks like inspection is key, since they consume resources and time. Strong inspection practices throughout the process can ultimately reduce the cost of manufacturing a product, such as by immediately scrapping a part that is not going to meet the requirements before it is fully finished.

One last component of the digital perspective is the quality assurance (QA) and intellectual property (IP) protection. With digital files, QA and IP. protection are two sides of the same coin. With current tools, it is possible to pre-check the setup of a build to ensure what is to be made can be made. Additionally, tools that observe the build/print process can leverage machine learning to determine if human intervention is required or if the build should be terminated.

The build files themselves can be encrypted. There are several reasons for wanting to encrypt the build file:

- Protect the IP of the design which has economic value,
- Ensure that the wrong file isn't used, and
- Ensure that the file to be built is what gets built and no damage or interference will occur.

People

Investments in people are usually of good value. In addition to building engagement with the team, investing in skills will yield a productive benefit. If anything, AM shows us that training and upskilling can be the difference between economic success or failure. Simply by looking at the role of design in AM, it has been shown numerous times how the design impacts the viability of AM.

It should be noted that investments in people should be made across the organization, not only in engineering or manufacturing. AM is disruptive so when an organization uses the same alphabet, they can more accurately and quickly communicate. The economic benefit to upskilling the organization is getting the design community to think and uses DfAM skills, but also engage and drive support from program management, accounting and supply chain as all of these organization can drive value in AM if they truly understand what is possible and not viable.

Outsourcing and Learning Curves

As has been discussed so far, AM is a series of processes. To achieve the best economic outcome, determining which processes should be done in house or outsourced is a logical step. From an economic standpoint, we achieve optimal efficiency when all of the capital equipment is utilized as much as possible. From an innovation perspective, innovating on several fronts is inadvisable and expensive. In this section we will review typical reasons for outsourcing in AM. As a part of this discussion we will also introduce the concept of a learning curve. A learning curve is used where multiple processes are coupled together to reflect the learning over time to make the per unit cost decrease. The cost to produce the first part is always higher than the Nth part due to learning.

Outsourcing

If there is limited in-house expertise, outsourcing is a compelling option. It could be that a company specializes in design versus part manufacture. Even if the company is competent in part manufacture, should they be involved in every aspect of AM production? Integrating all of the processes into a single facility can be very expensive, especially when the minimum capacity for one process far exceeds the maximum capacity in another, as in the previous sintering furnace example. Additionally, adding in-house capability that will go underutilized increases overall costs without adding any offsetting revenue.

Logistically, being able to align the processing can add many queues. This could be critical when assessing the overall manufacturing time and working inventory. A company often pays for the material when it arrives, but isn't able to receive payment for its effort until the part is built and delivered. The time in between requires the company to keep inventory, and reducing this time is strongly encouraged.

Ultimately, the decision to outsource or insource (keep everything in-house) involves several factors, but typically requires a balance between efficiency and quality. Access to customers, knowledge of materials, protection of intellectual property, or competitive experience could all be compelling reasons to insource a process. A company must know why it is keeping a process in house, so that if the rationale is no longer true at some later point, the company can consider outsourcing and make the correct choice.

8.5 Sustainability Impacts of AM

Learning Objectives

By the end of this section, students will be able to:

- Describe potential ways in which AM can improve sustainability in manufacturing.
- Describe potential ways in which AM can improve sustainability in product usage.

There are less-tangible and perhaps less-quantifiable benefits of additive manufacturing as it relates to the supply chain, work in progress, inventory and sustainability. We will again use our maturity model as the framework for this discussion.

AM is generally considered to be sustainable because of the following reasons.

- Less waste because of the nature of the additive process, unlike parts that are stamped or sculpted out of a larger piece of material
- No specialized tooling or fixtures required for AM
- Can build functionally light weight parts, while maintaining strength that reduce energy consumption while the part is in service
- Reduces the need for large amounts of raw material within the supply chain and transportation
- Largely material-efficient when compared with traditional machining and casting
- Can produce optimized geometries with near-perfect (compared with wrought material) strength-to-weight ratios
- Less impact of the part over its life cycle, resulting in a lower carbon footprint, less embodied energy, and better economic model
- Can create on-demand spare parts, reducing or eliminating inventory
- Can produce complex parts with reduced peak stress or high-corrosion areas that will require fewer replacements in the lifecycle of a system or facility

In the following sections, the Maturity Model will be used as a reference for the product and the Supply Chain, Inventory and Sustainability benefits of AM will be described.

Level 0

Supply Chain

At level zero, organizations are flexing the first elements of the AM supply chain to understand what is possible. They need to understand the AM supply chain and that begins to reduce risk.

Work In Process and Inventory

If they can use AM for prototypes, they are likely to have less Work in Process (WIP) and less need for inventory. AM printers become the tools used, and they are not fixed to a special part or part number necessarily.

Reductions in both inventory and WIP are possible at Level 0.

Sustainability

The use of AM promotes more efficient use of materials in the first instance. First products typically use materials very inefficiently to show product viability first and foremost. Avoiding fixed tooling can then be another benefit when in product design, the final geometry is likely to change based on test feedback which means more tooling may be required.

Level 1

Supply Chain

At level one, companies are reinforcing supply chain benefits through temporary or flexible tooling and fixtures. The supply chain can become less complex because the organization is agile and flexible and can print on demand.

Work In Process and Inventory

WIP is reduced on one hand through tooling minimization and less tooling. Shop fixtures and jigs may add some complexity but are generally low value and pay for themselves. In general, trackable inventory of tools should decrease.

Reductions in both inventory and WIP are possible at Level 1.

Sustainability

Producing fixtures and shop aids promotes less time re-working parts and better productivity through a reduction in injuries from repetitive tasks. Where fixed tooling comes into the picture, companies can use processes like casting for shorter runs because the tooling is easier and cheaper to make, thus making use of existing assets. The case for material efficiency is the strongest.

Level 2

Supply Chain

At level two, organizations are dynamically exercising the a new supply chain, and maintaining schedule is very important to maintain cost efficiency. At this stage, the organization is learning and reducing risk.

Work In Process and Inventory

Companies are likely to have less WIP and less inventory at level two because they are putting most of the effort in the printing process. AM printers can be used to make more than 1-part number.

Sustainability

AM will drive the more efficient use of materials. It is likely that companies are reducing the overall path of the part and therefore reducing carbon emissions to move the part from one location to another.

Level 3

Supply Chain

At level three, the supply chain is compressing as the company reduces part count and process steps.

Work In Process and Inventory

The company has fewer parts and therefore less inventory. Because it has reduced process steps, the company may also have less tooling and WIP.

Reductions in both inventory and WIP are expected at Level 3.

Sustainability

AM begins to make an major impact on sustainability at Level 3. Using more efficient use of materials is a start. Less energy is consumed because they are are making fewer parts. Unitizing also then enables savings in emissions moving and shipping them around by consolidating the supply chain. It also makes an impact on reducing the weight or increasing the efficiency of the overall system.

Level 4

Supply Chain

At level 4, the company has largely optimized the supply chain around AM. The process is much leaner and exhibits the 90% learning curve mentioned earlier.

Work In Process and Inventory

The company has consolidated parts and processes so WIP and Inventory are optimized for financial performance.

Sustainability

The AM solution has higher performance or is enabling better performance of the system it is in. It has all of the benefits of Level 3. It helps the system perform better, which itself could reduce energy consumption.

Summary

Humans have carved things out of rock and wood, or formed parts from metal for centuries. Building up a part is relatively new. While there are some foundations and borrowed technology from casting, powder metallurgy and polymer manufacturing, how we define a layer; how we use energy and how we input feedstock mix together to create this additive approach.

Ultimately, understanding the economics of AM unleashes its potential, but also requires asking and answering a series of questions. What requirements need to be met or what must be true for you to succeed? Are you seeking to save money? Reducing schedule? Improving performance? Can you monetize schedule or performance? These analyses will assist the business case.

Developing a business case for Additive Manufacturing (AM) involves assessing technology, materials, design, economics, quality, safety, and regulatory requirements. Key considerations include the selection of AM processes, material cost and performance, design efficiency, and post-processing requirements. The AM cost model comprises material, printing, and post-processing costs, emphasizing the impact of layer thickness, build speed, and machine productivity on overall expenses. For instance, thicker layers can reduce print time but may affect resolution and downstream costs.

Each AM process has unique cost drivers. Laser Powder Bed Fusion (PBF) incurs high costs in printing and post-processing, while Directed Energy Deposition (DED) varies by feedstock type. Metal Binder Jetting features lower printing costs but requires extensive post-processing. Materials like powders and wires are often more expensive than conventional forms, but AM's efficiency in material usage can offset these costs. Understanding these cost drivers isn't a one-time process; new equipment, material types, and methods can change the dynamics at any time.

Economic considerations also include sustainability benefits such as reduced waste, on-demand part production, and optimized geometries.

Business cases must align processes, machines, and people to maximize productivity. AM offers flexibility, but success depends on careful alignment of technology, materials, design, and operations to achieve cost and performance goals.

References: Ries, E. (2011).*The lean startup: How today's entrepreneurs use continuous innovation to create radically successful businesses*. New York: Crown Business.

Key Terms

8.4 AM Economics

Actual print speed, Effective print speed, final part cost, Capital Expenditure (CAPEX), Batch Series, lean manufacturing

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