



ATME College of Engineering

13th KM, Mysuru-Kanakapura Rd, Mysuru-28

Department of Mechanical Engineering



ADDITIVE MANUFACTURING,

BME741A

VII Sem

2026-27

Name of the Student: _____

University Seat No. : _____

Semester: _____ *Batch No. :* _____

ATME COLLEGE OF ENGINEERING

VISION

Development of academically excellent, culturally vibrant, socially responsible and globally competent human resources.

MISSION

- To keep pace with advancements in knowledge and make the students competitive and capable at the global level.
- To create an environment for the students to acquire the right physical, intellectual, emotional and moral foundations and shine as torch bearers of tomorrow's society.
- To strive to attain ever-higher benchmarks of educational excellence.

DEPARTMENT OF MECHANICAL ENGINEERING

VISION

To impart excellent technical education in mechanical engineering to develop technically competent, morally upright and socially responsible mechanical engineering professionals.

MISSION:

- To provide an ambience to impart excellent technical education in mechanical engineering.
- To enable the students to acquire skill development, knowledge of Research and recent trends in Mechanical Engineering which will help them in lifelong learning
- To engage students in co-curricular and extra-curricular activities to impart social & ethical values and imbibe leadership quality.

PROGRAM EDUCATIONAL OBJECTIVES (PEO'S)

After successful completion of program, the graduates will

PEO 1: Able to have successful professional career in the allied areas and be proficient to perceive higher education..

PEO 2: Attain the ability to understand the need, technical ability to analyze, design and manufacture the product.

PEO 3: Work effectively, ethically and socially responsible in allied fields of mechanical engineering.

PEO 4: Work in a team to meet personal and organizational objectives and to contribute to the development of the society in large.

PROGRAM OUTCOMES (PO'S)

The Mechanical engineering program students will attain:

PO1.Engineering knowledge: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems

PO2.Problem analysis: Identify, formulate, research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences

PO3.Design/development of solutions: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations

PO4.Conduct investigations of complex problems: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions

PO5. Modern tool usage: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations

PO6.The engineer and society: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice

PO7.Environment and sustainability: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development

PO8.Ethics: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice

PO9.Individual and team work: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings

PO10.Communication: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions

PO11.Project management and finance: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments

PO12.Life-long learning: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change

PROGRAM SPECIFIC OUTCOMES (PSO'S)

After successful completion of program, the graduates will be

PSO 1: Ability to apply and interpret the acquired mechanical engineering knowledge for advancement in Industrial, Societal, and Environmental arenas.

PSO 2: Ability to meet the needs of Industries in the field of design, manufacturing and testing using mechanical engineering software.

COURSE MODULE

Faculty Name/s:				Academic Year:2026 - 27			
Department: Mechanical Engineering							
Course Code	Course Title	Core/Elective	Prerequisite	Contact Hours			Total Hrs/ Sessions
				L	T	P	
18ME741A	Additive Manufacturing	Core	Basic Manufacturing concepts	3	-	-	40
Course Objectives	Course objectives: This course (18ME72) will enable students to:						
	CLO1: To know the principle methods, areas of usage, possibilities and limitations of the Additive Manufacturing technologies.						
	CLO2: To be familiar with the characteristics of the different materials those are used in Additive Manufacturing.						
	CLO3: To know the principles of polymerization and powder metallurgy process, extrusion-based system printing processes, sheet lamination processes, beam deposition processes, direct write technologies and Direct Digital Manufacturing.						
	CLO4: To get exposed to process selection, software issues and post processing.						
Topics Covered as per Syllabus							
<u>MODULE-I</u>							
Introduction and basic principles: Need for Additive Manufacturing, Generic AM process, stereolithography or 3dprinting, rapid proto typing, the benefits of AM, distinction between AM and CNC machining, other related technologies- reverse engineering technology.							
Development of Additive Manufacturing Technology: Introduction, computers, computer-aided design technology, other associated technologies, the use of layers, classification of AM processes, metal systems, hybrid systems, milestones in AM development.							
Additive Manufacturing Process chain: Introduction, the eight steps in additive manufacture, variations from one AM machine to another, metal systems, maintenance of equipment, materials handling issues, design for AM, and application areas.							
<u>MODULE-2</u>							
Photo polymerization processes: Stereolithography (SL), Materials, SL resin curing process, Microstereolithography, Process Benefits and Drawbacks, Applications of Photo polymerization Processes.							
Powder bed fusion processes: Introduction, Selective laser Sintering (SLS), Materials, Powder fusion mechanism, SLS Metal and ceramic part creation, Electron Beam melting (EBM), Process Benefits and Drawbacks, Applications of Powder Bed Fusion Processes.							
Extrusion-based systems: Fused Deposition Modelling (FDM), Principles, Materials, Plotting and path control, Bio-Extrusion, Process Benefits and Drawbacks, Applications of Extrusion-Based Processes.							
<u>MODULE - 3</u>							
Printing Processes: evolution of printing as an additive manufacturing process, research achievements in printing deposition, technical challenges of printing, printing process modeling, material modification methods, three-dimensional printing, advantages of binder printing							
Sheet Lamination Processes: Materials, Laminated Object Manufacturing (LOM), Ultrasonic Consolidation (UC), Gluing, Thermal bonding, LOM and UC applications.							
Beam Deposition Processes: introduction, general beam deposition process, description material delivery, BD systems, process parameters, typical materials and microstructure, processing–structure–properties relationships, BD benefits and drawbacks.							
Direct Write Technologies: Background, ink -based DW laser transfer, DW thermal spray, DW beam deposition, DW liquid-phase direct deposition.							
<u>MODULE-4</u>							
Guidelines for Process Selection: Introduction, selection methods for apart, challenges of selection, example system for preliminary selection, production planning and control.							
Software issues for Additive Manufacturing: Introduction, preparation of cad models – the STL file, problems with STL files, STL file manipulation.							
Post- Processing: Support material removal, surface texture improvements, preparation for use as a pattern, property enhancements using non-thermal techniques and thermal techniques.							
<u>MODULE-5</u>							
The use of multiple materials in additive manufacturing: Introduction, multiple material approaches, discrete multiple material processes, porous multiple material processes, blended multiple material processes, commercial							

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applications using multiple materials, future directions.

AM Applications: Functional models, Pattern for investment and vacuum casting, medical models, art models, Engineering analysis models, Rapid tooling, new materials development, Bi-metallic parts, Remanufacturing. Application: Examples for Aerospace, defence, automobile, Bio-medical and general engineering industries.

Direct digital manufacturing: Align Technology, siemens and phonak, DDM drivers, manufacturing vs. prototyping, life- cycle costing, future of direct digital manufacturing.

List of Text Books

1. Additive Manufacturing Technologies Rapid Prototyping to Direct Digital Manufacturing, I. Gibson I D. W. Rosen I B. Stucker, Springer New York Heidelberg Dordrecht, London.

List of Reference Books

1. "Rapid Prototyping": Principles & Applications Chua Chee Kai, Leong Kah Fai, World Scientific, 2003.
2. Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing, 2nd Ed. (2015), Ian Gibson, David W. Rosen, Brent Stucker
3. "Understanding Additive Manufacturing", Andreas Gebhardt, Hanser Publishers, 2011

List of URLs, Text Books, Notes, Multimedia Content, etc

Video Demonstration of Different types of automation and Mechanisms

<https://nptel.ac.in/courses/112/103/112103306/>
<https://www.youtube.com/watch?v=7L42aRs68WI>
<https://www.youtube.com/watch?v=gcia0aqZMf0>

Printed Copy (Soft Copy): Available

Course Outcomes	Students will be able to:
	CO1-Demonstrate the knowledge of the broad range of AM processes, devices, capabilities and materials that are available.
	CO2-Describe the various software tools, processes and techniques that enable advanced/additive manufacturing.
	CO3-Apply the concepts of additive manufacturing to design and create components that satisfy product development/prototyping requirements, using advanced/additive manufacturing devices and processes.
	CO4-Elucidate characterization techniques in additive manufacturing.
	CO5-Illustrate the latest trends and business opportunities in additive manufacturing.

The weightage of Continuous Internal Evaluation (CIE) is 50% and for Semester End Exam (SEE) is 50%. The minimum passing mark for the CIE is 40% of the maximum marks (20 marks out of 50) and for the SEE minimum passing mark is 35% of the maximum marks (18 out of 50 marks). A student shall be deemed to have satisfied the academic requirements and earned the credits allotted to each subject/ course if the student secures a minimum of 40% (40 marks out of 100) in the sum total of the CIE (Continuous Internal Evaluation) and SEE (Semester End Examination) taken together.

Continuous Internal Evaluation:

- The CIE is the sum of Average of Two Internal Assessment Tests each of 25 marks and Any two Assessment methods for 25 marks.
- The first test will be administered after 4050% of the syllabus has been covered, and the second test will be administered after 8590% of the syllabus has been covered
- Any two assessment methods mentioned in the 22OB , if an assignment is projectbased then only one assignment for the course shall be planned. The teacher should not conduct two assignments at the end of the semester if two assignments are planned.
- For the course, CIE marks will be based on a scaledown sum of two tests and other methods of assessment for a total of 50 marks

Internal Assessment Test question paper is designed to attain the different levels of Bloom's taxonomy as per the outcome defined for the course.

Semester End Examination:

Theory SEE will be conducted by University as per the scheduled timetable, with common question papers for the course (duration 03 hours).

1. The question paper will have ten questions. Each question is set for 20 marks.
2. There will be 2 questions from each module. Each of the two questions under a module (with a maximum of 3 sub questions), should have a mix of topics under that module.
3. The students have to answer 5 full questions, selecting one full question from each module.
4. Marks scored shall be proportionally reduced to 50 marks.

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Suggested Learning Resources:	Books
1. Additive Manufacturing Technologies Rapid Prototyping to Direct Digital Manufacturing I. Gibson I D. W. Rosen I B. Stucker Springer New York Heidelberg Dordrecht, London ISBN: 978 1 441911193 eISBN: 978 14419 11209 DOI 10.1007/978 14419 11209 2. “Rapid Prototyping: Principles & Applications Chua Chee Kai, Leong Kah Fai World Scientific 2003 3. Rapid Prototyping: Theory & Practice Ali K. Kamrani, Springer 2006 Emand Abouel Nasr, 4. Rapid Manufacturing: The Technologies and Applications of Rapid Prototyping and Rapid Tooling” D.T. Pham, S.S. Dimov Springer 2001 5. Rapid Prototyping: Principles and Applications in Manufacturing Rafiq Nooran John Wiley & Sons 2006 6. Additive Manufacturing Technology Hari Prasad, A.V. Suresh Cengage 2019 7. Understanding additive manufacturing: rapid prototyping, rapid tooling, rapid manufacturing Andreas Gebhard	
Activity Based Learning (Suggested Activities in Class)	
➤ Case studies ➤ Quiz ➤ Topic Seminar presentation ➤ Assignments	

The Correlation of Course Outcomes (CO's) and Program Outcomes (PO's)

Subject Code:	BME741A	TITLE: Additive Manufacturing						Faculty Name:				
List of Course Outcomes	Program Outcomes											
	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12
CO-1	2	-	2	-	2	-	-	-	-	-	-	2
CO-2	2	-	2	-	2	-	-	-	-	-	-	2
CO-3	2	-	2	-	2	-	-	-	-	-	-	2
CO-4	2	-	2	-	-	-	-	-	-	-	-	2
CO-5	2	-	2	-	-	-	-	-	-	-	-	2

Note: 3 = Strong Contribution 2 = Average Contribution 1 = Weak Contribution - = No Contribution

The Correlation of Course Outcomes (CO's) and Program Specific Outcomes (PSO's)

Subject Code: BME741A		TITLE: Additive Manufacturing		Faculty Name:			
List of Course Outcomes	Program Specific Outcomes						
	PSO1			PSO2			
CO-1	2			2			
CO-2	2			2			
CO-3	2			2			
CO-4	2			2			
CO-5	2			2			

Note: 3 = Strong Contribution 2 = Average Contribution 1 = Weak Contribution - = No Contribution

MODULE 1

Introduction and basic principles: Need for Additive Manufacturing, Generic AM process, Stereolithography or 3d printing, rapid proto typing, the benefits of AM, distinction between AM and CNC machining, other related technologies- reverse engineering technology.

Development of Additive Manufacturing Technology: Introduction, computers, computer-aided sign technology, other associated technologies, the use of layers, classification of AM processes, metal systems, hybrid systems, milestones in AM development.

Additive Manufacturing Process chain: Introduction, the eight steps in additive manufacture, variations from one AM machine to another, metal systems, maintenance of equipment, materials handling issues, design for AM, and application areas.

INTRODUCTION AND BASIC PRINCIPLES

NEED FOR ADDITIVE MANUFACTURING

The term Rapid Prototyping (or RP) is used in a variety of industries to describe a process for rapidly creating a system or part representation before final release or commercialization. In other words, the emphasis is on creating something quickly and that the output is a prototype or basis model from which further models and eventually the final product will be derived. Management consultants and software engineers both use the term Rapid Prototyping to describe a process of developing business and software solutions in a piecewise fashion that allows clients to test ideas and provide feedback during the development process. In a product development context, the term rapid prototyping was used widely to describe technologies which created physical prototypes directly from digital data. This text is about these technologies, first developed for prototyping, but now used for many more purposes.

Users of RP technology have come to realize that this term is inadequate and does not effectively describe more recent applications of the technology. Improvements in the quality of the output from these machines have meant that there is a much closer link to the final product. Many parts are in fact now directly manufactured in these machines; so it is not possible for us to label them as “prototypes.”

The term Rapid Prototyping also overlooks the basic principle of these technologies in that they all fabricate parts using an additive approach. A recently formed Technical Committee within ASTM International agreed that new terminology should be adopted. While this is still under debate, recently adopted ASTM consensus standards now use the term Additive Manufacturing.

Referred to in short as AM, the basic principle of this technology is that a model, initially generated using a three-dimensional Computer Aided Design (3D CAD) system, can be fabricated directly without the need for process planning. Although this is not in reality as simple as it first sounds, AM technology certainly significantly simplifies the process of producing complex 3D objects directly from CAD data. Other manufacturing processes require a careful and detailed analysis of the part geometry to determine things like the order in which different features can be fabricated, what tools and processes must be used, and what additional fixtures may be required to complete the part. In contrast, AM needs only some basic dimensional details and a small amount of understanding as to how the AM machine works and the materials that are used.

The key to how AM works is that parts are made by adding material in layers; each layer is a thin cross-section of the part derived from the original CAD data. Obviously in the physical world, each layer must have a finite thickness to it and so the resulting part will be an approximation of the original data, as illustrated by Fig. 1. The thinner each layer is, the closer the final part will be to the original. All commercialized AM machines to date use a layer-based approach; and the major ways that they differ are in the materials that can be used, how the layers are created, and how the layers are bonded to each other. Such differences will determine factors like the accuracy of the final part plus its material properties and mechanical properties. They will also determine factors like how quickly the part can be made, how much postprocessing is required, the size of the AM machine used, and the overall cost of the machine and process.

This chapter will introduce the basic concepts of Additive Manufacturing and describe a generic AM process from design to application. It will go on to discuss the implications of AM on design and manufacturing and attempt to help in understanding how it has changed the entire product development process. Since AM is an increasingly important tool for product development, the chapter ends with a discussion of some related tools in the product development process.



Fig. 1 CAD image of a teacup with further images showing the effects of building using different layer thicknesses

GENERIC AM PROCESS

AM involves a number of steps that move from the virtual CAD description to the physical resultant part. Different products will involve AM in different ways and to different degrees. Small, relatively simple products may only make use of AM for visualization models, while larger, more complex products with greater engineering content may involve AM during numerous stages and iterations throughout the development process. Furthermore, early stages of the product development process may only require rough parts, with AM being used because of the speed at which they can be fabricated. At later stages of the process, parts may require careful cleaning and postprocessing (including sanding, surface preparation and painting) before they are used, with AM being useful here because of the complexity of form that can be created without having to consider tooling. Later on, we will investigate thoroughly the different stages of the AM process, but to summarize, most AM processes involve, to some degree at least, the following eight steps (as illustrated in Fig. 2).

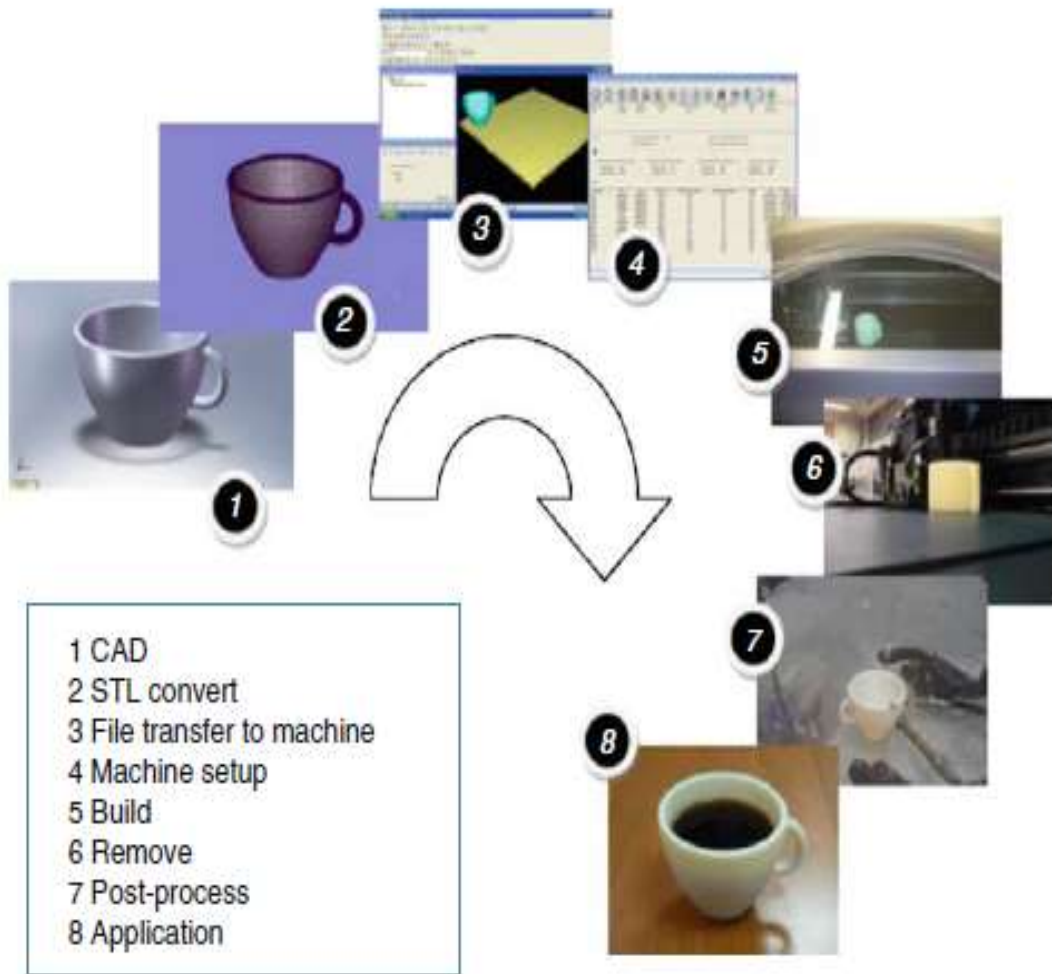


Fig. 2 Generic process of CAD to part, showing all 8 stages

Step 1: CAD

All AM parts must start from a software model that fully describes the external geometry. This can involve the use of almost any professional CAD solid modeling software, but the output must be a 3D solid or surface representation. Reverse engineering equipment (e.g., laser scanning) can also be used to create this representation.

Step 2: Conversion to STL

Nearly every AM machine accepts the STL file format, which has become a de facto standard, and nearly every CAD system can output such a file format. This file describes the external closed surfaces of the original CAD model and forms the basis for calculation of the slices.

Step 3: Transfer to AM Machine and STL File Manipulation

The STL file describing the part must be transferred to the AM machine. Here, there may be some general manipulation of the file so that it is the correct size, position, and orientation for building.

Step 4: Machine Setup

The AM machine must be properly set up prior to the build process. Such settings would relate to the build parameters like the material constraints, energy source, layer thickness, timings, etc.

Step 5: Build

Building the part is mainly an automated process and the machine can largely carry on without supervision. Only superficial monitoring of the machine needs to take place at this time to ensure no errors have taken place like running out of material, power or software glitches, etc.

Step 6: Removal

Once the AM machine has completed the build, the parts must be removed. This may require interaction with the machine, which may have safety interlocks to ensure for example that the operating temperatures are sufficiently low or that there are no actively moving parts.

Step 7: Postprocessing

Once removed from the machine, parts may require an amount of additional cleaning up before they are ready for use. Parts may be weak at this stage or they may have supporting features that must be removed. This therefore often requires time and careful, experienced manual manipulation.

Step 8: Application

Parts may now be ready to be used. However, they may also require additional treatment before they are acceptable for use. For example, they may require priming and painting to give an acceptable surface texture and finish. Treatments may be laborious and lengthy if the finishing requirements are very demanding.

STEREOLITHOGRAPHY OR 3D PRINTING

These two terms were initially used to describe specific machines. Stereolithography (SL) was termed by the US company 3D Systems and 3D Printing (3DP) was widely used by researchers at MIT who invented an ink-jet printing-based technology. Both terms allude to the use of 2D processes (lithography and printing) and extending them into the third dimension. Since most people are very familiar with printing technology, the idea of printing a physical three-dimensional object should make sense. Many consider that eventually the term 3D Printing will become the most commonly used wording to describe AM technologies.

RAPID PROTOTYPING

Rapid Prototyping was termed because of the process this technology was designed to enhance or replace. Manufacturers and product developers used to find prototyping a complex, tedious, and expensive process that often impeded the developmental and creative phases during the introduction of a new product. RP was found to significantly speed up this process and thus the term was adopted. However, users and developers of this technology now realize that AM technology can be used for much more than just prototyping.

Significant improvements in accuracy and material properties have seen this technology catapulted into testing, tooling, manufacturing, and other realms that are outside the “prototyping” definition. However, it can also be seen that most of the other terms described above are also flawed in some way. One possibility is that many will continue to use the term RP without specifically restricting it to the manufacture of prototypes, much in the way that IBM makes things other than business machines and that 3M manufactures products outside of the mining industry. It will be interesting to watch how terminology develops in the future.

Where possible, we have used the term Additive Manufacturing throughout this book as the generic word for the suite of technologies covered by this book. It should be noted that, in the literature, most of the terms introduced above are interchangeable; but different terminology may emphasize the approach used in a particular instance. Thus, both in this book and while reading other literature, the reader must consider the context to best understand what each of these terms means.

THE BENEFITS OF AM

Many people have described this technology as revolutionizing product development and manufacturing. Some have even gone on to say that manufacturing, as we know it today, may not exist if we follow AM to its ultimate conclusion. We might, therefore, like to ask “why is this the case?” What is it about AM that enthuses and inspires some to make these kinds of statements?

First, let’s consider the “rapid” character of this technology. The speed advantage is not just in terms of the time it takes to build parts. The speeding up of the whole product development process relies much on the fact that we are using computers throughout. Since 3D CAD is being used as the starting point and the transfer to AM is relatively seamless, there is much less concern over data conversion or interpretation of the design intent. Just as 3D CAD is becoming What You

See Is What You Get (WYSIWYG), so it is the same with AM and we might just as easily say that What you See Is What You Build (WYSIWYB). The seamlessness can also be seen in terms of the reduction in process steps. Regardless of the complexity of parts to be built, building within an AM machine is generally performed in a single step. Most other manufacturing processes would require multiple and iterative stages to be carried out. As you include more features in a design, the number of these stages may increase dramatically. Even a relatively simple change in the design may result in a significant increase in the time required to build using conventional methods. AM can, therefore, be seen as a way to more effectively predict the amount of time to fabricate models, regardless of what changes may be implemented during this formative stage of the product development.

Similarly, the number of processes and resources required can be significantly reduced when using AM. If a skilled craftsman was requested to build a prototype according to a set of CAD drawings, he may find that he must manufacture the part in a number of stages. This may be because he must employ a variety of construction methods, ranging from hand carving, through molding and forming techniques, to CNC machining. Hand carving and similar operations are tedious, difficult, and prone to error. Molding technology can be messy and obviously requires the building of one or more molds. CNC machining requires careful planning and a sequential approach that may also require construction of fixtures before the part itself can be made. All this presupposes that these technologies are within the repertoire of the craftsman and readily available.

AM can be used to remove or at least simplify many of these multi-stage processes. With the addition of some supporting technologies like silicon-rubber molding, drills, polishers, grinders, etc. it can be possible to manufacture a vast range of different parts with different characteristics. Workshops which adopt AM technology can be much cleaner, more streamlined and more versatile than before.

DISTINCTION BETWEEN AM AND CNC MACHINING

As mentioned in the discussion on Automated Fabrication, AM shares some of its DNA with Computer Numerical Controlled machining technology. CNC is also computer-based technology that is used to manufacture products. CNC differs mainly in that it is primarily a subtractive rather than additive process, requiring a block of material that must be at least as big as the part that is to be made. This section discusses a range of topics where comparisons between CNC machining and AM can be made. The purpose is not really to influence choice of one technology over another rather than to establish how they may be

implemented for different stages in the product development process, or for different types of products.

- **MATERIAL**

AM technology was originally developed around polymeric materials, waxes and paper laminates. Subsequently, there has been introduction of composites, metals, and ceramics. CNC machining can be used for soft materials, like medium-density fibreboard (MDF), machinable foams, machinable waxes, and even some polymers. However, use of CNC to shape softer materials is focused on preparing these parts for use in a multistage process like casting. When using CNC machining to make final products, it works particularly well for hard, relatively brittle materials like steels and other metal alloys to produce high accuracy parts with well-defined properties. Some AM parts, in contrast, may have voids or anisotropy that are a function of part orientation, process parameters or how the design was input to the machine, whereas CNC parts will normally be more homogeneous and predictable in quality.

- **SPEED**

High speed CNC machining can generally remove material much faster than AM machines can add a similar volume of material. However, this is only part of the picture, as AM technology can be used to produce a part in a single stage. CNC machines require considerable setup and process planning, particularly as parts become more complex in their geometry. Speed must therefore be considered in terms of the whole process rather than just the physical interaction of the part material. CNC is likely to be a multistage manufacturing process, requiring repositioning or relocation of parts within one machine or use of more than one machine. To make a part in an AM machine, it may only take a few hours; and in fact, multiple parts are often batched together inside a single AM build. Finishing may take a few days if the requirement is for high quality. Using CNC machining, this same process may take weeks.

- **COMPLEXITY**

As mentioned above, the higher the geometric complexity, the greater the advantage AM has over CNC. If CNC is being used to create a part directly in a single piece, then there are some geometric features that cannot be fabricated. Since a machining tool must be carried in a spindle, there may be certain accessibility constraints or clashes preventing the tool from being located on the machining surface of a part. AM processes are not constrained in the same way and undercuts and internal features can be easily built without specific process planning. Certain parts cannot be fabricated by CNC unless they are broken up into

components and reassembled at a later stage. Consider, for example, the possibility of machining a ship inside a bottle. How would you machine the ship while it is still inside the bottle? Most likely you would machine both elements separately and work out a way to combine them together as an assembly process. With AM you can build the ship and the bottle all at once. An expert in machining must therefore analyze each part prior to it being built to ensure that it indeed can be built and to determine what methods need to be used. While it is still possible that some parts cannot be built with AM, the likelihood is much lower and there are generally ways in which this may be overcome without too much difficulty.

- **ACCURACY**

AM machines generally operate with a resolution of a few tens of microns. It is common for AM machines to also have variable resolution along different orthogonal axes. Typically, the vertical build axis corresponds to layer thickness and this would be of a lower resolution compared with the two axes in the build plane. Accuracy in the build plane is determined by the positioning of the build mechanism, which will normally involve gearboxes and motors of some kind. This mechanism may also determine the minimum feature size as well. For example, SL uses a laser as part of the build mechanism that will normally be positioned using galvanometric mirror drives. The resolution of the galvanometers would determine the overall dimensions of parts built, while the diameter of the laser beam would determine the minimum wall thickness. The accuracy of CNC machines on the other hand is mainly determined by a similar positioning resolution along all three orthogonal axes and by the diameter of the rotary cutting tools. There are factors that are defined by the tool geometry, like the radius of internal corners, but wall thickness can be thinner than the tool diameter since it is a subtractive process. In both cases very fine detail will also be a function of the properties of the build material.

- **GEOMETRY**

AM machines essentially break up a complex, 3D problem into a series of simple 2D cross-sections with a nominal thickness. In this way, the connection of surfaces in 3D is removed and continuity is determined by how close the proximity of one cross-section is with an adjacent one. Since this cannot be easily done in CNC, machining of surfaces must normally be generated in 3D space. With simple geometries, like cylinders, cuboids, cones, etc., this is a relatively easy process defined by joining points along a path; these points being quite far apart and the tool orientation being fixed. In cases of freeform surfaces, these points can become very close together with many changes in orientation. Such geometry can become

extremely difficult to produce with CNC, even with 5-axis control or greater.

Undercuts, enclosures, sharp internal corners and other features can all fail if these features are beyond a certain limit. Consider, for example, the features represented in the part in Fig. 3. Many of them would be very difficult to machine without manipulation of the part at various stages.

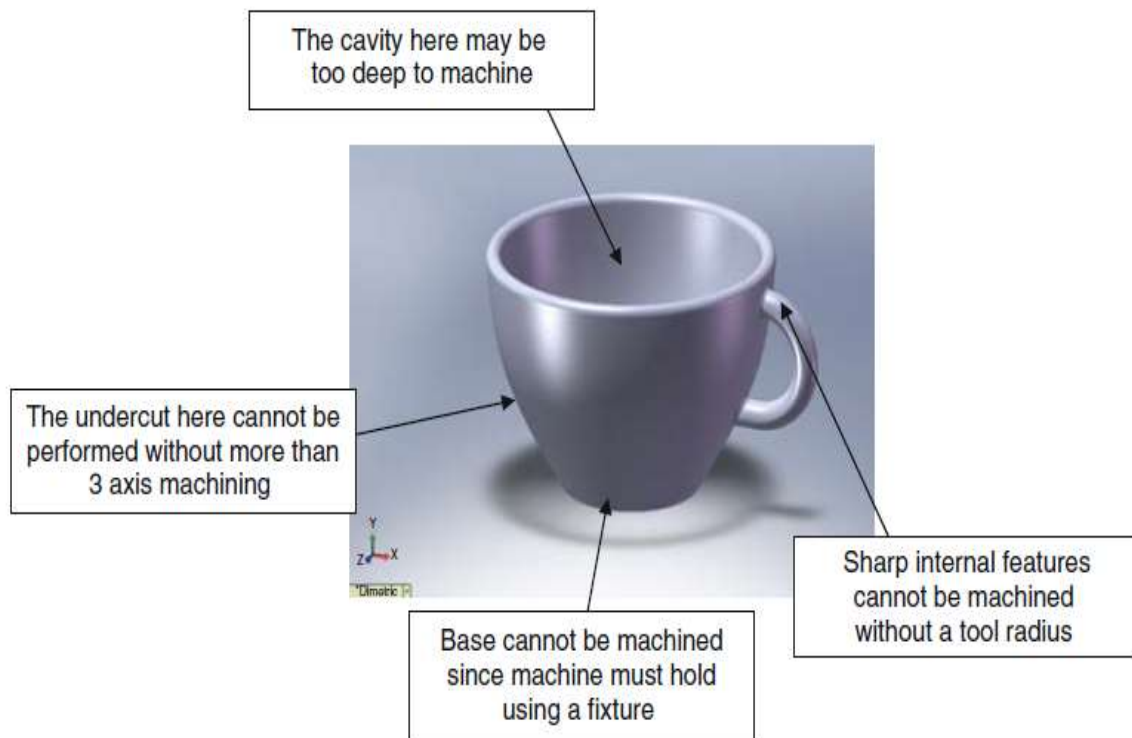


Fig. 3 Features that represent problems using CNC machining

- **PROGRAMMING**

Determining the program sequence for a CNC machine can be very involved, including tool selection, machine speed settings, approach position, and angle, etc. Many AM machines also have options that must be selected, but the range, complexity and implications surrounding their choice are minimal in comparison. The worst that is likely to happen in most AM machines is that the part will not be built very well if the programming is not done properly. Incorrect programming of a CNC machine could result in severe damage to the machine and may even be a safety risk.

OTHER RELATED TECHNOLOGIES

The most common input method for AM technology is to accept a file converted into the STL file format originally built within a conventional 3D CAD system. There are, however, other ways in which the STL files can be generated and other technologies that can be used in conjunction with AM technology. This section will describe a few of these are

1. Reverse Engineering Technology
2. Computer-Aided Engineering
3. Haptic-Based CAD

REVERSE ENGINEERING TECHNOLOGY

More and more models are being built from data generated using reverse engineering (RE) 3D imaging equipment and software. In this context, RE is the process of capturing geometric data from another object. This data is usually initially available in what is termed “point cloud” form, meaning an unconnected set of points representing the object surfaces. These points need to be connected together using RE software like Geomagic [6], which may also be used to combine point clouds from different scans and to perform other functions like hole-filling and smoothing. In many cases, the data will not be entirely complete. Samples may, for example, need to be placed in a holding fixture and thus the surfaces adjacent to this fixture may not be scanned. In addition, some surfaces may obscure others, like with deep crevices and internal features; so that the representation may not turn out exactly how the object is in reality.

Engineered objects would normally be scanned using laser-scanning or touchprobe technology. Objects that have complex internal features or anatomical models may make use of Computerized Tomography (CT), which was initially developed for medical imaging but is also available for scanning industrially produced objects. This technique essentially works in a similar way to AM, by scanning layer by layer and using software to join these layers and identify the surface boundaries. Boundaries from adjacent layers are then connected together to form surfaces. The advantage of CT technology is that internal features can also be generated. High energy X-rays are used in industrial technology to create high resolution images of around 1 mm. Another approach that can help digitize objects is the Capture Geometry Inside technology that also works very much like a reverse of AM technology, where 2D imaging is used to capture cross-sections of a part as it is machined away layer by layer. Obviously, this is a destructive approach to geometry capture so it cannot be used for every type of product. AM can be used to reproduce the articles that were scanned, which essentially would form a kind of 3D facsimile (3D Fax) process. More likely, however, the data will be modified and/or combined with other data to form complex, freeform artifacts that are taking advantage of the “complexity for free” feature of the technology. An example may be where individual patient data is combined with an engineering design to form a customized medical implant.

DEVELOPMENT OF ADDITIVE MANUFACTURING TECHNOLOGY

INTRODUCTION

Additive Manufacturing (AM) technology came about as a result of developments in a variety of different technology sectors. Like with many manufacturing technologies, improvements in computing power and reduction in mass storage costs paved the way for processing the large amounts of data typical of modern 3D Computer-Aided Design (CAD) models within reasonable time frames. Nowadays, we have become quite accustomed to having powerful computers and other complex automated machines around us and sometimes it may be difficult for us to imagine how the pioneers struggled to develop the first AM machines.

This chapter highlights some of the key moments that catalogue the development of Additive Manufacturing technology. It will describe how the different technologies converged to a state where they could be integrated into AM machines. It will also discuss milestone AM technologies. Furthermore, we will discuss how the application of Additive Manufacturing has evolved to include greater functionality and embrace a wider range of applications beyond the initial intention of just prototyping.

COMPUTERS

Like many other technologies, AM came about as a result of the invention of the computer. However, there was little indication that the first computers built in the 1940s (like the Zuse Z3, ENIAC and EDSAC computers) would change lives in the way that they so obviously have. Inventions like the thermionic valve, transistor, and microchip made it possible for computers to become faster, smaller, and cheaper with greater functionality. This development has been so quick that even Bill Gates of Microsoft was caught off-guard when he thought in 1981 that 640 kb of memory would be sufficient for any Windows-based computer. In 1989, he admitted his error when addressing the University of Waterloo Computer Science Club. Similarly in 1977, Ken Olsen of Digital Electronics Corp. (DEC) stated that there would never be any reason for people to have computers in their homes when he addressed the World Future Society in Boston.

That remarkable misjudgement may have caused Olsen to lose his job not long afterwards. One key to the development of computers as serviceable tools lies in their ability to perform tasks in real-time. In the early days, serious computational tasks took many hours or even days to prepare, run, and complete. This served as a limitation to everyday computer use and

it is only since it was shown that tasks can complete in real-time that computers have been accepted as everyday items rather than just for academics or big business. This has included the ability to display results not just numerically but graphically as well. For this we owe a debt of thanks at least in part to the gaming industry, which has pioneered many developments in graphics technology with the aim to display more detailed and more “realistic” images to enhance the gaming experience.

AM takes full advantage of many of the important features of computer technology, both directly (in the AM machines themselves) and indirectly (within the supporting technology), including:

- **Processing power:**

Part data files can be very large and require a reasonable amount of processing power to manipulate while setting up the machine and when slicing the data before building. Earlier machines would have had difficulty handling large CAD data files.

- **Graphics capability:**

AM machine operation does not require a big graphics engine except to see the file while positioning within the virtual machine space. However, all machines benefit from a good graphical user interface (GUI) that can make the machine easier to set up, operate, and maintain.

- **Machine control:**

AM technology requires precise positioning of equipment in a similar way to a Computer Numerical Controlled (CNC) machining center, or even a high-end photocopy machine or laser printer. Such equipment requires controllers that take information from sensors for determining status and actuators for positioning and other output functions. Computation is generally required in order to determine the control requirements. Conducting these control tasks even in real-time does not normally require significant amounts of processing power by today’s standards. Dedicated functions like positioning of motors, lenses, etc. would normally require individual controller modules.

A computer would be used to oversee the communication to and from these controllers and pass data related to the part build function.

- **Networking:**

Nearly every computer these days has a method for communicating with other computers around the world. Files for building would normally be designed on another computer to that running the AM machine. Earlier systems would have required the files to be loaded

from disk or tape. Nowadays almost all files will be sent using an Ethernet connection, often via the Internet.

- **Integration:**

As is indicated by the variety of functions, the computer forms a central component that ties different processes together. The purpose of the computer would be to communicate with other parts of the system, to process data, and to send that data from one part of the system to the other. Figure 4 shows how the above-mentioned technologies are integrated to form an AM machine.

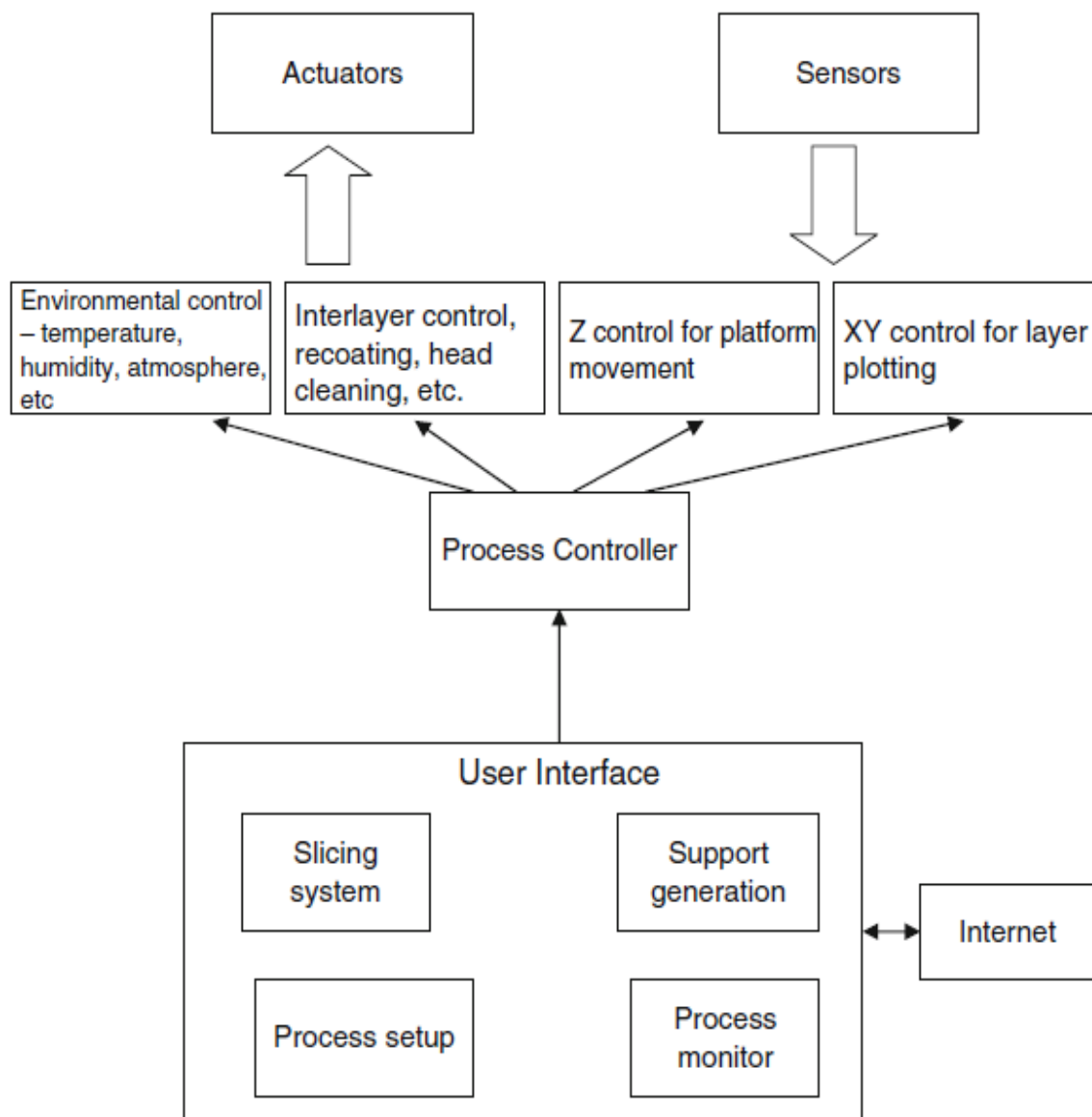


Fig. 4 General integration of an AM machine

Earlier computer-based design environments required physically large mainframe and mini computers. Workstations that generally ran the graphics and input/output functions were connected to these computers. The computer then ran the complex calculations for

manipulating the models. This was a costly solution based around the fact that the processor and memory components were very expensive elements. With the reduction in the cost of these components, Personal Computers (PCs) became viable solutions. Earlier PCs were not powerful enough to replace the complex functions that workstation-based computers could perform, but the speedy development PCs soon overcame all but the most computationally expensive requirements.

Without computers there would be no capability to display 3D graphic images. Without 3D graphics, there would be no Computer-Aided Design. Without this ability to represent objects digitally in 3D, we would have a limited desire to use machines to fabricate anything but the simplest shapes. It is safe to say, therefore, that without the computers we have today, we would not have seen Additive Manufacturing develop.

COMPUTER-AIDED DESIGN TECHNOLOGY

Today, every engineering student must learn how to use computers for many of their tasks, including the development of new designs. CAD technologies are available for assisting in the design of large buildings and of nano-scale microprocessors. CAD technology holds within it the knowledge associated with a particular type of product, including geometric, electrical, thermal, dynamic, and static behavior. CAD systems may contain rules associated with such behaviors that allow the user to focus on design and functionality without worrying too much whether a product can or cannot work. CAD also allows the user to focus on small features of a large product, maintaining data integrity and ordering it to understand how subsystems integrate with the remainder.

Additive Manufacturing technology primarily makes use of the output from mechanical engineering, 3D Solid Modeling CAD software. It is important to understand that this is only a branch of a much larger set of CAD systems and, therefore, not all CAD systems will produce output suitable for layer-based AM technology. Currently, AM technology focuses on reproducing geometric form; and so the better CAD systems to use are those that produce such forms in the most precise and effective way.

Early CAD systems were extremely limited by the display technology. The first display systems had little or no capacity to produce anything other than alphanumeric text output. Some early computers had specialized graphic output devices that displayed graphics separate from the text commands used to drive them. Even so, the geometric forms were shown primarily in a vector form, displaying wire-frame output. As well as the heavy demand on the computing power required to display the graphics for such systems, this was because most displays were monochrome, making it very difficult to show 3D geometric

forms on screen without lighting and shading effects. CAD would not have developed so quickly if it were not for the demands set by Computer-Aided Manufacture (CAM). CAM represents a channel for converting the virtual images developed in CAD into the physical products that we use in our everyday lives. It is doubtful that without the demands associated with this conversion from virtual to real that CAD would have developed so far or so quickly. This, in turn, was fuelled and driven by the developments in associated technologies, like processor, memory, and display technologies. CAM systems produce the code for numerically controlled (NC) machinery, essentially combining coordinate data with commands to select and actuate the cutting tools. Early NC technologies would take CAM data relating to the location of machined features, like holes, slots, pockets, etc. These features would then be fabricated by machining from a stock material. As NC machines proved their value in their precise, automated functionality, so the sophistication of the features increased. This has now extended to the ability to machine highly complex, freeform surfaces. However, there are two key limitations to all NC machining:

- Almost every part must be made in stages, often requiring multiple passes for material removal and setups
- All machining is performed from an approach direction (sometimes referred to as 2.5D rather than fully 3D manufacture). This requires that the stock material be held in a particular orientation and that not all the material can be accessible at any one stage in the process.

NC machining, therefore, only requires surface modeling software. All early CAM systems were based on surface modeling CAD. AM technology was the first automated computer-aided manufacturing process that truly required 3D solid modeling CAD. It was necessary to have a fully enclosed surface to generate the driving coordinates for AM. This can be achieved using surface modeling systems, but because surfaces are described by boundary curves it is often difficult to precisely and seamlessly connect these together. Even if the gaps are imperceptible, the resulting models may be difficult to build using AM. At the very least, any inaccuracies in the 3D model would be passed on to the AM part that was constructed. Early AM applications often displayed difficulties because of associated problems with surface modeling software.

Since it is important for AM systems to have accurate models that are fully enclosed, the preference is for solid modeling CAD. Solid modeling CAD ensures that all models made have a volume and, therefore, by definition are fully enclosed surfaces. While surface modeling can be used in part construction, we can not always be sure that the final model is

faithfully represented as a solid. Such models are generally necessary for Computer-Aided Engineering (CAE) tools like Finite Element Analysis (FEA), but are also very important for other CAM processes.

CAD technology has rapidly improved along the following lines:

1. Realism:

With lighting and shading effects, ray tracing and other photorealistic imaging techniques, it is becoming possible to generate images of the CAD models that are difficult to distinguish from actual photographs. In some ways, this reduces the requirements on AM models for visualization purposes.

2. Usability and user interface:

Early CAD software required the input of text-based instructions through a dialog box. Development of Windows-based graphical user interfaces (GUIs) have led to graphics-based dialogs and even direct manipulation of models within virtual 3D environments. Instructions are issued through the use of drop-down menu systems and context-related commands. To suit different user preferences and styles, it is often possible to execute the same instruction in different ways. Keyboards are still necessary for input of specific measurements, but the usability of CAD systems has improved dramatically. There is still some way to go to make CAD systems available to those without engineering knowledge or without training, however.

3. Engineering content:

Since CAD is almost an essential part of a modern engineer's training, it is vital that the software includes as much engineering content as possible. With solid modeling CAD it is possible to calculate the volumes and masses of models, investigate fits and clearances according to tolerance variations, and to export files with mesh data for Finite Element Analysis. FEA is often even possible without having to leave the CAD system.

4. Speed:

As mentioned previously, the use of NURBS assists in optimizing CAD data manipulation. CAD systems are constantly being optimized in various ways, mainly by exploiting the hardware developments of computers.

5. Accuracy:

If high tolerances are expected for a design, then it is important that calculations are precise. High precision can make heavy demands on processing time and memory.

6. Complexity:

All of the above characteristics can lead to extremely complex systems. It is a challenge to software vendors to incorporate these features without making them unwieldy and unworkable.

It is quite possible to directly manipulate the CAD file to generate the slice data that will drive an AM machine, and this is commonly referred to as direct slicing. However, this would mean every CAD system must have a direct slicing algorithm that would have to be compatible with all the different types of AM technology. Alternatively, each AM system vendor would have to write a routine for every CAD system. Both of these approaches are impractical. The solution is to use a generic format that is specific to the technology. This generic format was developed by 3D Systems, USA, who was the first company to commercialize AM technology and called the file format “STL” after their stereolithography technology (an example of which is shown in Fig 5).



Fig. 5 A CAD model on the left converted into STL format on the right

The STL file format was made public domain to allow all CAD vendors to access it easily and hopefully integrate it into their systems. This strategy has been successful and STL is now a standard output for nearly all solid modeling CAD systems and has also been adopted by AM system vendors. STL uses triangles to describe the surfaces to be built. Each triangle is described as three points and a facet normal vector indicating the outward side of the triangle, in a manner similar to the following:

facet normal _4.470293E_02 7.003503E_01 _7.123981E-01

outer loop

vertex _2.812284E+00 2.298693E+01 0.000000E+00

vertex _2.812284E+00 2.296699E+01 _1.960784E_02

vertex _3.124760E+00 2.296699E+01 0.000000E+00

endloop

endfacet

The demands on CAD technology in the future are set to change with respect to AM. As we move toward more and more functionality in the parts produced by AM, we must understand that the CAD system must include rules associated with AM. To date, the focus has been on the external geometry. In the future, we may need to know rules associated with how the AM systems function so that the output can be optimized.

OTHER ASSOCIATED TECHNOLOGIES

Aside from computer technology there are a number of other technologies that have developed along with AM that are worthy of note here since they have served to contribute to further improvement of AM systems.

1. LASERS

Many of the earliest AM systems were based on laser technology. The reasons are that lasers provide a high intensity and highly collimated beam of energy that can be moved very quickly in a controlled manner with the use of directional mirrors. Since AM requires the material in each layer to be solidified or joined in a selective manner, lasers are ideal candidates for use, provided the laser energy is compatible with the material transformation mechanisms. There are two kinds of laser processing used in AM; curing and heating. With photopolymer resins the requirement is for laser energy of a specific frequency that will cause the liquid resin to solidify, or “cure.” Usually this laser is in the ultraviolet range but other frequencies can be used. For heating, the requirement is for the laser to carry sufficient thermal energy to cut through a layer of solid material, to cause powder to melt, or to cause sheets of material to fuse. For powder processes, for example, the key is to melt the material in a controlled fashion without creating too great a build-up of heat; so that when the laser energy is removed, the molten material rapidly solidifies again. For cutting, the intention is to separate a region of material from another in the form of laser cutting. Earlier AM machines used tube lasers to provide the required energy but many manufacturers have more recently switched to solid-state technology, which provides greater efficiency, lifetime, and reliability.

2. PRINTING TECHNOLOGIES

Ink-jet or droplet printing technology has rapidly developed in recent years. Improvements in resolution and reduction in costs has meant that high-resolution printing, often with multiple colors, is available as part of our everyday lives. Such improvement in resolution has also been supported by improvement in material handling capacity and reliability. Initially, colored inks were low viscosity and fed into the print heads at ambient temperatures. Now it is possible to generate much higher pressures within the droplet

formation chamber so that materials with much higher viscosity and even molten materials can be printed. This means that droplet deposition can now be used to print photocurable and molten resins as well as binders for powder systems. Since print heads are relatively compact devices with all the droplet control technology highly integrated into these heads (like the one shown in Fig.6), it is possible to produce low-cost, high-resolution, high-throughput AM technology. In the same way that other AM technologies have applied the mass-produced laser technology, other technologies have piggy-backed upon the larger printing industry.

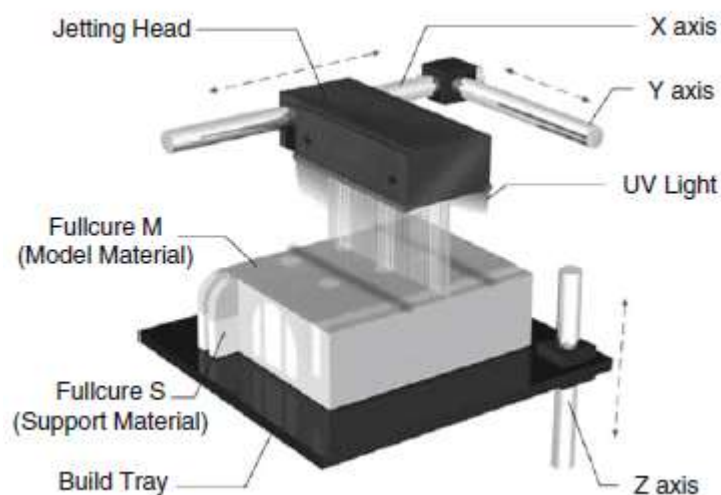


Fig. 6 Printer technology used on an AM machine (photo courtesy of Object)

3. Programmable Logic Controllers

The input CAD models for AM are large data files generated using standard computer technology. Once they are on the AM machine, however, these files are reduced to a series of process stages that require sensor input and signaling of actuators. This is process and machine control that often is best carried out using microcontroller systems rather than microprocessor systems. Industrial microcontroller systems form the basis of Programmable Logic Controllers (PLCs), which are used to reliably control industrial processes. Designing and building industrial machinery, like AM machines, is much easier using building blocks based around modern PLCs for coordinating and controlling the various steps in the machine process.

4. Materials

Earlier AM technologies were built around materials that were already available and that had been developed to suit other processes. However, the AM processes are somewhat unique and these original materials were far from ideal for these new applications. For example, the early photocurable resins resulted in models that were brittle and that warped

easily. Powders used in laser melting processes degraded quickly within the machine and many of the materials used resulted in parts that were quite weak. As we came to understand the technology better, materials were developed specifically to suit AM processes. Materials have been tuned to suit more closely the operating parameters of the different processes and to provide better output parts. As a result, parts are now much more accurate, stronger, and longer lasting and it is even possible to process metals with some AM technologies.

In turn, these new materials have resulted in the processes being tuned to produce higher temperature materials, smaller feature sizes, and faster throughput.

5. Computer Numerically Controlled Machining

One of the reasons AM technology was originally developed was because CNC technology was not able to produce satisfactory output within the required time frames. CNC machining was slow, cumbersome, and difficult to operate. AM technology on the other hand was quite easy to set up with quick results, but had poor accuracy and limited material capability. As improvements in AM technologies came about, vendors of CNC machining technology realized that there was now growing competition. CNC machining has dramatically improved, just as AM technologies have matured. It could be argued that high-speed CNC would have developed anyway, but some have argued that the perceived threat from AM technology caused CNC machining vendors to rethink how their machines were made. The development of hybrid prototyping technologies, such as Space Puzzle Molding that use both high-speed machining and additive techniques for making large, complex and durable molds and components, as shown in Fig.7 illustrate how the two can be used interchangeably to take advantage of the benefits of both technologies.

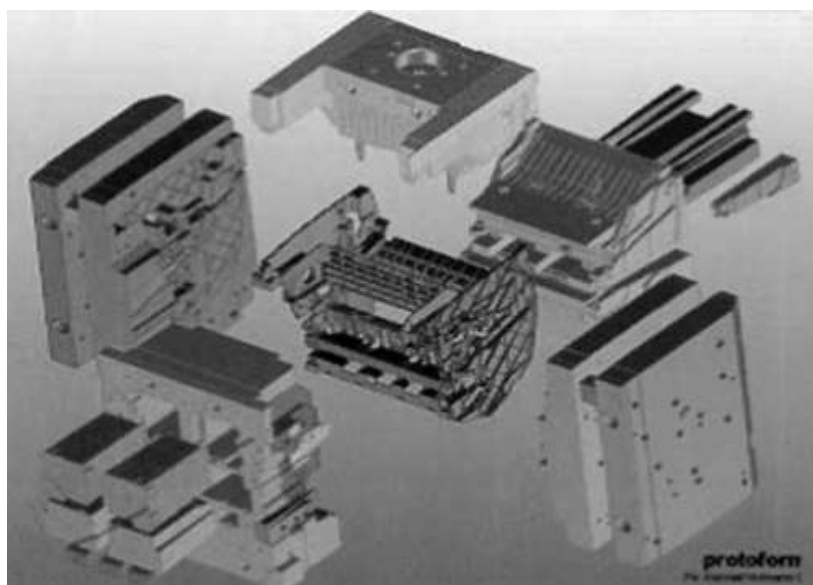


Fig. 7 Space Puzzle Molding, where molds are constructed in segments for fast and easy fabrication and assembly

For geometries that can be machined using a single set-up orientation, CNC machining is often the fastest, most cost-effective method. For parts with complex geometries or parts which require a large proportion of the overall material volume to be machined away as scrap, AM can be used to more quickly and economically produce the part than when using CNC.

THE USE OF LAYERS

A key enabling principle of AM part manufacture is the use of layers as finite 2D cross-sections of the 3D model. Almost every AM technology builds parts using layers of material added together; and certainly, all commercial systems work that way, primarily due to the simplification of building 3D objects. Using 2D representations to represent cross-sections of a more complex 3D feature has been used in many applications outside AM. The most obvious example of this is how cartographers use a line of constant height to represent hills and other geographical reliefs. These contour lines, or iso-heights, can be used as plates that can be stacked to form representations of geographical regions. The gaps between these 2D cross sections cannot be precisely represented and are therefore approximated, or interpolated, in the form of continuity curves connecting these layers. Such techniques can also be used to provide a 3D representation of other physical properties, like isobars or isotherms on weather maps.

Architects have also used such methods to represent landscapes of actual or planned areas, like that used by an architect firm in Fig.8

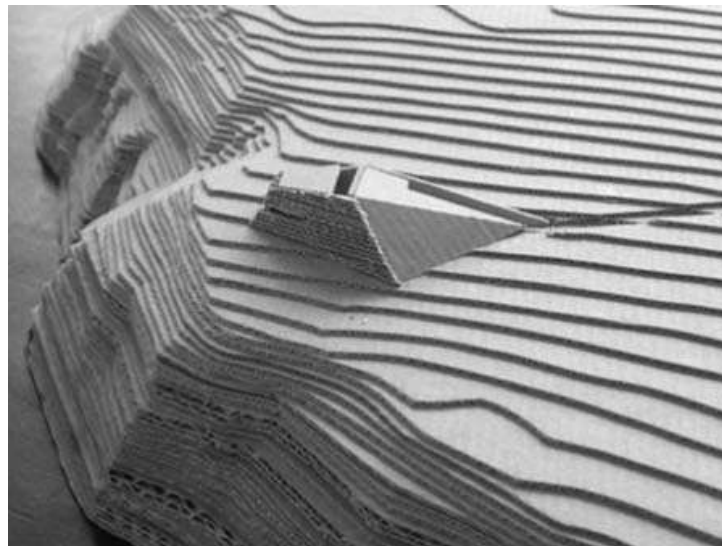


Fig. 8 An architectural landscape model, illustrating the use of layers

The concept is particularly logical to manufacturers of buildings who also use an additive approach, albeit not using layers. Consider how the pyramids in Egypt and in South America

were created. Notwithstanding how they were fabricated, it's clear that they were created using a layered approach, adding material as they went.

CLASSIFICATION OF AM PROCESSES

There are numerous ways to classify AM technologies. A popular approach is to classify according to baseline technology, like whether the process uses lasers, printer technology, extrusion technology, etc. Another approach is to collect processes together according to the type of raw material input. The problem with these classification methods is that some processes get lumped together in what seems to be odd combinations (like Selective Laser Sintering being grouped together with 3D Printing) or that some processes that may appear to produce similar results end up being separated (like Stereolithography and Object). It is probably inappropriate, therefore, to use a single classification approach. An excellent and comprehensive classification method is described by Pham, which uses a two-dimensional classification method as shown in Fig. 9.

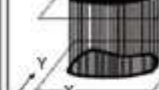
	1D Channel	2x1D Channels	Array of 1D Channels	2D Channel
Liquid Polymer	 SLA (3D Sys)	 Dual beam SLA (3D Sys)	 Objet	 Envisiontech MicroTEC
Discrete Particles	SLS (3D Sys), LST (EOS), LENS Phenix, SDM	LST (EOS)	3D Printing	DPS
Molten Mat.	FDM, Solidscape		ThermoJet	
Solid Sheets	Solido PLT (KIRA)			

Fig. 9 Layered Manufacturing (LM) processes as classified by Pham

The first dimension relates to the method by which the layers are constructed. Earlier technologies used a single point source to draw across the surface of the base material. Later systems increased the number of sources to increase the throughput, which was made possible with the use of droplet deposition technology, for example, which can be constructed into a one-dimensional array of deposition heads. Further throughput improvements are possible with the use of 2D array

technology using the likes of Digital Micro-mirror Devices (DMDs) and high resolution display technology, capable of exposing an entire surface in a single pass. However, just using this classification results in the previously mentioned anomalies where numerous

dissimilar processes are grouped together. This is solved by introducing a second dimension of raw material to the classification.

Pham uses four separate material classifications; liquid polymer, discrete particles, molten material, and laminated sheets. Some more exotic systems mentioned in this book may not fit directly into this classification. An example is the possible deposition of composite material using an extrusion-based technology. This fits well as a 1D channel but the material is not explicitly listed, although it could be argued that the composite is extruded as a molten material. Furthermore, there may come systems in the future that use 3D holography to project and fabricate complete objects in a single pass. As with many classifications, there can sometimes be processes or systems that lie outside them. If there are sufficient systems to warrant an extension to this classification, then it should not be a problem.

It should be noted that, in particular 1D and 2*1D channel systems combine both vector and raster-based scanning methods. Often, the outline of a layer is traced first before being filled in with regular or irregular scanning patterns. The outline is generally referred to as vector scanned while the fill pattern can often be generalized as a raster pattern. The array methods tend not to separate the outline and the fill.

Most AM technology started using a 1D channel approach, although one of the earliest and now obsolete technologies, Solid Ground Curing from Cubital, used liquid photopolymers and essentially (although perhaps arguably) a 2D channel method. As technology developed, so more of the boxes in the classification array began to be filled. The empty boxes in this array may serve as a guide to researchers and developers for further technological advances.

1. Liquid Polymer Systems
2. Discrete Particle Systems
3. Molten Material Systems
4. Solid Sheet Systems
5. New AM Classification Schemes

METAL SYSTEMS

One of the most important recent developments in AM has been the proliferation of direct metal processes. Machines like the EOSint-M and Laser-Engineered Net Shaping (LENS) have been around for a number of years. Recent additions from other companies and improvements in laser technology, machine accuracy, speed, and cost have opened up this market.

Most direct metal systems work using a point-wise method and nearly all of them utilize metal powders as input. The main exception to this approach is the sheet lamination approaches, particularly the Ultrasonic Consolidation process from the Solidica, USA, which uses sheet metal laminates that are ultrasonically welded together. Of the powder systems, almost every newer machine uses a powder spreading approach similar to the Selective Laser Sintering process, followed by melting using an energy beam. This energy is normally a high-power laser, except in the case of the Electron Beam Melting (EBM) process by the Swedish company Arcam. Another approach is the LENS powder delivery system used by Optomec. This machine employs powder delivery through a nozzle placed above the part. The powder is melted where the material converges with the laser and the substrate. This approach allows the process to be used to add material to an existing part, which means it can be used for repair of expensive metal components that may have been damaged, like chipped turbine blades and injection mold tool inserts.

HYBRID SYSTEMS

Some of the machines described above are, in fact, hybrid additive/subtractive processes rather than purely additive. Including a subtractive component can assist in making the process more precise. An example is the use of planar milling at the end of each additive layer in the Sanders and object machines. This stage makes for a smooth planar surface onto which the next layer can be added, negating cumulative effects from errors in droplet deposition height.

It should be noted that when subtractive methods are used, waste will be generated. Machining processes require removal of material that in general cannot easily be recycled. Similarly, many additive processes require the use of support structures and these too must be removed or “subtracted.”

It can be said that with the object process, for instance, the additive element is dominant and that the subtractive component is important but relatively insignificant. There have been a number of attempts to merge subtractive and additive technologies together where the subtractive component is the dominant element.

An excellent example of this is the Strat conception approach, where the original CAD models are divided into thick machinable layers. Once these layers are machined, they are bonded together to form the complete solid part. This approach works very well for very large parts that may have features that would be difficult to machine using a multi-axis machining center due to the accessibility of the tool. This approach can be applied to foam

and wood-based materials or to metals. For structural components it is important to consider the bonding methods.

For high strength metal parts diffusion bonding may be an alternative. A lower cost solution that works in a similar way is Subtractive RP (SRP) from Roland, who is also famous for plotter technology. SRP makes use of Roland desktop milling machines to machine sheets of material that can be sandwiched together, similar to Strat conception. The key is to use the exterior material as a frame that can be used to register each slice to others and to hold the part in place. With this method not all the material is machined away and a web of connecting spars are used to maintain this registration.

Another variation of this method that was never commercialized was Shaped Deposition Manufacturing (SDM), developed mainly at Stanford and Carnegie- Mellon Universities in the USA. With SDM, the geometry of the part is devolved into a sequence of easier to manufacture parts that can in some way be combined together. A decision is made concerning whether each subpart should be manufactured using additive or subtractive technology dependent on such factors as the accuracy, material, geometrical features, functional requirements, etc. Furthermore, parts can be made from multiple materials, combined together using a variety of processes, including the use of plastics, metals and even ceramics. Some of the materials can also be used in a sacrificial way to create cavities and clearances.

Additionally, the “layers” are not necessarily planar, nor constant in thickness. Such a system would be unwieldy and difficult to realize commercially, but the ideas generated during this research have influenced many studies and systems thereafter.

MILESTONES IN AM DEVELOPMENT

We can look at the historical development of AM in a variety of different ways. The origins may be difficult to properly define and there was certainly quite a lot of activity in the 1950s and 1960s, but development of the associated technology (computers, lasers, controllers, etc.) caught up with the concept in the early 1980s.

Interestingly, parallel patents were filed in 1984 in Japan (Murutani), France (Andre et al.) and in the US (Masters in July and Hull in August). All of these patents described a similar concept of fabricating a 3D object by selectively adding material layer by layer. While earlier work in Japan is quite well-documented, proving that this concept could be realized, it was the patent by Charles Hull that is generally recognized as the most influential since it

gave rise to 3D Systems. This was the first company to commercialize AM technology with the Stereolithography apparatus (Fig.10).



Fig. 10 The first AM technology from Hull, who founded 3D systems

Further patents came along in 1986, resulting in three more companies, Helisys (Laminated Object Manufacture or LOM), Cubital (with Solid Ground Curing, SGC), and DTM with their Selective Laser Sintering (SLS) process. It's interesting to note neither Helisys or Cubital exist anymore, and only SLS remains as a commercial process with DTM merging with 3D Systems in 2001. In 1989, Scott Crump patented the Fused Deposition Modeling (FDM) process, forming the Stratasys Company. Also in 1989 a group from MIT patented the 3D Printing (3DP) process. These processes from 1989 are heavily used today, with FDM variants currently being the most successful. Rather than forming a company, the MIT group licensed the 3DP technology to a number of different companies, who applied it in different ways to form the basis for different applications of their AM technology. The most successful of these is ZCorp, which focuses mainly on lowcost technology.

Ink-jet technology has become employed to deposit droplets of material directly onto a substrate, where that material hardens and becomes the part itself rather than just as a binder. Sanders developed this process in 1994 and the Objet Company also used this technique to print photocurable resins in droplet form in 2001. There have been numerous failures and successes in AM history, with the previous paragraphs mentioning only a small number. However, it is interesting to note that some technology may have failed because of poor business models or by poor timing rather than having a poor process. Helisys appears to have failed with their LOM machine, but there have been at least four variants from Singapore, China, Japan, and Israel. The most recent Solido process laminates polymer sheets together rather than the paper sheets used in the original LOM machine. Perhaps this

is a better choice of material and perhaps the technology is in a better position to become successful now compared with the original machines that are 20-years old. Another example may be the defunct Ballistic Particle Manufacturing process, which used a 5-axis mechanism to direct wax droplets onto a substrate. Although no company currently uses such an approach for polymers, similar 5-axis deposition schemes are being used for depositing metal.

ADDITIVE MANUFACTURING PROCESS CHAIN

INTRODUCTION

Every product development process involving an Additive Manufacturing machine requires the operator to go through a set sequence of tasks. Easy-to-use “desktop” or “3D printing” machines emphasize the simplicity of this task sequence. These desktop machines are characterized by their low cost, simplicity of use, and ability to be placed in an office environment. For these machines each step is likely to have few options and require minimal effort. However, this also means that there are generally fewer choices, with perhaps a limited range of materials and other variables to experiment with. The larger and more versatile machines are more capable of being tuned to suit different user requirements and therefore are more difficult to operate, but with a wider variety of possible results and effects that may be put to good use by an experienced operator. Such machines also usually require more careful installation in workshop environments. The objective is to allow the reader to understand how these machines may differ and also to see how each task works and how it may be exploited to the benefit of higher quality results.

THE EIGHT STEPS IN ADDITIVE MANUFACTURE

This above-mentioned sequence of steps is generally appropriate to all AM technologies. There will be some variations dependent on which technology is being used and also on the design of the particular part. Some steps could be quite involved for some machines but may be trivial for others. While most of the initial discussion below is with respect to production of polymer parts, most steps can be generalized to metal systems as well.

Step 1: Conceptualization and CAD

The first step in any product development process is to come up with some idea as to how the product will look and function. Conceptualization can take many forms, from textual and narrative descriptions to sketches and representative models. If AM is to be used, the product description must be in a form that allows a physical model to be made. It may be that AM technology will not be used to realize the final product, but for complex products

there are likely to be many stages in the development process where models can be used. For these purposes it is therefore important that the model description be entered into a computer. AM technology would not exist if it were not for 3D CAD. Only after we gained the ability to represent solid objects in computers were we able to develop technology to physically reproduce such objects. Initially, this was the principle surrounding CNC machining technology in general. AM can thus be described as a direct or streamlined Computer Aided Design to Computer Aided Manufacturing (CAD/CAM) process. Unlike most other CAD/CAM technologies, there is little or no intervention between the design and manufacturing stages for AM.

The generic AM process must therefore start with 3D CAD information, as shown in Fig. 11. There may be a variety of ways as to how the 3D source data can be created. This model description could be generated by a computer user, using a user-interface, or via reverse engineering technologies. Most 3D CAD systems are solid modeling systems with some surface modeling components. That is to say that solid models are sometimes constructed by combining surfaces together or by adding thickness to a surface. In the past, 3D CAD modeling software had difficulty creating fully enclosed solid models, and often models would appear to the casual observer to be enclosed but in fact were not. Such models could result in unpredictable output from AM machines, with different AM technologies treating gaps in different ways.

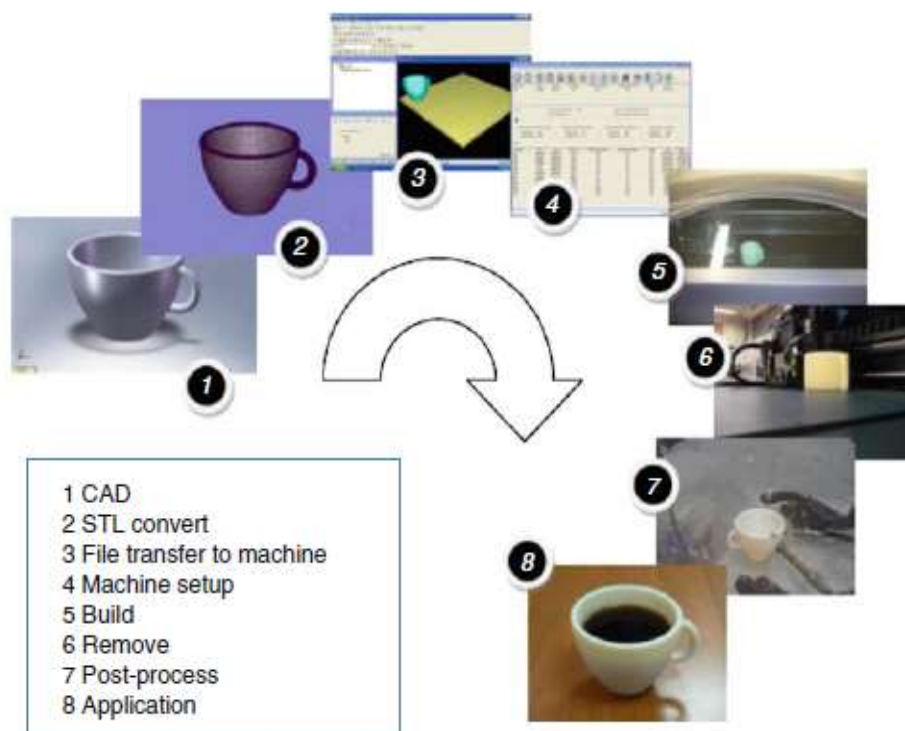


Fig. 11 The eight stages of the AM process

Today, CAD software has developed to the extent that there are very few problems with surface discontinuities, with extensive checking and correction software built in to most systems. Most CAD packages treat surfaces as construction tools that are used to act on solid models and this has the effect of maintaining the integrity of the solid data. Provided it can fit inside the machine, typically any CAD model can be made using AM technology without too many difficulties.

However, there still remains some older or poorly developed 3D CAD software that may result in solids that are not fully enclosed and produce unreliable AM output. Problems of this manner are normally detected once the CAD model has been converted into the STL format for building using AM technology.

Step 2: Conversion to STL

Nearly every AM technology uses the STL file format. The term STL was derived from STereoLithography, which was the first commercial AM technology from 3D Systems in the 1990s. Considered a de facto standard, STL is a simple way of describing a CAD model in terms of its geometry alone. It works by removing any construction data, modeling history, etc., and approximating the surfaces of the model with a series of triangular facets. The minimum size of these triangles can be set within most CAD software and the objective is to ensure the models created do not show any obvious triangles on the surface. The triangle size is in fact calculated in terms of the minimum distance between the plane represented by the triangle and the surface it is supposed to represent. In other words, a basic rule of thumb is to ensure that the minimum triangle offset is smaller than the resolution of the AM machine. The process of converting to STL is automatic within most CAD systems, but there is a possibility of errors occurring during this phase. There have therefore been a number of software tools developed to detect such errors and to rectify them if possible.

STL file repair software, like the MAGICS software from the Belgian company Materialise, is used when there are problems with the file generated by the CAD system that may prevent the part from being built correctly. With complex geometries, it may be difficult to detect such problems when inspecting the CAD or the subsequently generated STL data. If the errors are small then they may even go unnoticed until after the part has been built. Such software may therefore be applied as a checking stage to ensure that there are no problems with the STL file data before the build is performed.

Since STL is essentially a surface description, the corresponding triangles in the files must be pointing in the correct direction; in other words, the surface normal vector associated with the triangle must indicate which side of the triangle is outside vs. inside the part. The

cross-section that corresponds to the part layers of a region near an inverted normal vector may therefore be the inversion of what is desired.

Additionally, complex and highly discontinuous geometry may result in triangle vertices that do not align correctly. This may result in gaps in the surface. Various AM technologies may react to these problems in different ways. Some machines may process the STL data in such a way that the gaps are bridged. This bridge may not represent the desired surface, however, and it may be possible that additional, unwanted material may be included in the part.

While most errors can be detected and rectified automatically, there may also be a requirement for manual intervention. Software should therefore highlight the problem, indicating what is thought to be inverted triangles for instance. Since geometries can become very complex, it may be difficult for the software to establish whether the result is in fact an error or something that was part of the original design intent.

Step 3: Transfer to AM Machine and STL File Manipulation

Once the STL file has been created, it can be sent directly to the target AM machine. Ideally, it should be possible to press a “print” button and the machine should build the part straight away. This is not usually the case however and there may be a number of actions required prior to building the part.

The first task would be to verify that the part is correct. AM system software normally has a visualization tool that allows the user to view and manipulate the part. The user may wish to reposition the part or even change the orientation to allow it to be built at a specific location within the machine. It is quite common to build more than one part in an AM machine at a time. This may be multiples of the same part (thus requiring a copy function) or completely different STL files. STL files can be linearly scaled quite easily. Some applications may require the AM part to be slightly larger or slightly smaller than the original to account for process shrinkage or coatings; and so, scaling may be required prior to building. Applications may also require that the part be identified in some way and some software tools have been developed to add text and simple features to STL formatted data for this purpose. This would be done in the form of adding 3D embossed characters. More unusual cases may even require segmentation of STL files (e.g., for parts that may be too large) or even merging of multiple STL files. It should be noted that not all AM machines will have all the functions mentioned here, but numerous STL file manipulation software tools are available for purchase or, in some cases, for free download.

Step 4: Machine Setup

All AM machines will have at least some setup parameters that are specific to that machine or process. Some machines are only designed to run perhaps one or two different materials and with no variation in layer thickness or other build parameters.

These types of machine will have very few setup changes to make from build to build. Other machines are designed to run with a variety of materials and may also have some parameters that require optimization to suit the type of part that is to be built, or permit parts to be built quicker but with poorer layer resolution, for example. Such machines can have numerous setup options available. It is common in the more complex cases to have default settings or save files from previously defined setups to help speed up the machine setup process and to prevent mistakes being made. Normally, an incorrect setup procedure will still result in a part being built. The final quality of that part may, however, be unacceptable.

Step 5: Build

Although benefitting from the assistance of computers, the first few stages of the AM process are semi-automated tasks that may require considerable manual control, interaction, and decision making. Once these steps are completed, the process switches to the computer-controlled building phase. This is where the previously mentioned layer-based manufacturing takes place. All AM machines will have a similar sequence of layer control, using a height adjustable platform, material deposition, and layer cross-section formation. Some machines will combine the material deposition and layer formation simultaneously while others will separate them. All machines will repeat the process until either the build is complete or there is no source material remaining. In either case, the machine will alert the user to take action.

Step 6: Removal and Clean up

Ideally, by this stage the output from the AM machine should be ready for use. While sometimes this may be the case, more often than not parts will still require a significant amount of manual finishing before they are ready for use. In all cases, the part must be either separated from a build platform on which the part was produced or removed from excess build material surrounding the part. Some AM processes use additional material other than that used to make the part itself (secondary support materials). This material will be used to aid the building process in some way. Later descriptions of the AM processes will discuss the need for these support structures to help keep the part from collapsing or warping during the building process. At this stage, it is not necessary to understand exactly how support structures work, but it is necessary to know that they need to be dealt with. While some

processes have been developed to produce easy-to-remove supports, there is still often a significant amount of manual work required at this stage. There is also a degree of manual skill required since mishandling of parts and poor technique in support removal can result in a low quality output. Different AM parts have different cleanup requirements, but suffice it to say that all processes have some requirement at this stage. The cleanup stage may also be considered as the initial part of the post-processing stage.

Step 7: Post-process

Post-processing refers to the (usually manual) stages of finishing the parts for application purposes. This may involve abrasive finishing, like polishing and sandpapering, or application of coatings. This stage in the process is very application-specific. Some applications may only require a minimum of postprocessing; taking advantage of the speed at which the parts are made. Other applications may require very careful handling of the parts to maintain good precision and finish. Different AM processes have different results in terms of accuracy and material properties. Some processes produce relatively fragile components that may require the use of infiltration and/or surface coatings to strengthen the final part. As already stated, this is primarily a manual task due to the complexity of most AM parts. However, some of the tasks can benefit from the use of power tools and additional equipment, like polishing tubs or drying and baking ovens.

Step 8: Application

Following post-processing, parts are ready for use. It should be noted that, although parts may be made from similar materials to those available from other manufacturing processes (like molding and casting), parts may not behave according to standard material specifications. Some AM processes inherently create parts with small voids or bubbles trapped inside them, which could be the source for part failure under mechanical stress. In addition, some processes may cause the material to degrade during build or for materials not to bond, link, or crystallize in an optimum way. In almost every case, the properties are anisotropic (different properties in different direction). This may result in parts that behave differently than if they were made using a more conventional manufacturing approach. However, AM materials and processes are improving all the time, and many applications do not require high performance from many of their components. The number of applications for the output from AM processes is therefore constantly increasing.

VARIATIONS FROM ONE AM MACHINE TO ANOTHER

The above generic process steps can be applied to every commercial AM technology. As has been noted, different technologies may require more or less attention for a number of these stages. Here we discuss the implications of these variations, not only from process to process but also in some cases within a specific technology.

The nominal layer thickness for most machines is around 0.1 mm. However, it should be noted that this is just a rule of thumb. For example, the layer thickness for most FDM Dimension machines is 0.254 mm. Contrast that with standard layer thicknesses between 0.05 and 0.1 mm for SL technology. Many technologies have the capacity to vary the layer thickness. The reasoning is that thicker layer parts are quicker to build but are less precise. This may not be a problem for some applications where it may be more important to make the parts as quickly as possible.

Fine detail in a design may cause problems with some AM technologies, such as wall thickness; particularly if there is no choice but to build the part vertically. This is because even though positioning within the machine may be very precise, there is a finite dimension to the droplet size, laser diameter, or extrusion head that essentially defines the finest detail or thinnest wall that can be fabricated.

There are other factors that may not only affect the choice of process but also influence some of the steps in the process chain. In particular, the use of different materials even within the same process may affect the time, resources, and skill required to carry out a stage. For example, the use of water soluble supports in FDM may require specialist equipment but will also provide better finish to parts with less hand finishing required than when using conventional supports. Alternatively, some polymers require special attention, like the use (or avoidance) of particular solvents or infiltration compounds. A number of processes benefit from application of sealants or even infiltration of liquid polymers. These materials must be compatible with the part material both chemically and mechanically. Post-processing that involves heat must include awareness of the heat resistance or melting temperature of the materials involved. Abrasive or machining-based processing must also require knowledge of the mechanical properties of the materials involved. If considerable finishing is required, it may also be necessary to include an allowance in the part geometry, perhaps by using scaling of the STL file or offsetting of the part's surfaces, so that the part does not become worn away too much.

Variations between AM technologies will become clarified further in the following chapters, but a general understanding can be had by considering whether the build material is

processed as a powder, molten material, solid sheet, vat of liquid photopolymer, or ink-jet deposited photopolymer.

METAL SYSTEMS

As previously mentioned, operation of metal-based AM systems is conceptually similar to polymer systems. However, the following points are worth considering.

i. The Use of Substrates

Most metal systems make use of a base platform or substrate onto which parts are built and from which they must be removed using machining, wire cutting, or a similar method. The need to attach the parts to a base platform is mainly because of the high temperature gradients between the temporarily molten material and its surroundings. If the material did not adhere to a solid platform then there would be a tendency for the part to warp as it cools, which means further layers of powder cannot be spread evenly. Therefore, even though these are mainly powder-based systems, there is still a need for supports.

ii. Energy Density

The energy requirements for melting metals to over 1,000_C is obviously much higher than heating polymers to around 200_C. Heat shielding, insulation, temperature control, and atmospheric control are much more stringent than in the lower cost polymer systems.

iii. Weight

Metal powder systems may process lightweight titanium powders but they also process high-density tool steels. The powder handling technology must be capable of withstanding the mass of these materials. This means that power requirements for positioning and handling equipment must be quite substantial or gear ratios must be high (and corresponding travel speeds lower) to deal with these tasks.

iv. Accuracy

Metal powder systems are generally at least as accurate as corresponding polymer powder systems. Surface finish is characteristically grainy but part density and part accuracy are very good. Surface roughness is in the order of a few tens to a few hundreds of microns depending on the process and can be likened in general appearance to precision casting technology. For metal parts, this is often not satisfactory and at least some shot-peening is required to smooth the surface. Key mating features on metal parts often require surface machining or grinding. The part density will be high (generally over 99%), although some voids may still be seen.

v. Speed

Since there are heavy requirements on the amount of energy to melt the powder particles and to handle the powders within the machine, the build speed is generally slower than a comparable sized polymer system. Laser powers are not excessively high, usually just a few hundred watts (polymer systems start at around 50 watts of laser power). This means that the laser scanning speed is quite low to ensure enough energy is delivered to the powder.

MAINTENANCE OF EQUIPMENT

While numerous stages in the AM process have been discussed, it is important to realize that many machines require careful maintenance. Some machines use fragile laser or printer technology that must be carefully monitored and that should preferably not be used in a dirty or noisy (both electrical noise and mechanical vibration) environment. Similarly, many of the feed materials require careful handling and should be used in low humidity conditions. While machines are designed to operate unattended, it is important to include regular checks in the maintenance schedule. As indicated earlier, AM processes fall outside of many materials and process standards. However, many machine vendors recommend and provide test patterns that should be used periodically to confirm that the machines are operating within acceptable limits.

Laser-based systems are generally expensive because of the cost of the laser itself. Furthermore, maintenance of a laser can be very expensive since the expected lifetime can be as low as 4,000 operating hours for tube lasers and up to more than 15,000 h for solid state lasers. Printheads are also components that have finite lifetimes for the printer-based systems. The fine nozzle dimensions and the use of relatively high viscosity fluids mean they are quite prone to clogging and contamination effects. Replacement costs are, however, generally quite low.

MATERIALS HANDLING ISSUES

In addition to the machinery, AM materials often require careful handling. The raw materials used in some AM processes have limited shelf-life and must also be kept in conditions that prevent them from chemical reaction or degradation. Exposure to moisture and to excess light should be avoided. Most processes use materials that can be used for more than one build. However, it may be that this could degrade the material if used many times over and therefore a procedure for maintaining consistent material quality through recycling should also be observed.

While there are some health concerns with extended exposure to some photopolymer resins, most AM polymer raw materials are safe to handle. Powder materials may in general be medically inert, but excess amounts of powder can make the workplace slippery, contaminate mechanisms, etc. This may cause particular problems if machines are to be used in a design center environment rather than in a workshop. AM system vendors have spent considerable effort to simplify and facilitate material handling. Loading new materials is now often a procedure that can be done offline or with minimal changeover time so that machines can run continuously. Software systems are often tuned to the materials so that they can recognize different materials and adjust build parameters accordingly.

Many materials are carefully tuned to work with a specific AM technology. There are often warranty issues surrounding the use of third party materials that users should be aware of since there is a potential danger to the equipment or reduction in part quality. For example, SLS powders may have additives that prevent degradation due to oxidation since they are kept at elevated temperatures for long periods of time. Also, FDM filaments are extruded to a very tight diametric tolerance not normally available from conventional extruders. Since the FDM material drive pushes the filament through the machine, variations in diameter may cause slippage. Furthermore, build parameters are designed around the standard materials used. Since there are huge numbers of material formulations, changing one material for another, even though they are apparently the same, may still require careful build setup.

Some machines allow the user to recycle some or all of the material from a build that did not form the earlier part. This is particularly true with the powder-based systems. Also SL resins can be reused. However, there may be artifacts and other contaminants in the recycled materials and it is important to carefully inspect, sift, or sieve the material before returning it to the machine. Many SLS builds have been spoiled, for example, by hairs that have come off a paintbrush used to clean the parts from a previous build.

DESIGN FOR AM

Designers and operators should consider a number of build-related factors when considering the set-up of an AM, including the following sections.

1. Part Orientation

If a cylinder was built on its end, then it would consist of a series of circular layers built on top of each other. Although layer edges may not be precisely vertical in all AM processes, the result would still normally be a very well defined cylinder with a relatively smooth edge. The same cylinder built on its side, so that the circular end is vertical, will have distinct layer patterning on the sides. This will result in less accurate reproduction of the original CAD

data with a poorer esthetic appearance. Orientation of the part within the machine can affect part accuracy. Since many parts will have complex features along multiple axes, there may not be an ideal orientation for a particular part. Furthermore, it may be more important to maintain the geometry of some features when compared with others, so correct orientation may be a judgment call. This judgment may also be in contrast with other factors like the time it takes to build a part (e.g., taller builds take longer than shorter ones so high aspect ratio parts may be better built lying down), whether a certain orientation will generate more supports, or whether certain surfaces should be built face-up to ensure good surface finish in areas that are not in contact with support structures.

2. Removal of Supports

For those technologies that require supports it is a good idea to try and minimize the amount. No matter which system you use, any down-facing surface will be marginally poorer in surface quality than surfaces that point upwards and to the outside. Supports exacerbate this situation. Wherever the supports meet the part there will be small marks and reducing the number of supports would make the part more accurate and reduce the amount of part clean-up and post-process finishing.

However, as mentioned above, some surfaces may not be as important as others and so positioning of the part must be weighed against the relative importance of an affected surface.

Parts that require supports may also require planning for their removal. Supports may be located in difficult to reach regions within the part. For example, a hollow cylinder with end caps built vertically will require supports for the top surface. However, if there is no access hole then these supports cannot be removed. Inclusion of access holes (which could be plugged later) is a possible solution to this, as may be breaking up the part so the supports can be removed before reassembly. Similarly, SL parts may require drain holes for any trapped liquid resin.

3. Hollowing Out Parts

Parts that have thick walls may be designed to include hollow features if this doesn't impede the final functionality. The main benefits of doing this are the reduced time that may result during building of the part and the reduced cost from the use of less material. As mentioned previously, some liquid-based resin systems would require drain holes to remove excess resin from inside the part, which may not be an ideal solution. For these and other systems it may be that a honeycomb- or truss-like internal structure can assist in providing support within the part. All these approaches must be balanced against the additional time that it

would take to design such a part. However, there are software systems that would allow this to be done automatically.

4. Inclusion of Undercuts and Other Manufacturing

Constraining Features AM models can be used at various stages of the product development process. When evaluating initial designs, focus may be on the esthetics or ultimate functionality of the part. Consideration of how to include manufacturing-related features would have lower priority at this stage. Conventional manufacturing would require considerable planning to ensure that a part is fabricated correctly. Undercuts, draft angles, holes, pockets, etc. must be created in a specific order when using multiplestage processes. While this can be ignored when designing the part for additive processes, it is important not to forget them. Design at this stage may help in optimizing the parts since it would be possible to determine where and what type of rib, boss, and other strengthening approaches should be used on the final part. If the final part is to be injection molded, the AM part can be used to determine the best location for the parting lines in the mold.

5. Interlocking Features

AM machines have a finite build volume and large parts may not be capable of being built inside them. A solution may be to break the design up into segments that can fit into the machine and manually assemble them together later. The designer must therefore consider the best way to break up the parts. The regions where the breaks are made can be designed in such a way to facilitate reassembly. Techniques can include incorporation of interlocking features and maximizing surface area so that adhesives can be most effective. Such regions should also be in easy to reach but difficult to observe locations.

This approach of breaking parts up may still be helpful even when they can still fit inside the machine. Consider the design shown in Fig. 3.2. If it was built as a single part, it would take a long time and require a significant amount of supports (as shown in the left-hand figure). If the part were built as two separate pieces the resulting height would be significantly reduced and there would be few supports. The part could be glued together later. This glued region may be slightly weakened, but the individual segments may be stronger. Since the example has a thin wall section, the top of one of the bands will exhibit more stair-stepping and may also be a little weaker than the rest of the part. For the bonded region, it is possible to include large overlapping regions that will enable more effective bonding.

6. Reduction of Part Count in an Assembly

There are numerous sections in this book that discuss Direct Digital Manufacturing. This involves the direct manufacture of parts on AM machines for end use. The AM part is therefore toward the end of the product development process and the design does not need to consider alternative manufacturing processes. This in turn means that if the part can be simplified using AM, then this should be done. For example, it is possible to build fully assembled hinge structures by providing clearance around the moving features. What would conventionally be made up of a number of components in an assembly can possibly be designed as a single unit.

7. Identification Markings/Numbers

Although AM parts are often unique, it may be difficult for a company to keep track of them when they are possibly building hundreds of parts per week. It is a straightforward process to include identifying features on the parts. This can be done when designing the CAD model but that may not be possible since the models may come from a third party. There are a number of software systems that provide tools for labelling parts by embossing alphanumeric characters onto them as 3D models.

APPLICATION AREAS THAT DON'T INVOLVE CONVENTIONAL CAD MODELING

Additive manufacturing technology opens up opportunities for many applications that do not take the standard product development route. The capability of integrating AM with customizing data or data from unusual sources makes for rapid response and an economical solution. The following sections are examples where nonstandard approaches are applicable.

1. MEDICAL MODELING

There is an excellent opportunity to use AM in making models based on an individual person's medical data. The data can be incorporated into the system in a variety of different ways. Such data is based on 3D scanning obtained from systems like Computerized Tomography (CT), Magnetic Resonance Imaging (MRI), 3D ultrasound, etc. This data often needs considerable processing to extract the relevant sections before it can be built as a model or further incorporated into a product design. There are only a handful of software systems that can process the medical data in a suitable way, and a range of applications is starting to emerge. For example, materialise was involved in the development of software that is used in the production of hearing aids. AM technology helps in customizing these hearing aids from data that is collected from the ear canals of individual patients.

2. REVERSE ENGINEERING DATA

Medical data from patients is just one application that benefits from being able to collect and process complex surface information. For nonmedical data collection the more common approach is to use laser scanning technology. Such technology has the capacity to faithfully collect surface data from many types of surfaces that are difficult to model because they cannot be easily defined geometrically. Similar to the medical data, although the models can just be reproduced within the AM machine (like a kind of 3D fax machine), the general intention is to merge this data into products.

3. ARCHITECTURAL MODELING

Architectural models are usually created to emphasize certain features within a building design and so designs are modified to show textures, colors, and shapes that may not be exact reproductions of the final design. Therefore, architectural packages may require features that are tuned to the AM technology.

MODULE 2

Photo Polymerization Processes: Stereolithography (SL), Materials, SL resin curing process, Micro-stereolithography, Process Benefits and Drawbacks, Applications of Photo polymerization Processes.

Powder Bed Fusion Processes: Introduction, Selective laser Sintering (SLS), Materials, Powder fusion mechanism, SLS Metal and ceramic part creation, Electron Beam melting (EBM), Process Benefits and Drawbacks, Applications of Powder Bed Fusion Processes.

Extrusion-Based Systems: Fused Deposition Modelling (FDM), Principles, Materials, Plotting and path control, Bio-Extrusion, Process Benefits and Drawbacks, Applications of Extrusion-Based Processes.

PHOTO POLYMERIZATION PROCESSES

INTRODUCTION

Photopolymerization processes make use of liquid, radiation curable resins, or photopolymers as their primary materials. Most photopolymers react to radiation in the ultraviolet (UV) range of wavelengths, but some visible light systems are used as well. Upon irradiation, these materials undergo a chemical reaction to become solid. This reaction is called photopolymerization, and is typically complex, involving many chemical participants.

Various types of radiation may be used to cure commercial photopolymers, including gamma rays, X-rays, electron beams, UV, and in some cases visible light. In SL systems, UV and visible light radiation are used most commonly. In the microelectronics industry, photomask materials are often photopolymers and are typically irradiated using far UV and electron beams. In contrast, the field of dentistry uses visible light predominantly.

Two primary configurations were developed for photopolymerization processes in a vat, plus one additional configuration that has seen some research interest. Although photopolymers are also used in some ink-jet printing processes, this method of line-wise processing is not covered in this chapter, as the basic processing steps are more similar to the printing processes.

The configurations discussed in this chapter include:

- Vector scan, or point-wise, approaches typical of commercial SL machines | Mask projection, or layer-wise, approaches, that irradiate entire layers at one time, and
- Two-photon approaches that are essentially high-resolution point-by-point approaches

These three configurations are shown schematically in Fig. 4.1. Note that in the vector scan and two-photon approaches, scanning laser beams are needed, while the mask projection approach utilizes a large radiation beam that is patterned by another device, in this case a Digital Micromirror Device TM (DMD).

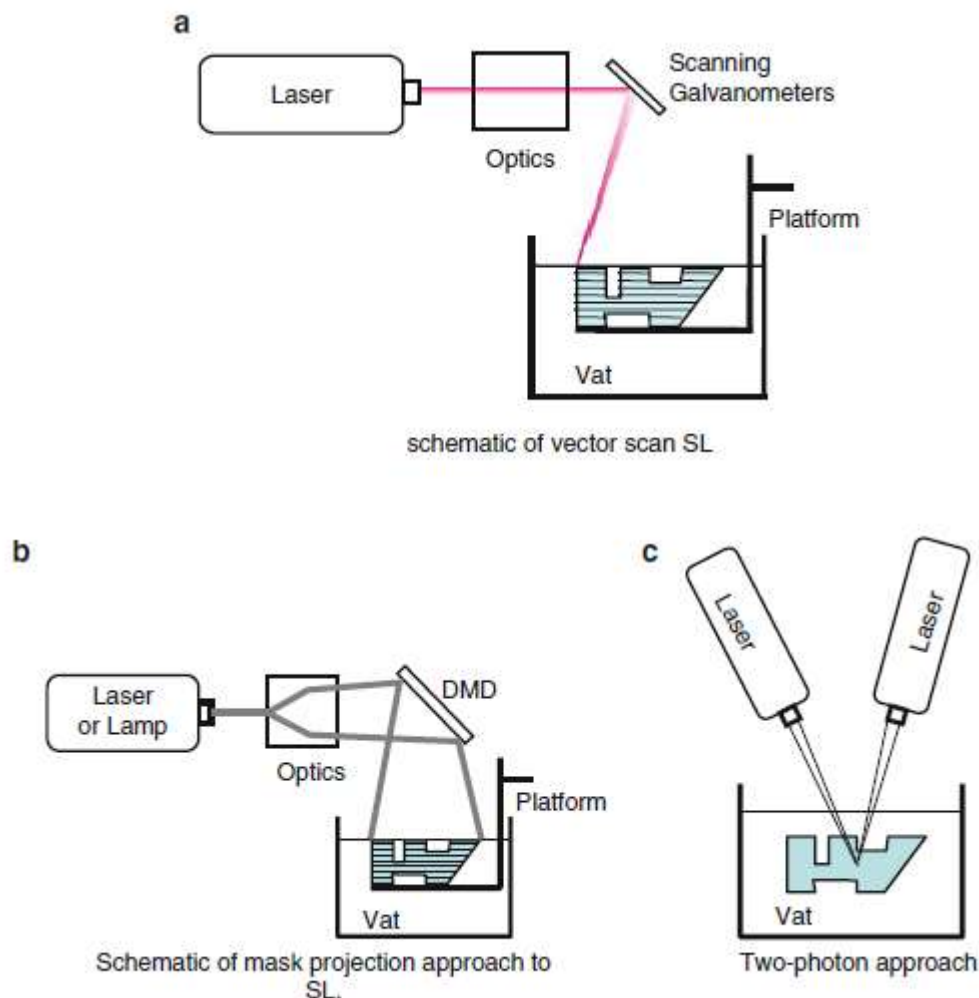


Fig. 4.1 Schematic diagrams of three approaches to photopolymerization processes

In the two-photon case, photopolymerization occurs at the intersection of two scanning laser beams, although other configurations use a single laser and different Photo initiator chemistries. Another distinction is the need to recoat, or apply a new layer of resin, in the vector scan and mask projection approaches, while in the two-photon approach, the part is fabricated below the resin surface, making recoating unnecessary.

Approaches that avoid recoating are faster and less complicated. In this chapter, we first introduce photopolymer materials, then present the vector scan SL machines, technologies, and processes. Mask projection approaches are presented and contrasted with the vector scan approach. Additional configurations, along with their applications, are presented at the end of the chapter. Advantages, disadvantages, and uniqueness's of each approach and technology are highlighted.

PHOTOPOLYMERIZATION MATERIALS

Some background of UV photopolymers will be presented in this section that is common to all configurations of photopolymerization processes. Two sections on reaction rates and characterization methods conclude this section.

1. UV CURABLE PHOTOPOLYMERS

As mentioned, photopolymers were developed in the late 1960s. In addition to the applications, they are used as photoresists in the microelectronics industry. This application has had a major impact on the development of epoxy-based photopolymers. Photoresists are essentially one-layer SL, but with critical requirements on accuracy and feature resolution. Various types of radiation may be used to cure commercial photopolymers, including gamma rays, X-rays, electron beams, UV, and in some cases visible light, although UV and electron beam are the most prevalent. In AM, many of these radiation sources have been utilized in research, however only UV and visible light systems are utilized in commercial systems. In SL systems, for example, UV radiation is used exclusively although, in principle, other types could be used. In the SLA-250 from 3D Systems, a helium-cadmium (HeCd) laser is used with a wavelength of 325 nm. In contrast, the solid-state lasers used in the other SL models are Nd:YVO₄. In mask projection DMD-based systems, UV and visible-light radiation is used.

Thermoplastic polymers that are typically injection molded have a linear or branched molecular structure that allows them to melt and solidify repeatedly. In contrast, SL photopolymers are cross-linked and, as a result, do not melt and exhibit much less creep and stress relaxation. Figure 4.2 shows the three polymer structures mentioned.

However, the epoxy resins have disadvantages of slow photospeed and brittleness of the cured parts. The addition of some acrylate to epoxy resins is required to rapidly build part strength so that they will have enough integrity to be handled without distortion during fabrication. The acrylates are also useful to reduce the brittleness of the epoxy parts. Another disadvantage of epoxy resins is their sensitivity to humidity, which can inhibit polymerization.

As a result, most SL resins commercially available today are epoxides with some acrylate content. It is necessary to have both materials present in the same formulation to combine the advantages of both curing types. The improvement in accuracy resulting from the use of hybrid resins has given SL a tremendous boost.

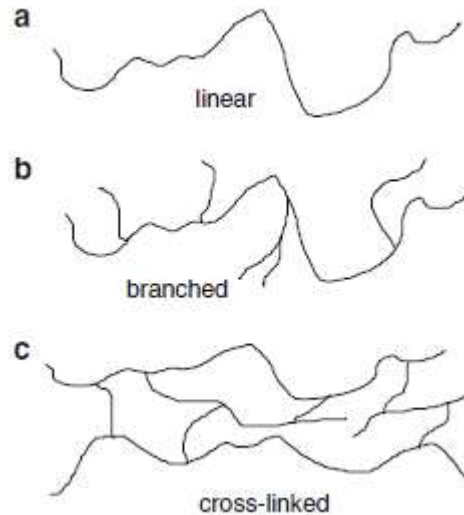


Fig. 4.2 Schematics of polymer types

OVERVIEW OF PHOTOPOLYMER CHEMISTRY

SL photopolymers are composed of several types of ingredients: photoinitiators, reactive diluents, flexibilizers, stabilizers, and liquid monomers. Broadly speaking, when UV radiation impinges on SL resin, the photoinitiators undergo a chemical transformation and become “reactive” with the liquid monomers. A “reactive” photoinitiator reacts with a monomer molecule to start a polymer chain. Subsequent reactions occur to build polymer chains and then to cross-link – creation of strong covalent bonds between polymer chains. Polymerization is the term used to describe the process of linking small molecules (monomers) into larger molecules (polymers) composed of many monomer units. Two main types of photopolymer chemistry are commercially evident:

- Free-radical photopolymerization – acrylate
- Cationic photopolymerization – epoxy and vinylether

The molecular structures of these types of photopolymers are shown in Fig. 4.5. Symbols C and H denote carbon and hydrogen atoms, respectively, while R denotes a molecular group which typically consists of one or more vinyl groups. A vinyl group is a molecular structure with a carbon–carbon double bond. It is these vinyl groups in the R structures that enable photopolymers to become cross-linked.

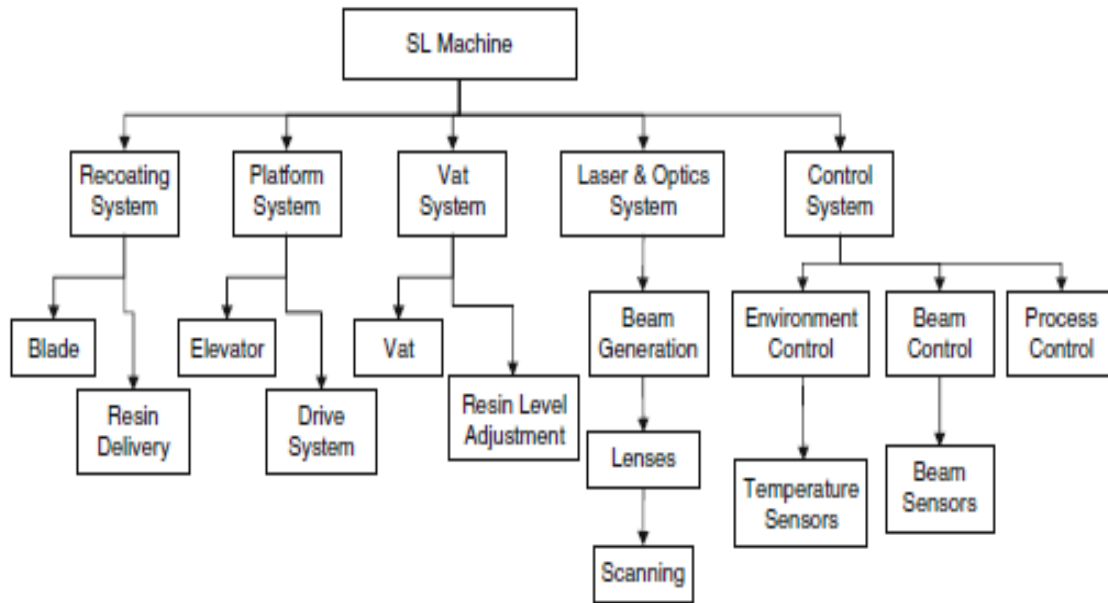


Fig. 4.5 Subsystems for SL technology

Free-radical photopolymerization was the first type that was commercially developed. Such SL resins were acrylates. Acrylates form long polymer chains once the photoinitiator becomes “reactive,” building the molecule linearly by adding monomer segments. Cross-linking typically happens after the polymer chains grow enough so that they become close to one another. Acrylate photopolymers exhibit high photospeed (react quickly when exposed to UV radiation), but have a number of disadvantages including significant shrinkage and a tendency to warp and curl. As a result, they are rarely used now without epoxy or other photopolymer elements.

The most common cationic photopolymers are epoxies, although vinyl ethers are also commercially available. Epoxy monomers have rings, as shown in Fig. 4.3. When reacted, these rings open, resulting in sites for other chemical bonds. Ring opening is known to impart minimal volume change on reaction, because the number and types of chemical bonds are essentially identical before and after reaction. As a result, epoxy SL resins typically have much smaller shrinkages and much less tendency to warp and curl. Almost all commercially available SL resins have significant amounts of epoxies. Polymerization of SL monomers is an exothermic reaction, with heats of reaction around 85 kJ/mol for an example acrylate monomer. Despite high heats of reaction, a catalyst is necessary to initiate the reaction. As described earlier, a photoinitiator acts as the catalyst.

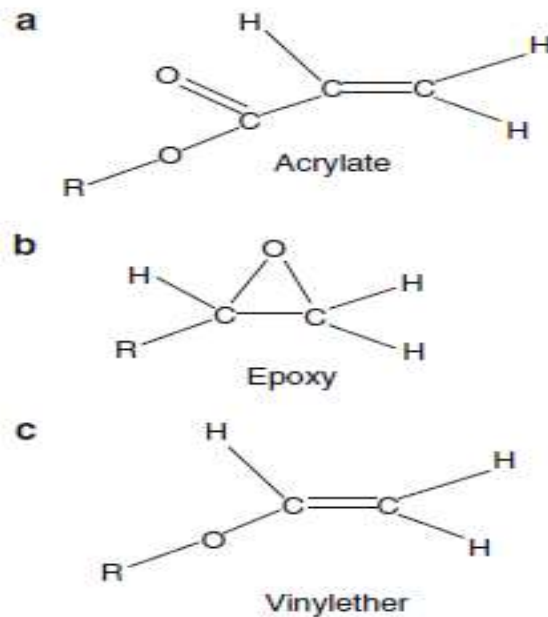


Fig. 4.3 Molecular structure of SL monomers

Schematically, the free radical-initiated polymerization process can be illustrated as shown in Fig. 4.4. On average, for every two photons (from the laser), one radical will be produced. That radical can easily lead to the polymerization of over 1,000 monomers, as shown in the intermediate steps of the process, called propagation.

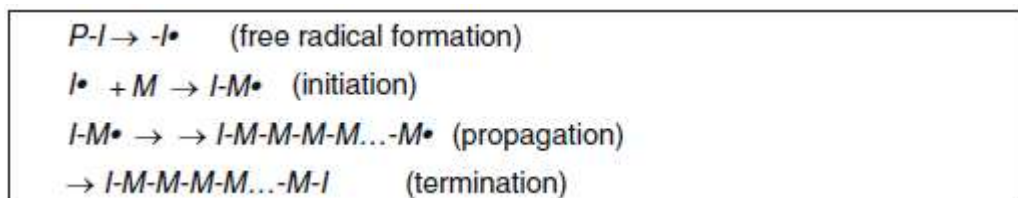


Fig. 4.4 Free-radical polymerization process

In general, longer polymer molecules are preferred, yielding higher molecular weights. This indicates a more complete reaction. In Fig. 4.4, the P-I term indicates a photoinitiator, the $\cdot I$ symbol is a free radical, and M is a monomer. Polymerization terminates from one of three causes, recombination, disproportionation, or occlusion. Recombination occurs when two polymer chains merge by joining two radicals. Disproportionation involves essentially the cancellation of one radical by another, without joining. Occlusion occurs when free radicals become “trapped” within a solidified polymer, meaning that reaction sites remain available, but are prevented from reacting with other monomers or polymers by the limited mobility within the polymer network. These occluded sites will most certainly react eventually, but not with another polymer chain or monomer. Instead, they will react with oxygen or another reactive species that diffuses into the occluded region. This may be a

cause of aging or other changes in mechanical properties of cured parts, which should be a topic of future research. Cationic photopolymerization shares the same broad structure as free-radical polymerization, where a photoinitiator generates a cation as a result of laser energy, the cation reacts with a monomer, propagation occurs to generate a polymer, and a termination process completes the reaction. A typical catalyst for a cationic polymerization is a Lewis Acid, such as BF_3 . Initially, cationic photopolymerization received little attention, but that has changed during the 1990s due to advances in the microelectronics industry, as well as interest in SL technology. We will not investigate the specifics of cationic reactions here, but will note that the ring opening reaction mechanism of epoxy monomers is similar to radical propagation in acrylates.

SL RESIN CURING PROCESS

Background on SL materials and energy sources enables us to investigate the curing process of photopolymers in SL machines. We will begin with an investigation into the fundamental interactions of laser energy with photopolymer resins. Through the application of the Beer–Lambert law, the theoretical relationship between resin characteristics and exposure can be developed, which can be used to specify laser scan speeds. This understanding can then be applied to investigate mechanical properties of cured resins. From here, we will briefly investigate the ranges of size scales and time scales of relevance to the SL process. Much of this section is adapted from.

Nomenclature:

C_d ¼ cure depth ¼ depth of resin cure as a result of laser irradiation [mm]

D_p ¼ depth of penetration of laser into a resin until a reduction in irradiance of $1/e$ is reached
¼ key resin characteristic [mm]

E = exposure, possibly as a function of spatial coordinates [energy/unit area] [mJ/mm^2]

E_c ¼ critical exposure ¼ exposure at which resin solidification starts to occur [mJ/mm^2]

E_{max} ¼ peak exposure of laser shining on the resin surface (center of laser spot) [mJ/mm^2]

$H(x,y,z)$ ¼ irradiance (radiant power per unit area) at an arbitrary point in the resin ¼ time derivative of $E(x,y,z)$. [W/mm^2]

P_L ¼ output power of laser [W]

V_s ¼ scan speed of laser [mm/s]

W_0 ¼ radius of laser beam focused on the resin surface [mm]

1. IRRADIANCE AND EXPOSURE

As a laser beam is scanned across the resin surface, it cures a line of resin to a depth that depends on many factors. However, it is also important to consider the width of the cured line as well as its profile. The shape of the cured line depends on resin characteristics, laser energy characteristics, and the scan speed. We will investigate the relationships among all of these factors in this subsection.

The first concept of interest here is irradiance, the radiant power of the laser per unit area, $H(x,y,z)$. As the laser scans a line, the radiant power is distributed over a finite area (beam spots are not infinitesimal). Figure 4.6 shows a laser scanning a line along the x-axis at a speed V_s . Consider the z-axis oriented perpendicular to the resin surface and into the resin, and consider the origin such that the point of interest, p_0 , has an x coordinate of 0. The irradiance at any point x,y,z in the resin is related to the irradiance at the surface, assuming that the resin absorbs radiation according to the Beer–Lambert Law.

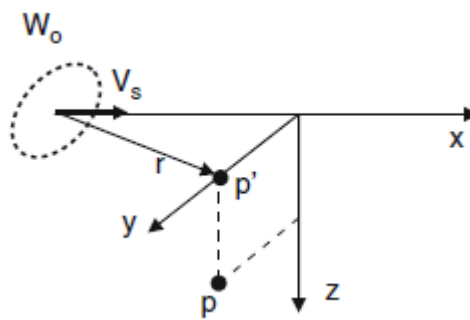


Fig. 4.6 Scan line of Gaussian laser

2. LASER–RESIN INTERACTION

In this subsection, we will utilize the irradiance and exposure relationships to determine the shape of a scanned vector line and its width. As we will see, the cross-sectional shape of a cured line becomes a parabola. Figure 4.7 illustrates the parabolic shape of a cured scan line.

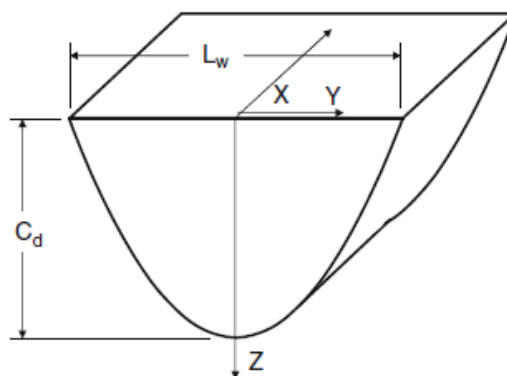


Fig. 4.7 Cured line showing parabolic shape, cure depth, and line width

3. PHOTOSPEED

Photospeed is typically used as an intuitive approximation of SL photosensitivity. But it is useful in that it relates to the speed at which the laser can be scanned across the polymer surface to give a specified cure depth. The faster the laser can be scanned to give a desired cure depth, the higher the photospeed. Photospeed is a characteristic of the resin and does not depend upon the specifics of the laser or optics subsystems. In particular, photospeed is indicated by the resin constants E_c and D_p .

So how is exposure varied? Exposure is varied by simply using different scan velocities in different regions of the WINDOWPANE part. The different scan velocities will result in different cure depths. In practice is very useful since we want to directly control cure depth, and want to determine how fast to scan the laser to give that cure depth. Of course, for the WINDOWPANE experiment.

4. TIME SCALES

It is interesting to investigate the time scales at which SL operates. On the short end of the time scale, the time it takes for a photon of laser light to traverse a photopolymer layer is about a picosecond (10^{-12} s). Photon absorption by the photoinitiator and the generation of free radicals or cations occur at about the same time frame. A measure of photopolymer reaction speed is the kinetic reaction rates, k_t , which are typically several microseconds.

The time it takes for the laser to scan past a particular point on the resin surface is related to the size of the laser beam. We will call this time the characteristic exposure time, t_e . Values of t_e are typically 50–2000 ms, depending on the scan speed (500–5000 mm/s). Laser exposure continues long after the onset of polymerization.

Continued exposure generates more free radicals or cations and, presumably, generates these at points deeper in the photopolymer. During and after the laser beam traverses the point of interest, cross-linking occurs in the photopolymer.

The onset of measurable shrinkage, $t_{s,o}$, lags exposure by several orders of magnitude. This appears to be due to the rate of cross-linking, but for the epoxybased resins, may have more complicated characteristics. Time at corresponding completion of shrinkage is denoted $t_{s,c}$. For the acrylate-based resins of the early 1990s, times for the onset and completion of shrinkage were typically 0.4–1 and 4–10 s, respectively. Recall that epoxies can take hours or days to polymerize. Since shrinkage lags exposure, this is clearly a phenomena that complicates the SL process. Shrinkage leads directly to accuracy problems, including deviation from nominal dimensions, warpage, and curl.

The final time dimension is that of scan time for a layer, denoted t_d , which typically spans 10–300 s.

MICROSTEREOLITHOGRAPHY

Several processes were developed exclusively for microfabrication applications based on photopolymerization principles using both lasers and X rays as the energy source. These processes build complex shaped parts that are typically less than 1 mm in size. They are referred to as Microstereolithography (MSL), Integrated Hardened Stereolithography (IH), LIGA, Deep X-ray Lithography (DXRL), and other names. In this section, we will focus on those processes that utilize UV radiation to directly process photopolymer materials.

In contrast to convention SL, vector scan technologies for the micro-scale typically have moved the vat in x, y, and z directions, rather than scanning the laser beam. To focus a typical laser to spot sizes less than 20 μm requires the laser's focal length to be very short, causing difficulties for scanning the laser. For an SLA-250 with a 325 nm wavelength HeCd laser, the beam has a diameter of 0.33 mm and a divergence of 1.25 mrad as it exits the laser. It propagates 280 mm then encounters a diverging lens (focal length -25 mm) and a converging lens (focal length 100 mm) which is 85 mm away. Using simple thin-lens approximations, the distance from the converging lens to the focal point, where the laser reaches a spot size of 0.2 μm is 940 mm and its Rayleigh range is 72 mm. Hence, the focused laser spot is a long distance from the focusing optics and the Rayleigh range is long enough to enable a wide scanning region and a large build area.

In contrast, a typical calculation is presented here for a high resolution micro-SL system with a laser spot size of 10 μm . A 325 nm wavelength HeCd laser used in SL is included here to give the reader an idea of the challenge. The beam, as it exits the laser, has a diameter of 0.33 mm and a divergence of 1.25 mrad. It propagates 280 mm then encounters a diverging lens (focal length -25 mm) and a converging lens (focal length 36.55 mm). The distance from the converging lens to the focal point is 54.3 mm and its Rayleigh range is only 0.24 mm. It would be very difficult to scan this laser beam across a vat without severe spot distortions.

Scanning micro-SL systems have been presented in literature since 1993 with the introduction of the Integrated Hardening method of Ikuta and Hirowatari. They used a laser spot focused to a 5-mm diameter and the resin vat is scanned underneath it to cure a layer. Examples of devices built with this method include tubes, manifolds, and springs and flexible microactuators and fluid channels on silicon. Takagi and Nakajima have demonstrated the use of this technology for connecting MEMS gears together on a substrate.

The artifact fabricated using micro-SL can be used as a mold for subsequent electroplating followed by removal of the resin. This method has been able to achieve sub-1 mm minimum feature size.

The following specifications of a typical point-wise Microstereolithography process have been presented in

- 5-mm spot size of the UV beam
- Positional accuracy is 0.25 mm (in the x–y directions) and 1.0 mm in the z-direction
- Minimum size of the unit of hardened polymer is 5 mm _ 5 mm _ 3 mm (in x, y, z)
- Maximum size of fabrication structure is 10 mm _ 10 mm _ 10 mm

The capability of building around inserted components has also been proposed for components such as ultrafiltration membranes and electrical conductors. Applications include fluid chips for protein synthesis and bioanalysis. The bioanalysis system was constructed with integrated valves and pumps that include a stacked modular design, 13 _ 13 mm² and 3 mm thick, each of which has different fluid function. However, the full extent of integrated processing on silicon has not yet been demonstrated. The benefits of greater design flexibility and lower cost of fabrication may be realized in the future.

PROCESS BENEFITS AND DRAWBACKS

PROCESS BENEFITS

1. **It's quick.** A major advantage of stereolithography is that the part can be built in a relatively short period of time since curing is fast. The amount of time required depends on the size, complexity and layer thickness the part will be built with. Parts can take anywhere from a few short hours to a day or more.
2. **It's cheap.** The feedstocks used in stereolithography are generally quite cheap to produce in bulk, so the powders and photopolymer resin contribute very little to the cost of the process and therefore it is really only the cost of energy for the laser and automatic platform, which is negligible.
3. **It aids prototyping.** By creating a low-cost yet accurate model, the process can help you find potentially costly mistakes by detecting design flaws before the manufacturing process even starts. It can be a cost-effective option for low-volume production of parts and provides quick lead times for making these.
4. **It's a multi-material process.** Since its initial introduction, SLA has undergone refinement in terms of its standard processing capability, but also the range of materials that can be used with the process. In recent years there have been advances

in making it a standard process for joining metal and even ceramic powders prior to them being solidified via the sintering process. This means that almost any component can now be initially formed using SLA, and highly complex component parts required for high temperature or highly abrasive applications can be formed without having to use expensive machining techniques.

5. **It creates tools, quickly.** Aside from creating components, SLA is adept at generating tooling fixtures too. Typically an afterthought when considering production manufacturing, the need for effective tooling can take manufacturing engineers by surprise, but SLA offers the possibility of creating fixtures and fittings quickly and accurately.
6. **High quality parts.** While the surface finish on parts is a function of the particle size used to create it, SLA parts are renowned for being accurate to at least the tolerance of the stage movement – usually 0.002” to 0.006”, but possibly as low as 0.0005” – and with an acceptable surface finish in the as-moulded state. Obviously, a completed part is robust enough to undergo some post-processing using standard engineering processes to enhance its physical properties.
7. **Snap-together assemblies.** Because models can be taken straight from CAD as IGES files, it is possible to create assemblies based on many component parts that can be made to fit together to make a larger part. This same issue also applies to prototyping and the ability to quickly change and reprint a design if it needs modification.
8. **Scaling is easy.** Because it is driven by CAD, the process lends itself to scaling as whatever can be done within the CAD program can be directly translated to the modelling area, so if it is found that a component needs to be of a slightly different size, but maintain proportion, then scaling is a simple task.

PROCESS DRAWBACKS

1. **Photosensitive resin is a problem.** Handling the resin becomes a major factor with SLA as it must be handled in an appropriate way to prevent it from starting to form before it has been applied to the model. This may mean that moulding has to be carried out in darkened areas or include covered sections to prevent the resin from becoming affected.
2. **Newer processes may be better.** With new 3D modelling processes being refined all the time, there is always the possibility of something delivering the same level of quality and output, but at a lower purchase price and running cost.

APPLICATIONS OF PHOTO POLYMERIZATION PROCESSES.

1. Photopolymers in Adhesive and Coatings

The development of photopolymerizable materials for non-imaging applications represents significant progress for protective adhesives, coatings and inks. Inkjet, for example, is a digital printing process in which photopolymers can be applied directly onto paper, plastic and other substrates to render images and features. The material is cured and solidified by ultraviolet light to build layers on top of each other.

Materials can also be applied via needle dispense. And since there are many types of inkjettable photopolymers with different properties, it's possible to customize to the particular application of interest.

2. Photopolymers in Manufacturing

Stereolithography is just one type of 3D printing technology used for creating patterns and prototypes through photopolymerization. It's the process in which computer-aided exposure technologies convert liquid monomers into solid objects through light-initiated reactions. The photopolymers are resins that can create a wide variety of parts. Scott Turner, Senior Researcher at 3D Systems, is quoted in an Engineering.com article saying, "Modern manufacturing companies are looking for ways to transition their tooling assets from physical to digital, so they can be deployed when and where needed." Thanks to 3D printing, developers are able design and create parts much faster than conventional manufacturing methods.

3. Photopolymers in Microelectronics

Photopolymers play a critical role in the advancement of the microelectronics industry. There are two major applications for photopolymers: photoresists and permanent photopolymers. Photoresists are used to create the very fine circuitry found in microelectronics. However, they're not part of the final device. Permanent photopolymers, on the other hand, are part of the final device, and can serve as dielectric materials in displays and chips. In both cases, the materials are designed to change their properties upon irradiation (exposure to light). This irradiation can cause the materials to change properties, including solubility.

POWDER BED FUSION PROCESSES

INTRODUCTION

Powder bed fusion (PBF) processes were among the first commercialized AM processes. Developed at the University of Texas at Austin, USA, Selective Laser Sintering (SLS) was the first commercialized powder bed fusion process. All other PBF processes modify this basic approach in one or more ways to enhance machine productivity, enable different materials to be processed, and/or to avoid specific patented features.

All PBF processes share a basic set of characteristics. These include one or more thermal sources for inducing fusion between powder particles, a method for controlling powder fusion to a prescribed region of each layer, and mechanisms for adding and smoothing powder layers.

SELECTIVE LASER SINTERING (SLS)

In order to provide a baseline description of powder fusion processes, Selective Laser Sintering will be described as the paradigm approach to which the other powder bed fusion processes will be compared. As shown in Fig. 5.1, SLS fuses thin layers of powder (typically ~0.1 mm thick) which have been spread across the build area using a counter-rotating powder levelling roller.

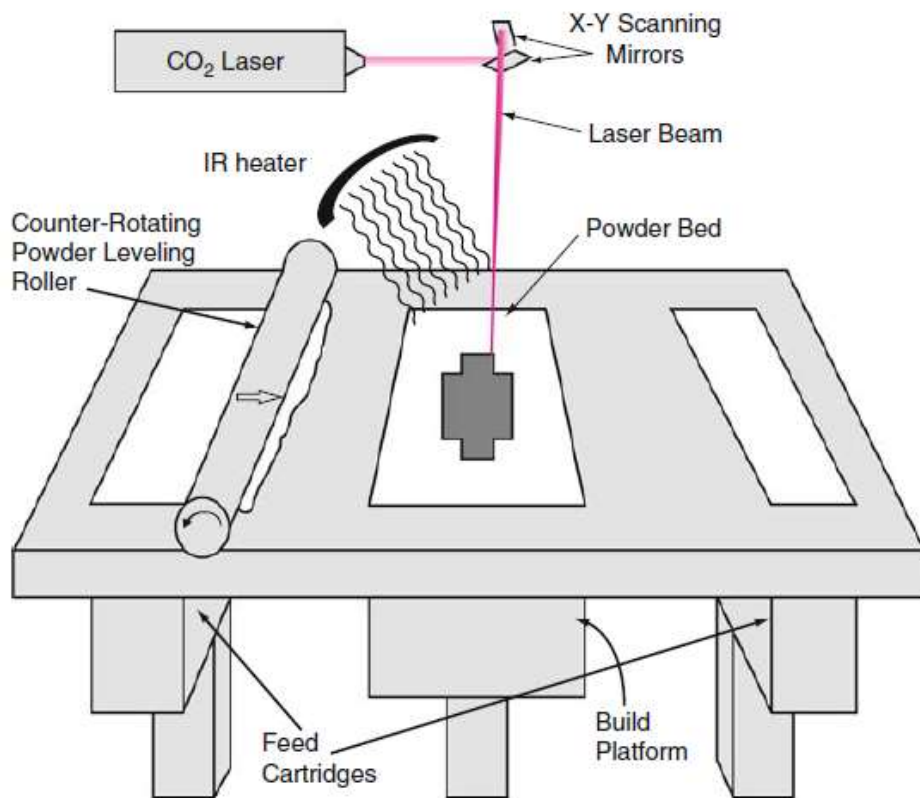


Fig. 5.1 Schematic of the Selective Laser Sintering process

The part building process takes place inside an enclosed chamber filled with nitrogen gas to minimize oxidation and degradation of the powdered material. The powder in the build platform is maintained at an elevated temperature just below the melting point and/or glass transition temperature of the powdered material. Infrared heaters are placed above the build platform to maintain an elevated temperature around the part being formed; as well as above the feed cartridges to pre-heat the powder prior to spreading over the build area. In some cases, the build platform is also heated using resistive heaters around the build platform. This pre-heating of powder and maintenance of an elevated, uniform temperature within the build platform is necessary to minimize the laser power requirements of the process (when pre-heating, less laser energy is required for fusion) and to prevent warping of the part during the build due to nonuniform thermal expansion and contraction (curling).

Once an appropriate powder layer has been formed and preheated, a focused CO₂ laser beam is directed onto the powder bed and is moved using galvanometers in such a way that it thermally fuses the material to form the slice cross-section. Surrounding powder remains loose and serves as support for subsequent layers, thus eliminating the need for the secondary supports which are necessary for photopolymer vat processes. After completing a layer, the build platform is lowered by one layer thickness and a new layer of powder is laid and leveled using the counter-rotating roller. The beam scans the subsequent slice cross-section. This process repeats until the complete part is built. A cool-down period is typically required to allow the parts to uniformly come to a low-enough temperature that they can be handled and exposed to ambient temperature and atmosphere. If the parts and/or powder bed are prematurely exposed to ambient temperature and atmosphere, the powders may degrade in the presence of oxygen and parts may warp due to uneven thermal contraction. Finally, the parts are removed from the powder bed, loose powder is cleaned off the parts, and further finishing operations, if necessary, are performed.

POWDER FUSION MECHANISMS

Since the introduction of SLS, each new powder bed fusion technology developer has introduced competing terminology to describe the mechanism by which fusion occurs, with variants of “sintering” and “melting” being the most popular. However, the use of a single word to describe the powder fusion mechanism is inherently problematic as multiple mechanisms are possible. There are 4 different fusion mechanisms which are present in PBF processes. These include solid-state sintering, chemically-induced binding, liquid-phase sintering, and full melting.

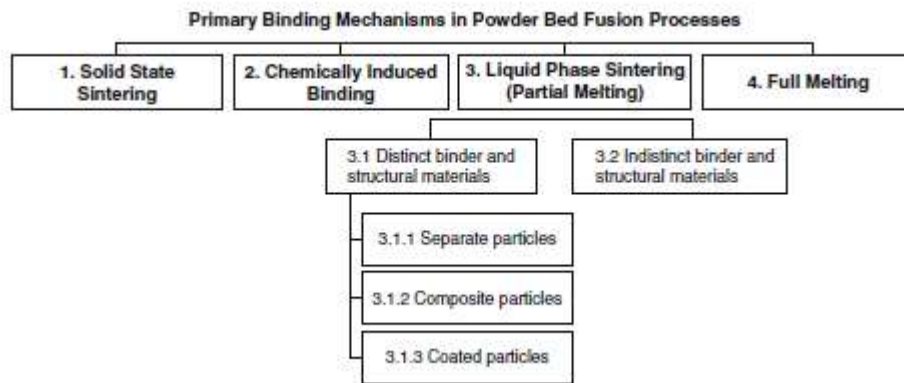


Fig. 5.5 Primary binding mechanisms in Powder Bed Fusion processes

Most commercial processes utilize primarily liquid-phase sintering and melting. A brief description of each of these mechanisms and their relevance to AM follows.

1. SOLID-STATE SINTERING

The use of the word sintering to describe mechanisms for fusing powders as a result of thermal processing predates the advent of AM. Sintering, in its classical sense, indicates the fusion of powder particles without melting (i.e., in their “solid state”) at elevated temperatures. This occurs at temperatures between one half of the absolute melting temperature and the melting temperature. The driving force for solid-state sintering is the minimization of total free energy, E_s , of the powder particles. The mechanism for sintering is primarily diffusion between powder particles.

Surface energy E_s is proportional to total particle surface area SA , through the equation $E_s = \gamma_s \cdot SA$ (where γ_s is the surface energy per unit area for a particular material, atmosphere, and temperature). When particles fuse at elevated temperatures (see Fig. 5.2), the total surface area decreases, and thus surface energy decreases. As the total surface area of the powder bed decreases, the rate of sintering slows. To achieve very low porosity levels, long sintering times or high sintering temperatures are required.

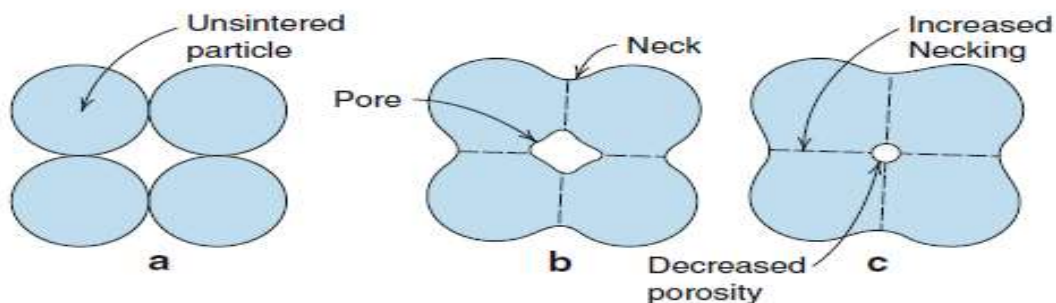


Fig. 5.2 Solid-State Sintering. (a) Closely packed particles prior to sintering. (b) articles agglomerate at temperatures above one half of the absolute melting temperature, as they seek to minimize free energy by decreasing surface area. (c) As sintering progresses, neck size increases and pore size decreases.

2. CHEMICALLY-INDUCED SINTERING

Chemically-induced sintering involves the use of thermally-activated chemical reactions between two types of powders or between powders and atmospheric gases to form a by-product which binds the powders together. This fusion mechanism is primarily utilized for ceramic materials. Examples of reactions between powders and atmospheric gases include: laser processing of SiC in the presence of oxygen, whereby SiO₂ forms and binds together a composite of SiC and SiO₂; laser processing of ZrB₂ in the presence of oxygen, whereby ZrO₂ forms and binds together a composite of ZrB₂ and ZrO₂; and laser processing of Al in the presence of N₂, whereby AlN forms and binds together the Al and AlN particles.

For chemically-induced sintering between powders, various research groups have demonstrated that mixtures of high-temperature structural ceramic and/or intermetallic precursor materials can be made to react using a laser. In this case, raw materials which exothermically react to form the desired byproduct are premixed and heated using a laser. By adding chemical reaction energy to the laser energy, high-melting-temperature structures can be created at relatively low laser energies.

One common characteristic of chemically-induced sintering is part porosity. As a result, post-process infiltration or high-temperature furnace sintering to higher densities is often needed to achieve properties that are useful for most applications. This post-process infiltration may involve other reactive elements, forming new chemical compounds after infiltration. The cost and time associated with postprocessing have limited the adoption of chemically-induced sintering in commercial machines.

3. LIQUID-PHASE SINTERING AND PARTIAL MELTING

Liquid-phase sintering (LPS) is arguably the most versatile mechanism for PBF. Liquid-phase sintering is a term used extensively in the powder processing industry to refer to the fusion of powder particles when a portion of constituents within a collection of powder particles become molten, while other portions remain solid. In LPS, the molten constituents act as the glue which binds the solid particles together.

As a result, high-temperature particles can be bound together without needing to melt or sinter those particles directly. LPS is used in traditional powder metallurgy to form, for instance, cemented carbide cutting tools where Co is used as the lowermelting-point constituent to glue together particles of WC.

There are many ways in which LPS can be utilized as a fusion mechanism in AM processes. For purposes of clarity, the classification proposed by Kruth et al. [1] has formed the basis for the distinctions discussed in the following section and shown in Fig. 5.4.

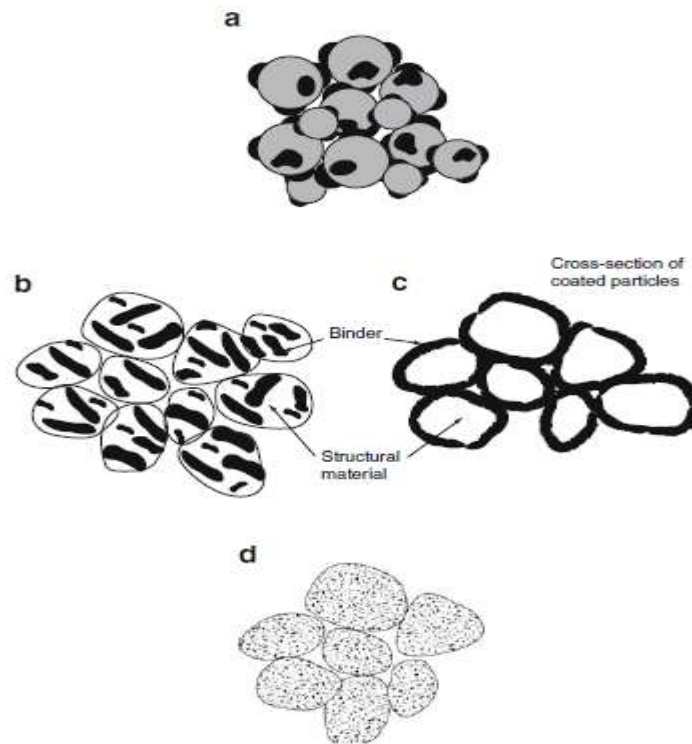


Fig. 5.4 Liquid Phase Sintering variations used in powder bed fusion processing: (a) separate particles, (b) composite particles, (c) coated particles, and (d) indistinct mixtures. Darker regions represent the lower-melting-temperature binder material.

Lighter regions represent the highmelting- temperature structural material. For indistinct mixtures, microstructural alloying eliminates distinct binder and structural regions

SLS METAL AND CERAMIC PART CREATION

1. METAL PARTS

There are four common approaches for using powder bed fusion processes in the creation of complex metal components: full melting, liquid-phase sintering, indirect processing, and pattern methods. As discussed previously, in the full melting approach a metallic powdered material is fully melted using a high-power laser or electron beam; and in the liquid-phase sintering approach a mixture of two metal powders or a metal alloy is used where a higher-melting-temperature constituent remains solid and a lower-melting-temperature constituent melts. In both of these approaches, a metal part is typically usable in the state in which it comes out of the machine, after separation from a build plate.

In indirect processing, a polymer coated metallic powder or a mixture of metallic and polymer powders are used for part construction. Figure 5.7 shows the steps involved in indirect processing of metal powders. During indirect processing, the polymer binder is melted and binds the particles together, and the metal powder remains solid. The metallic powder particles remain largely unaffected by the heat of the laser.

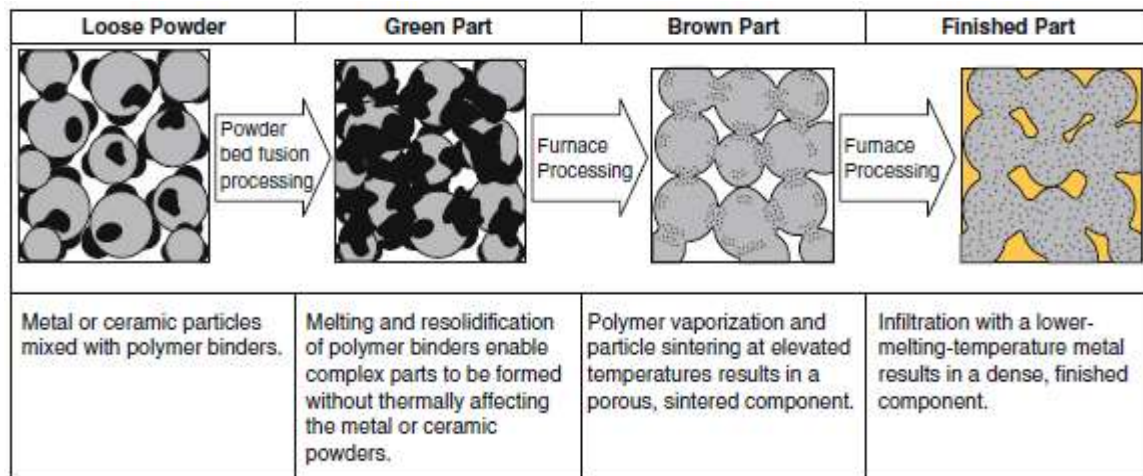


Fig. 5.7 Indirect processing of metal and ceramic powders using PBF

The parts produced are generally porous (sometimes exceeding 50 vol.% porosity). The polymer-bound green parts are subsequently furnace processed. Furnace processing occurs in two stages: (1) debinding and (2) infiltration or consolidation. During debinding, the polymer binder is vaporized to remove it from the green part. Typically, the temperature is also raised to the extent that a small degree of necking (sintering) occurs between the metal particles. Subsequently, the remaining porosity is either filled by infiltration of a lower melting point metal to produce a fully dense metallic part, or by further sintering and densification to reduce the part porosity. Infiltration is easier to control, dimensionally, as the overall shrinkage is much less than during consolidation. However, infiltrated structures are always composite in nature whereas consolidated structures can be made up of a single material type.

The last approach to metal part creation using PBF is the pattern approach. For the previous 3 approaches, metal powder is utilized in the PBF process; but in this final approach, the part created in the PBF process is a pattern used to create the metal part. The two most common ways PBF-created parts are utilized as patterns for metal part creation are as investment casting patterns or as sand-casting molds. In the case of investment casting, polystyrene or wax-based powders are used in the machine; and subsequently invested in ceramic during post-processing, and melted out during casting. In the case of sand-casting molds, mixtures of sand and a thermosetting binder are directly processed in the machine to form a sand-casting core, cavity or insert. These molds are then assembled and molten metal is cast into the mold, creating a metal part.

2. CERAMIC PARTS

Similar to metal parts, there are a number of ways that PBF processes are utilized to create ceramic parts. These include direct sintering, chemically-induced sintering, indirect

processing and pattern methods. In direct sintering, a high-temperature is maintained in the powder bed and a laser is utilized to accelerate sintering of the powder bed in the prescribed location of each layer. The resultant ceramic parts will be quite porous and thus are often post-processed in a furnace to achieve higher density. This high porosity is also seen in chemically-induced sintering of ceramics, as described earlier.

Indirect processing of ceramic powders is identical to indirect processing of metal powders (Fig. 5.7). After debinding, the ceramic brown part is consolidated to reduce porosity or is infiltrated. In the case of infiltration, when metal powders are used as the infiltrant then a ceramic/metal composite structure can be formed. In some cases, such as when creating SiC structures, a polymer binder can be selected, which leaves behind a significant amount of carbon residue within the brown part. Infiltration with molten Si will result in a reaction between the molten Si and the remaining carbon to produce more SiC, thus increasing the overall SiC content and reducing the fraction of metal Si in the final part. These and related approaches have been used to form interesting ceramic-matrix composites and ceramic-metal structures for a number of different applications.

ELECTRON BEAM MELTING (EBM)

Electron Beam Melting (EBM) has become a successful approach to PBF. In contrast to laser-based systems, EBM uses a high-energy electron beam to induce fusion between metal powder particles. This process was developed at Chalmers University of Technology, Sweden, and was commercialized by Arcam AB, Sweden in 2001.

Similarly to SLM; in the EBM process, a focused electron beam scans across a thin layer of pre-laid powder, causing localized melting and resolidification as per the slice cross-section. However, there are a number of differences between how SLM and EBM are typically practiced, which are summarized in Table 5.1.

Table 5.1 Differences between EBM and SLM

Table 5.1 Differences between EBM and SLM		
Characteristic	Electron beam melting	Selective laser melting
Thermal source	Electron beam	Laser
Atmosphere	Vacuum	Inert gas
Scanning	Deflection coils	Galvanometers
Energy absorption	Conductivity-limited	Absorptivity-limited
Powder pre-heating	Use electron beam	Use infrared heaters
Scan speeds	Very fast, magnetically-driven	Limited by galvanometer inertia
Energy costs	Moderate	High
Surface finish	Moderate to poor	Excellent to moderate
Feature resolution	Moderate	Excellent
Materials	Metals (conductors)	Polymers, metals and ceramics

Since the source of energy in EBM is electrons, there are a number of differences between EBM and SLM which are inherent. Other differences, however, are due to engineering trade-offs as practiced in EBM and SLM and are not necessarily inherent to the processing. A schematic illustration of an EBM apparatus is shown as Fig. 5.13.

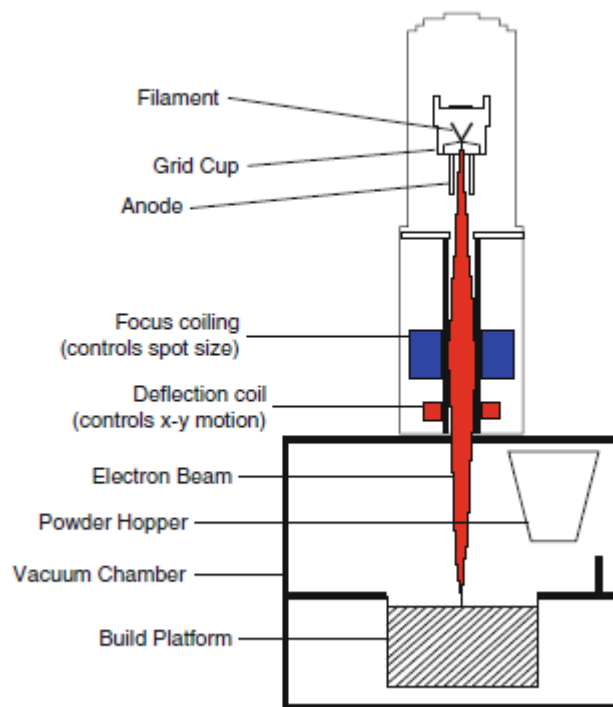


Fig. 5.13 Schematic of an EBM apparatus

Electron beams are inherently different from laser beams, as electron beams are made up of a stream of electrons moving near the speed of light, whereas, laser beams are made up of photons moving at the speed of light. When an electron beam is passed through a gas at atmospheric pressure, for instance, the electrons interact with the atoms in the gas and are deflected. In contrast, a laser beam can pass through a gas unaffected as long as the gas is transparent at the laser wavelength.

Thus, EBM is practiced in a low-partial-pressure vacuum environment (a small amount of inert gas is swept through to remove gaseous byproducts and oxygen), whereas SLM is practiced in an inert gas atmosphere at atmospheric pressure. Electrons have a negative charge and are focused and deflected magnetically, whereas photons are optically focused and deflected using mirrors attached to motors. As a result, since magnetic coils have an almost instantaneous response to changing input conditions, an electron beam can be scanned slowly or very rapidly. In essence an electron beam can be moved instantaneously from one location to another without needing to traverse the area in-between. In contrast,

galvanometers are mirrors attached to motors. For a laser beam focal spot to move from point A to point B, the galvanometer motors have to move the mirrors accordingly. Thus, virtually instantaneous motion is not possible and the scan speed is determined by the mass of the mirrors, the characteristics of the motors, and the distance from the mirrors to the powder bed.

Laser beams heat the powder when photons are absorbed by powder particles. Electron beams, however, heat powder by transfer of kinetic energy from incoming electrons into powder particles. As powder particles absorb electrons they gain an increasingly negative charge. This has two potentially detrimental effects: if the repulsive force of neighboring negatively charged particles overcomes the gravitational and frictional forces holding them in place, there will be a rapid expulsion of powder particles from the powder bed, creating a powder cloud; and increasing negative charges in the powder particles will tend to repel the incoming negatively charged electrons, thus creating a more diffuse beam. There are no such complimentary phenomena with photons. As a result, the conductivity of the powder bed in EBM must be high enough that powder particles do not become highly negatively charged, and scan strategies must be used to avoid build-up of regions of negatively charged particles. In practice, electron beam energy is more diffuse; in part, so as not to build up too great a negative charge in any one location. As a result, the effective melt pool size increases, creating a larger heat-affected zone.

Consequently, the minimum feature size, resolution and surface finish of an EBM process is typically larger than an SLM process. As mentioned above, in EBM the powder bed must be conductive. Thus, EBM can only be used to process conductive materials (e.g., metals) whereas, lasers can be used with any material that absorbs energy at the laser wavelength (e.g., metals, polymers and ceramics).

Electron beam generation is typically a much more efficient process than laser beam generation. When a voltage difference is applied to the heated filament in an electron beam system, most of the electrical energy is converted into the electron beam, and higher beam energies (above 1 kW) are available at a moderate cost. By contrast, it is common for only 10–20% of the total electrical energy input for laser systems to be converted into beam energy, with the remaining energy lost in the form of heat. In addition, lasers with beam energies above 1 kW are typically much more expensive than comparable electron beams with similar energies. Thus, electron beams are a less costly high energy source than laser beams. Newer fiber lasers, however, are more simple in their design, more reliable to maintain, and more efficient to use (with conversion efficiencies reported of 70–80% for

some fiber lasers) and thus, this energy cost advantage for electron beams may not be a major advantage in the future.

EBM powder beds are maintained at a higher temperature than SLM powder beds. There are several reasons for this. First, the higher energy input of the beam used in the EBM system naturally heats the surrounding loose powder to a higher temperature than the lower energy laser beams. In order to maintain a steady-state uniform temperature throughout the build (rather than having the build become hotter as the build height increases) the EBM process uses the electron beam to heat the metal substrate at the bottom of the build platform before laying a powder bed.

By defocusing the electron beam and scanning it very rapidly over the entire surface of the substrate or the powder bed, the bed can be preheated rapidly and uniformly to any pre-set temperature. As a result, the radiative and resistive heaters present in most SLM systems for powder bed heating are not typically used in EBM. By maintaining the powder bed at an elevated temperature, however, the resulting microstructure of a typical EBM part is significantly different from a typical SLM part (see Fig. 5.14). In particular, in SLM the individual laser scan lines are typically easily distinguishable, whereas individual scan lines are often indistinguishable in EBM microstructures. Rapid cooling in SLM creates smaller grain sizes; and subsequent layer deposits only partially re-melt the previously deposited layer. The powder bed is held at a low enough temperature that elevated temperature grain growth does not erase the layering effects. In EBM, the higher temperature of the powder bed, and the larger and more diffuse heat input result in a contiguous grain pattern that is more representative of a cast microstructure, with less porosity than an SLM microstructure. Although the microstructures presented in Fig. 5.14 are representative of the current practice of SLM and EBM, it should be noted that the presence of beam traces in the final microstructure (as seen in Fig. 5.14) is process parameter and material dependent. For certain alloys, such as titanium, it is not uncommon for contiguous grain growth across layers even for SLM. For other materials, such as those that have a higher melting point, the layering may be more prevalent. In addition, layering is more prevalent for process parameter combinations of: lower bed temperature, lower beam energy, faster scan rate, thicker layers, and/or larger scan spacing for both SLM and EBM.

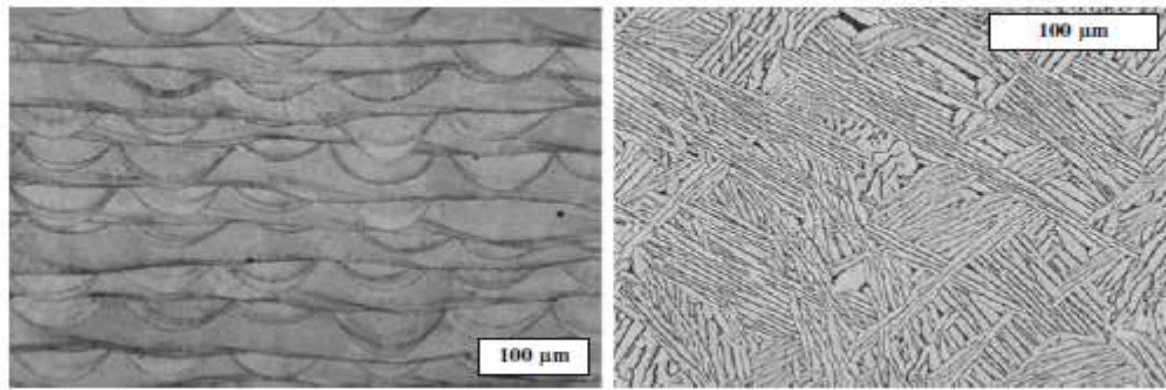


Fig. 5.14 Representative CoCrMo SLM microstructure (*left*, courtesy EOS), and Ti6Al4V EBM microstructure (*right*, courtesy Arcam)

One of the most promising aspects of EBM is the ability to move the beam nearly instantaneously. Although the current control system for EBM machines makes use of this capability, future improvements to scanning strategies may dramatically increase the build speed of EBM, helping to distinguish it even more from SLM for certain applications. For instance, when nonsolid cross-sections are created, in particular when scanning truss-like structures (with designed internal porosity), instantaneous beam motion from one scan location to another can dramatically speed up the production of the overall product. In addition, future scan strategies may help reduce the buildup of residual stresses in powder bed fusion processes.

It may be that future EBM scan strategies may enable complex free-form components to be made without attachment to a base substrate. This will have significant benefits for users, as the need to remove metal support structures means that postprocessing of EBM and SLM parts is nontrivial.

PROCESS BENEFITS AND DRAWBACKS

In PBF, the loose powder bed is a sufficient support material for polymer PBF. This saves significant time during part building and post-processing, and enables advanced geometries that are difficult to post-process when supports are necessary.

As a result, internal cooling channels and other complex features that would be impossible to machine are possible. Supports, however, are required for most metals. The high residual stresses experienced when processing metals means that support structures are typically required to keep the part from excessive warping. This means that post-processing of metal parts after AM can be expensive and time consuming. Small features (including internal cooling channels) can usually be formed without supports; but the part itself is usually constrained to a substrate at the bottom of the build platform to keep it from warping.

Accuracy and surface finish of powder-based AM processes are typically inferior to liquid-based processes. However, accuracy and surface finish are strongly influenced by the operating conditions and the powder particle size. Finer particle sizes produce smoother, more accurate parts but are difficult to spread and handle.

Larger particle sizes facilitate easier powder processing and delivery, but hurt surface finish, minimum feature size and minimum layer thickness. The build materials used in these processes typically exhibit 3–4% shrinkage, which can lead to part distortion. Materials with low thermal conductivity result in better accuracy as melt pool and solidification are more controllable and part growth is minimized when heat conduction is minimized.

With PBF processes, total part construction time can take longer than other additive manufacturing processes because of the pre-heat and cool-down cycles involved. However, as is the case with several newer machine designs, removable build platforms enable pre-heat and cool-down to occur off-line, thus enabling much greater machine productivity. Additionally, the ability to nest polymer parts in 3-dimensions, as no support structures are needed, mean that many parts can be produced in a single build; thus dramatically improving the productivity of these processes when compared with processes that require supports.

APPLICATIONS OF POWDER BED FUSION PROCESSES

1. Automotive applications of powder bed fusion

The applications of powder bed fusion in the automotive industry are many, from prototyping to light weighting of components. Listed below are some examples of where the technology is used in the automotive industry:

- **Tyre molds** – Tyre tread molds often contain very thin but complex features. They improve the tyres' functionality and give them a more stable tread profile throughout their lifespan. Powder bed fusion outfits Michelin tyre molds with extremely thin structures and other advanced geometry that would be impossible or extremely expensive to manufacture with standard techniques.
- **Seat belt bracket** – General motors have turned to powder bed fusion to reduce the weight and assembly complexity of their seat belt brackets. Using generative design, a single component was created that had the required structural strength and took the place of the eight sub-components of previous designs.
- **Brake caliper** – Bugatti 3D printed a titanium brake caliper that is normally made out of aluminium. The resulting caliper was stronger than the original and weighed 40% less.

2. Medical applications of powder bed fusion

The medical industry is a major adopter of 3D printing technology – especially powder bed fusion. This is in part due to the wide range of biocompatible materials that are well-suited to these printers as well as the fact that the process can produce a variety of complex geometries. Listed below are some applications of powder bed fusion for medical technology:

- **Jaw reconstruction** – An entire jaw bone was printed out of titanium and implanted into a patient. A custom jaw bone was designed based on x-rays of the patient's skull. This artificial jaw bone had cavities built into it to allow for muscle attachment and nerve growth.
- **Knee replacement** – The cartilage in knee joints wears down with time and in some cases the condition can no longer be managed with medication. In this case a metal knee joint may be implanted to reinforce the area. A custom knee joint is created from biocompatible material for each patient by making use of CT-scan data.
- **Hip joint** – 3D-printed hip joints were first implanted over a decade ago and have now become common. Tens of thousands of hip joints have been implanted into patients that make use of biocompatible titanium and complex porous structures to promote bone stitching into the joint. This technology has benefited a wide range of patients and offers a drastic improvement over older implants.

3. Aerospace applications of powder bed fusion

The aerospace industry, one of the early adopters of powder bed fusion for metal parts, operates at the very edge of material science and engineering technology in order to push the limits of what's possible. Listed below are some applications of powder bed fusion in aerospace engineering:

- **Rocket engine combustion chamber** – Launcher, an American rocket startup, used powder bed fusion to consolidate the various parts of a rocket engine combustion chamber into one component, drastically reducing part complexity. Furthermore, it allows for the inclusion of internal cooling channels within the structure of the rocket to further improve the engine's performance. This component experiences extreme temperatures and pressures and serves as a testament to the performance of 3D-printed parts.

- **GE9C Engine** – The engines on the Boeing 777x are the largest and most powerful commercial jet engines to date and incorporate over 300 3D-printed parts. They are 10% more fuel efficient when compared to their predecessors. This drastic increase proves that the applications of powder bed fusion are set to grow considerably within the aerospace industry.
- **Injector head** – The Ariane 6 rocket booster made use of powder bed fusion for the manufacture of a complex rocket engine part known as an injector head. This allowed for a simplification in the assembly from 248 parts to only one. It significantly reduced the production time from three months to a day and a half as well as halving the cost of the part.

EXTRUSION-BASED SYSTEMS

INTRODUCTION

This chapter deals with AM technologies that use extrusion to form parts. These technologies can be visualized as similar to cake icing, in that material contained in a reservoir is forced out through a nozzle when pressure is applied. If the pressure remains constant, then the resulting extruded material (commonly referred to as “roads”) will flow at a constant rate and will remain a constant cross-sectional diameter. This diameter will remain constant if the travel of the nozzle across a depositing surface is also kept at a constant speed that corresponds to the flow rate.

The material that is being extruded must be in a semi-solid state when it comes out of the nozzle. This material must fully solidify while remaining in that shape. Furthermore, the material must bond to material that has already been extruded so that a solid structure can result.

FUSED DEPOSITION MODELLING (FDM)

By far the most common extrusion-based AM technology is Fused Deposition Modeling (FDM), produced and developed by Stratasys, USA. FDM uses a heating chamber to liquefy polymer that is fed into the system as a filament. The filament is pushed into the chamber by a tractor wheel arrangement and it is this pushing that generates the extrusion pressure. A typical FDM machine can be seen in Fig. 6.6, along with a picture of an extrusion head. The initial FDM patent was awarded to Stratasys founder Scott Crump in 1992 and the company has gone from strength to strength to the point where there are more FDM machines than any other AM machine type in the world. The major strength of FDM is in the range of materials and the effective mechanical properties of resulting parts made using

this technology. Parts made using FDM are amongst the strongest for any polymer-based additive manufacturing process.

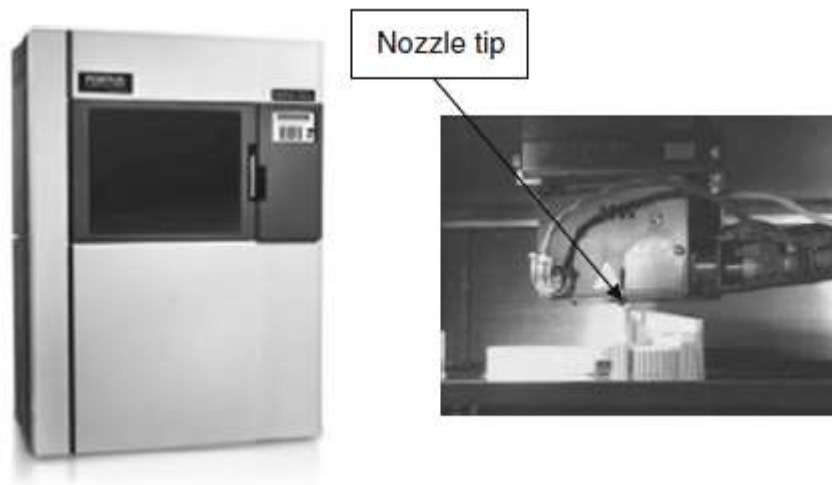


Fig. 6.6 Typical Stratasys machine showing the outside and the extrusion head inside

The main drawback to using this technology is the build speed. As mentioned earlier, the inertia of the plotting heads means that the maximum speeds and accelerations that can be obtained are somewhat smaller than other systems. Furthermore, FDM requires material to be plotted in a point-wise, vector fashion that involves many changes in direction.

The Stratasys FDM machine range is very wide, from low-cost, small-scale, minimal variable machines through to larger, more versatile, and more sophisticated machines that are inevitably more expensive. The company has separated its operations into subsidiaries, each dedicated to different extents of the FDM technology.

It should be noted that FDM machines that operate with different layer thicknesses do so because of the use of different nozzle diameters. These nozzles are manually changeable and only one nozzle can be used during a specific build. The nozzle diameter also controls the road width. Obviously, a larger diameter nozzle can extrude more material for a specific plotting speed and thus shorten the build time at the expense of lower precision.

FORTUS software options include the expected file preparation and build setup options. However, there are also software systems that allow the user to remotely monitor the build and schedule builds using a multiple machine setup. Stratasys has many customers who have purchased more than one machine and their software is aimed at ensuring these customers can operate them with a minimum of user intervention. Much of this support was developed because of another Stratasys subsidiary called Redeye, who use a large number of FDM machines as a service bureau for customers. Much of the operation of Redeye is based on customers logging in to an Internet account and uploading STL files. Parts are scheduled for

building and sent back to the customer within a few days, depending on part size, amount of finishing required, and order size. Stratasys also recognizes that many parts coming off their machines will not be immediately suitable for the final application and that there may be an amount of finishing required. To assist in this, Stratasys provides a range of finishing stations that are designed to be compatible with various FDM materials. Finishing can be a mixture of chemically induced smoothing (using solvents that lightly melt the part surface) or burnishing using sodium bicarbonate as a light abrasive cleaning compound. Also, although there is a range of different material colors for the ABS build material, many applications require the application of primers and coatings to achieve the right color and finish on a part.

MATERIALS

The most popular material is the ABSplus material, which can be used on all current Stratasys FDM machines. This is an updated version of the original ABS (acrylonitrile butadiene styrene) material that was developed for earlier FDM technology. Users interested in a translucent effect may opt for the ABSi material, which has similar properties to other materials in the ABS range. Some machines also have an option for ABS blended with Polycarbonate. Table 6.1 shows properties for various ABS materials and blends.

Table 6.1 Variations in properties for the ABS range of FDM materials

Property	ABS	ABSi	ABSplus	ABS/PC
Tensile strength	22 MPa	37 MPa	36 MPa	34.8 MPa
Tensile modulus	1,627 MPa	1,915 MPa	2,265 MPa	1,827 MPa
Elongation	6%	3.1%	4%	4.3%
Flexural strength	41 MPa	61 MPa	52 MPa	50 MPa
Flexural modulus	1,834 MPa	1,820 MPa	2,198 MPa	1,863 MPa
IZOD impact	106.78 J/m ²	101.4 J/m ²	96 J/m ²	123 J/m ²
Heat deflection @ 66 psi	90°C	87°C	96°C	110°C
Heat deflection @ 264 psi	76°C	73°C	82°C	96°C
Thermal expansion	5.60E-05 in/in/F	6.7E-6 in/in/F	4.90E-05 in/in/F	4.10E-5 in/in F
Specific gravity	1.05	1.08	1.04	1.2

These properties are quite similar to many commonly used materials. It should be noted, however, that parts made using these materials on FDM machines may exhibit regions of lower strength than shown in this table because of interfacial regions in the layers and possible voids in the parts. There are three other materials available for FDM technology that may be useful if the ABS materials cannot fulfill the requirements. A material that is predominantly PC-based can provide higher tensile properties, with a flexural strength of 104 MPa. A variation of this material is the PC-ISO, which is also PC-based, formulated to ISO 10993-1 and USP Class VI requirements. This material, while weaker than the normal PC with a flexural strength of 90 MPa, is certified for use in food and drug packaging and

medical device manufacture. Another material that has been developed to suit industrial standards is the ULTEM 9085 material. This has particularly favorable flame, smoke, and toxicity (FST) ratings that makes it suitable for use in aircraft, marine, and ground vehicles. If applications require improved heat deflection, then an option would be to use the Polyphenylsulfone (PPSF) material that has a heat deflection temperature at 264 psi of 189_C. It should be noted that these last three materials can only be used in the high-end machines and that they only work with breakaway support system, making their use somewhat difficult and specialized. The fact that they have numerous ASTM and similar standards attached to their materials indicates that Stratasys is seriously targeting final product manufacture (Direct Digital Manufacturing) as a key application for FDM.

Note that FDM works best with polymers that are amorphous in nature rather than the highly crystalline polymers that are more suitable for PBF processes. This is because the polymers that work best are those that are extruded in a viscous paste rather than in a lower viscosity form. As amorphous polymers, there is no distinct melting point and the material increasingly softens and viscosity lowers with increasing temperature. The viscosity at which these amorphous polymers can be extruded under pressure is high enough that their shape will be largely maintained after extrusion, maintaining the extrusion shape and enabling them to solidify quickly and easily. Furthermore, when material is added in an adjacent road or as a new layer, the previously extruded material can easily bond with it. This is different from Selective Laser Sintering, which relies on high crystallinity in the powdered material to ensure that there is a distinct material change from the powder state to a liquid state within a well-defined temperature region.

PLOTTING AND PATH CONTROL

As with nearly all additive manufacturing systems, extrusion-based machines mostly take input from CAD systems using the generic STL file format. This file format enables easy extraction of the slice profile, giving the outline of each slice. As with most systems, the control software must also determine how to fill the material within the outline. This is particularly crucial to this type of system, however, since extrusion heads physically deposit material that fills previously vacant space. There must be clear access for the extrusion head to deposit fill material within the outline without compromising the material that has already been laid down. Additionally, if the material is not laid down close enough to adjacent material, it will not bond effectively. In contrast, laser-based systems can permit, and in fact

generally require, a significant amount of overlap from one scan to the next and thus there are no head collision or overfilling-equivalent phenomena.

As mentioned earlier, part accuracy is maintained by plotting the outline material first, which will then act as a constraining region for the fill material. The outline would generally be plotted with a lower speed to ensure consistent material flow. The outline is determined by extracting intersections between a plane (representing the current cross section of the build) and the triangles in the STL file. These intersections are then ordered so that they form a complete, continuous curve for each outline (there may be any number of these curves, either separate or nested inside of each other, depending upon the geometry of that cross section). The only remaining thing for the software to do at this stage is to determine the start location for each outline. Since the extrusion nozzle is a finite diameter, this start location is defined by the center of the nozzle. The stop location will be the final point on this trajectory, located approximately one nozzle diameter from the start location. Since it is better to have a slight overlap than a gap and because it is very difficult to precisely control flow, there is likely to be a slight overfill and thus swelling in this start/stop region. If all the start/stop regions are stacked on top of each other, then there will be a “seam” running down the part. In most cases, it is best to have the start/stop regions randomly or evenly distributed around the part so that this seam is not obvious. However, a counter to this may be that a seam is inevitable and having it in an obvious region will make it more straightforward for removing during the post-processing stage.

Determining the fill pattern for the interior of the outlines is a much more difficult task for the control software. The first consideration is that there must be an offset inside the outline and that the extrusion nozzle must be placed inside this outline with minimal overlap. The software must then establish a start location for the fill and determine the trajectory according to a predefined fill pattern. This fill pattern is similar to those used in CNC planar pocket milling where a set amount of material must be removed with a cylindrical cutter. As with CNC milling, there is no unique solution to achieving the filling pattern. Furthermore, the fill pattern may not be a continuous, unbroken trajectory for a particular shape. It is preferable to have as few individual paths as possible but for complex patterns an optimum value may be difficult to establish. As can be seen with even the relatively simple cross section in Fig. 6.3, start and stop locations can be difficult to determine and are somewhat arbitrary. Even with a simpler geometry, like a circle that could be filled continuously using a spiral fill pattern, it is possible to fill from the outside-in or from the inside-out.

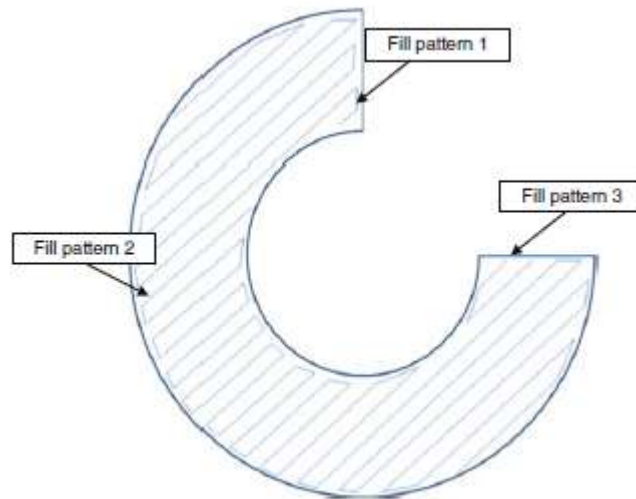


Fig. 6.3 A typical fill pattern using an extrusion-based system, created in three stages

Parts are weakened as a result of gaps between extruded roads. Since weave patterns achieve the best mechanical properties if they are extruded in a continuous path, there are many changes in direction. The curvature in the path for these changes in direction can result in gaps within the part as illustrated in Fig. 6.5. This figure illustrates two different ways to define the toolpath, one that will ensure no additional material will be applied to ensure no part swelling and good part accuracy.

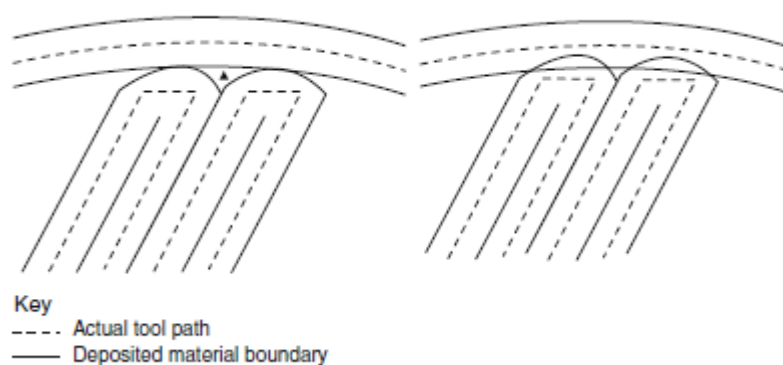


Fig. 6.5 Extrusion of materials to maximize precision (*left*) or material strength (*right*) by controlling voids

The second approach defines an overlap that will cause the material to flow into the void regions, but which may also cause the part to swell. However, in both cases gaps are constrained within the outline material laid down at the perimeter. Additionally, by changing the flow rate at these directional change regions, less or more material can be extruded into these regions to compensate for gaps and swelling. This means that the material flow from the extrusion head should not be directly proportional to the instantaneous velocity of the head when the velocity is low, but rather should be increased or decreased slightly,

depending on the toolpath strategy used. Furthermore, if the velocity is zero but the machine is known to be executing a directional change in a weave path, a small amount of flow should ideally be maintained. This will cause the affected region to swell slightly and thus help fill gaps. Obviously, care should be taken to ensure that excess material is not extruded to the extent that part geometry is compromised.

It can be seen that precise control of extrusion is a complex trade-off, dependent on a significant number of parameters, including:

- **Input pressure:** This variable is changed regularly during a build, as it is tightly coupled with other input control parameters. Changing the input pressure (or force applied to the material) results in a corresponding output flow rate change. A number of other parameters, however, also affect the flow to a lesser degree.
- **Temperature:** Maintaining a constant temperature within the melt inside the chamber would be the ideal situation. However, small fluctuations are inevitable and will cause changes in the flow characteristics. Temperature sensing should be carried out somewhere within the chamber and therefore a loosely coupled parameter can be included in the control model for the input feed pressure to compensate for thermal variations. As the heat builds up, the pressure should drop slightly to maintain the same flow rate.
- **Nozzle diameter:** This is constant for a particular build, but many extrusion based systems do allow for interchangeable nozzles that can be used to offset speed against precision.
- **Material characteristics:** Ideally, control models should include information regarding the materials used. This would include viscosity information that would help in understanding the material flow through the nozzle. Since viscous flow, creep, etc. are very difficult to predict, accurately starting and stopping flow can be difficult.
- **Gravity and other factors:** If no pressure is applied to the chamber, it is possible that material will still flow due to the mass of the molten material within the chamber causing a pressure head. This may also be exacerbated by gaseous pressure buildup inside the chamber if it is sealed. Surface tension of the melt and drag forces at the internal surfaces of the nozzle may retard this effect.
- **Temperature build up within the part:** All parts will start to cool down as soon as the material has been extruded. However, different geometries will cool at different rates. Large, massive structures will hold their heat for longer times than smaller,

thinner parts, due to the variation in surface to volume ratio. Since this may have an effect on the surrounding environment, it may also affect machine control.

Taking these and other factors into consideration can help one better control the flow of material from the nozzle and the corresponding precision of the final part. However, other uncontrollable or marginally controllable factors may still prove problematic to precisely control flow. Many extrusion-based systems, for instance, resort to periodically cleaning the nozzles from time to time to prevent build-up of excess material adhered to the nozzle tip.

BIO-EXTRUSION

Extrusion-based printing is a very common technique within the field of 3D printing which entails extruding, or forcing, a continuous stream of melted solid material or viscous liquid through a sort of orifice, often a nozzle or syringe. When it comes to extrusion based bioprinting, there are three main type of extrusion. These are pneumatic driven, piston driven, and screw driven. Each extrusion methods have their own advantages and disadvantages. Pneumatic extrusion used pressurized air to force liquid bioink through a depositing agent. The air used to move the bioink must be free of contaminants. Air filters are commonly used to sterilize the air before it is used. Piston driven extrusion utilizes a piston connected to a guide screw. The linear motion of the piston squeezes material out of the nozzle. Screw driven extrusion uses an auger screw to extrude material. The rotational motion forces the material down and out of the nozzle. Screw driven devices allow for the use of higher viscosity materials and provide more volumetric control. Once printed, many materials require a crosslinking step to achieve the desired mechanical properties for the construct, which can be achieved for example with the treatment of chemical agents or photo-crosslinkers.

Direct extrusion is one of the most common extrusion-based bioprinting techniques, wherein the pressurized force directs the bioink to flow out of the nozzle, and directly print the scaffold without any necessary casting. The bioink itself for this approach can be a blend of polymer hydrogels, naturally derived materials such as collagen, and live cells suspended in the solution. In this manner, scaffolds can be cultured post-print and not need further treatment for cellular seeding. Some focus in the use of direct printing techniques is based upon the use of coaxial nozzle assemblies, or coaxial extrusion. The coaxial nozzle setup enables the simultaneous extrusion of multiple material bioinks, capable of making multi-layered scaffolds in a single extrusion step. The development of tubular structures has found the layered extrusion achieved via these techniques desirable for the radial variability in

material characterization that it can offer, as the coaxial nozzle provides an inner and outer tube for bioink flow. Indirect extrusion techniques for bioprinting rather require the printing of a base material of cell-laden hydrogels, but unlike direct extrusion contains a sacrificial hydrogel that can be trivially removed post-printing through thermal or chemical extraction. The remaining resin solidifies and becomes the desired 3D-printed construct.

PROCESS BENEFITS AND DRAWBACKS

PROCESS BENEFITS

1. Low cost per part
2. Flexibility of operation
3. In hot extrusion, post execution alterations are easy because product is still in heated condition
4. Continuous operation
5. High production volumes
6. Many types of raw materials can be used
7. Good mixing (Compounding)
8. Surface finish obtained is good
9. Good mechanical properties obtained in cold extrusion

PROCESS DRAWBACKS

1. Variations in size of product
2. Product limitations because of only one type of cross section can be obtained at a time
3. High initial cost setup

APPLICATIONS OF EXTRUSION-BASED PROCESSES

- Extrusion is widely used in production of tubes and hollow pipes.
- Aluminum extrusion is used in structure work in many industries.
- This process is used to produce frames, doors, window etc. in automotive industries.
- Extrusion is widely used to produce plastic objects.