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"Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing", 2nd Edition

By Ian Gibson (Deakin University, Australia), David Rosen (Georgia Institute of Technology, USA) and Brent Stucker (University of Louisville, USA), Springer Science+Business Media, New York, USA, 2015, 498 pages, ISBN: 978-1-4939-2112-6, £81.00, €96.29, US$119.00

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Introduction

"Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing" is authored by Ian Gibson, David Rosen and Brent Stucker, who collectively possess 60 years' experience in the field of additive manufacturing (AM). This is the second edition of the book which aims to include current developments and innovations in a rapidly changing field. Its primary aim is to serve as a teaching aid for developing and established curricula, therefore becoming an all-encompassing introductory text for this purpose. It is also noted that researchers may find the text useful as a guide to the 'state-of-the-art' and to identify research opportunities.

The book is structured to provide justification and information for the use and development of AM by using standardised terminology to conform to standards (American Society for Testing and Materials (ASTM) F42) introduced since the first edition. The basic principles and historical developments for AM are introduced in summary in the first three chapters of the book and this serves as an excellent introduction for the uninitiated. Chapters 4–11 focus on the core technologies of AM individually and, in most cases, in comprehensive detail which gives those interested in the technical application and development of the technologies a solid footing. The remaining chapters provide guidelines and examples for various stages of the process including machine and/or materials selection, design considerations and software limitations, applications and post-processing considerations.

Principles and Processes

The first three chapters provide a basic understanding of why someone might want to utilise AM in the context of traditional methods as well as developments in AM since its inception. In the initial chapters the reason for introducing standardised terminology is justified in contrast to the historical terms. For example, the use of 'rapid prototyping' to describe the field is no longer relevant as the technology is now used for functional components as well.

Brief summaries of the process are also provided in these initial chapters in increasing detail as the reader approaches the technical chapters. This provides a realistic view of actions required throughout the process and gives context to references made throughout the book. In its simplest form the process can be universally summarised as:

- conceptualisation and computer aided design (CAD)
- conversion to STereoLithography (STL)/additive manufacturing file (AMF)
- transfer to AM machine and file manipulation
- machine setup
- build
- removal and cleanup
- post-processing
- application.

Additive Layer Manufacturing Technologies in Detail

Chapters 4–11 describe seven different printing processes in differing degrees of detail. Topics such as 'vat photopolymerisation' (VP) and 'powder bed fusion' (PBF) are covered in such comprehensive detail that their chapters are double the length compared with 'binder jetting' (BJ), despite the latter being a very well used industrial technique. Printable materials and delivery mechanisms are also listed here and the chapters include a 'process benefits and drawbacks' section, useful for the beginner. It should be noted that some processes (extrusion, sheet lamination and directed-energy deposition) are omitted from this review.

Vat Photopolymerisation

VP processes make use of liquid, light-curable resins as their primary materials. Upon irradiation, these materials undergo photopolymerisation, becoming solid. Ultraviolet (UV) light is projected onto the build plate, curing a layer before recoating. Methods for illuminating the photopolymers are presented, including masked projection, layer-wise processing and vector scan point-wise processing. Expressions relating laser power, scan speed, spot size and cure depth are derived, forming the basis of a process model which can be applied generally. Curable materials are discussed, including an overview of photopolymer chemistry and their interactions with radiation. Another method, called the 'two-photon' approach, describes how a dual light source can increase part resolution – feature sizes of 0.2 μm have been achieved. Advantages of VP include part accuracy, surface finish and process flexibility. The main drawback is their usage of photopolymers, which generally do not have the impact strength or durability of good quality injection moulded thermoplastics.

Powder Bed Fusion

PBF methods deposit layers of powder which are sequentially fused together by an energy source resulting in solid parts residing in a powder bed. The prominent methods are selective laser sintering (SLS) and electron beam melting (EBM), and these two are well compared: EBM processes benefit from the flexibility and high energy of their heat source, which can move nearly instantaneously and with split beams; EBM builds typically maintain the bed at high temperature and can create parts with a cast, low porosity, low residual stress microstructure. However their requirement for a vacuum chamber and conductive target material restricts material capabilities whereas SLS machines can process materials such as polymers and ceramics in gaseous atmospheres. This chapter builds on the process model from the previous chapter, applying the concepts to the fusion process of solids and methods for reducing internal stresses in solidified parts. PBF is a well commercialised technology, but due to the lapsing of major patents there are some open-source machines available which have led inventors to create non-engineering applications of the technology too.

Materials Jetting

The first generation of materials jetting (MJ) machines was commercialised in the 1980s. They relied on heated waxy thermoplastics deposited by inkjet printheads, lending themselves to modelling and investment casting manufacture; however the more recent focus has been on deposition of acrylate photopolymers, wherein droplets of liquid monomer are formed and then exposed to UV light to initiate polymerisation. Machines with build spaces as big as 1000 × 800 × 800 mm are available, as well as multi-material capability which can print 1000+ materials by varying the composition of several photopolymers. Research groups around the world are working on other material groups such as non-photopolymers, ceramic suspensions and low melting point metals (including aluminium). The challenge of forming molten droplets, then controlling deposition and solidification characteristics has kept these material systems in the research arena. A section on the fluid mechanics of droplet formation and jetting is included in a process model for the MJ process (a section which is also relevant to Chapter 8).

Binder Jetting

BJ methods were primarily developed at Massachusetts Institute of Technology (MIT), USA, during the early 1990s and feature a powder bed similar to that of the PBF process (Chapter 5). However, instead of using an energy source to fuse the material together, an inkjet head deposits a binder onto each layer to form part cross-sections. The binder forms agglomerates with the powder particles and provides bonding with the layer below. The chapter describes some commercial materials available, and notes that many of them require post-processing to increase strength, for example by infiltration with another material. Materials include polymers (for example, poly(methyl methacrylate) (PMMA)), ceramics, foundry sands and metals such as 420 stainless steel or Inconel alloy 625 infiltrated with bronze. This technology can be scaled up quite easily, as demonstrated by machines with an incredible 4 × 2 × 1 m build volume. Although the subject of ink drop formation is covered in the previous chapter, a discussion surrounding ink interaction with the powder bed is missing here. Disappointingly for a process described as one of the most readily scalable, the chapter is one of the shortest – although some aspects, such as powder handling, are discussed in other chapters.

Guidelines for Process Selection and Ancillary Process Tasks

The remainder of the book provides outlines and information on software applications and physical processes necessary for gaining maximum advantage from AM.

Process Selection

There are software applications where the performance attributes of each AM technology option are weighted and ranked based on the relevance of the input parameters (for example geometric considerations and mechanical properties). A particular example, RM Select, is provided (installation file and manual are available (1, 2)). This information is particularly pertinent to those interested in production applications of AM.

Post-processing

AM is often viewed as a complete process and therefore, to the uninitiated, it can be a surprise to learn of the requirement for post-processing. The book introduces the various types of support structures required to achieve and maintain all levels of geometric complexity and the subsequent post-processing methods and design considerations to aid their removal. Depending on the application of the part, surface finishing may also be required. In this case it may be necessary to design extra material in the areas to be post-processed to ensure the desired dimensions are maintained.

Powder bed methods possess 'natural' supports where the built object is encased in excess material. They are named as such as they are an intrinsic part of the process. The main disadvantage of natural supports is that the part must be designed so that the excess material can be removed, for example for powder bed methods parts that are designed to be hollow must have an escape hole for loose powder. In this case the excess material is recycled as much as possible with some sieving usually required.

'Synthetic' supports are required for methods that do not have 'natural' supports or for methods that have stresses as an intrinsic part of the process, for example powder bed fusion parts need to be tethered to the substrate to prevent warping from stresses created by the presence of significant temperature gradients. It is noted that these stresses can be reduced, and therefore the requirement for synthetic supports is decreased, by raising the temperature of the build environment. For MJ and materials extrusion methods the support structures can be constructed from the build material or a secondary material. In the case of secondary materials a second 'printhead' or a purge cycle is required to prevent contamination. If the 'synthetic' supports are constructed of the build material then they must be designed such that they can be easily removed in post-processing, it is common for printer software to include automatic support generation. Alternatively, the 'synthetic' supports can be constructed of a secondary material with differential solubility (with respect to the build material) and can simply be dissolved away post-process.

Post-processing is an integral procedure of AM and understanding the many factors to streamline and safeguard the integrity of the printed part is paramount.

Software Issues and Considerations

The file standard for AM technologies is the STL file format. The origin of this file extension hails to the first stereolithography machines commercialised by 3D Systems Inc, USA. This format is expressed as a list, either in binary or American Standard Code for Information Interchange (ASCII) (text), of the vertices of triangular facets used to approximate the surface of the digital part. This approximation is most relevant, with respect to deviation from the true geometry, when there are a significant number of curves in the part. The orientation of the facets is defined by the unit normally expressed in vector coordinates.

Due to the nature of the process, i.e. layer-by-layer, there is also the requirement to 'slice' the file prior to initiating the printing process. The generation of the support structures may be done before or during the slicing operation.

One problem with STL, unlike other CAD formats, is that there are no units associated with the file itself. Therefore the scale/dimensions must be checked to ensure the correct dimensions are applied. This can be particularly important for international communications, for example USA to EU or *vice versa*. Furthermore, it should be noted that not all graphics software packages can create STL files with adequate accuracy. One common issue when converting to STL is the creation of parts with holes (i.e. incomplete surfaces), which are not compatible with AM machines. More modern dedicated AM software packages are emerging, making this issue less prevalent.

Colour and materials properties are another factor to include into the definition of a part to print. For coloured parts this can be done by colouring of individual facets with solid colour (colour STL) or an image (virtual reality modelling language (VRML)). The advantage of applying an image is that the applied colour is not limited by the resolution of the facet. As the STL file format is surface data only there is the assumption that the underlying material is homogeneous. For AM technologies capable of multi-material printing the file typically has to be defined as distinct objects with materials properties defined for each. As yet, there is not an agreed upon standard file format for multi-material objects.

Design Considerations

Particular focus is made on the use of designed cellular structures and void filling. These structures can be symmetrical or conformal (with variable cell size to appropriately fill the void space). The primary advantage of using cellular structures is the reduction of the required build material without compromising overall strength. Cellular structures are a particular strength of AM processes given the fact that the entire structure can be designed, and with the help of software applications, optimised to achieve the most efficient strength-to-weight properties. The output cannot always be reproduced but a near approximation can be achieved with little compromise in performance. Examples of topology optimisation software given are Abaqus from Dassault Systèmes and OptiStruct from Altair.

Applications

This section offers a flavour of the multitude of possible applications of AM technologies. 'Rapid tooling' refers to the use of AM to create production tools. Typically these are reusable moulds, impressions or patterns from which the tools can be created. This method may be applied, in particular, if the material required for part production is not currently available in an AM technology or the mould can be improved upon by utilising the design freedoms of AM, for example conformal cooling channels for injection moulds. Medical and aerospace/automotive applications have received significant attention from the implementation of AM technologies. Medical procedures can be streamlined by developing surgical guides and tools. Prostheses and implants are of particular interest for the application of AM as they can be customised on a case-by-case basis. Significant research efforts are currently being employed to print with living cells and biomaterials for direct transplant. Another method is to print a biocompatible scaffold for post-process treatment with living cells to encourage natural material growth, for example Osteopore produces 'bioresorbable' implants to encourage natural bone growth over trephination holes from neurosurgery.

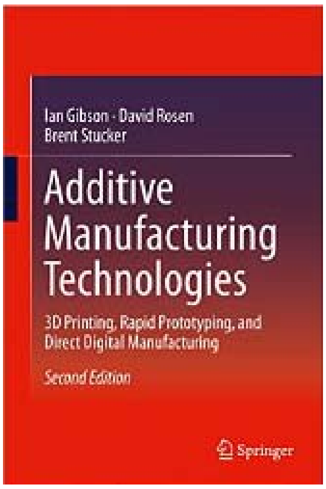
Aerospace applications of AM have been quite diverse with examples of engine system and non-structural components. The primary benefit for the aerospace industry is improved fuel efficiency by better performance and lighter weight components.

Business Opportunities and Future Directions

The book is rounded out by highlighting the fact that AM offers genuinely new avenues for production and product development and thus adjusted business models and practices could be required to accommodate the rapidly changing landscape of manufacturing.

Conclusion

Readers desiring a comprehensive introduction to the many technologies of AM should be satisfied. Although it is aimed primarily at students and educators, the authors do very well to appeal to those in research and manufacturing positions too. Excellent explanations of basic concepts through to the state-of-the-art make this a great starting point for in-depth research, whilst the process selection tools and business opportunities chapters will be very useful for manufacturers looking to explore this technology.



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The Reviewers

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