J. Paulo Davim (Ed.)

Additive and Subtractive Manufacturing

De Gruyter Series in Advanced Mechanical Engineering

Series Editor
J. Paulo Davim

Volume 4

Additive and Subtractive Manufacturing

Emergent Technologies

Edited by
J. Paulo Davim

DE GRUYTER
OLDENBOURG

Editor
Prof. Dr. J. Paulo Davim
University of Aveiro
Dept. of Mechanical Engineering
Campus Santiago
3810-193 Aveiro
Portugal
pdavim@ua.pt

ISBN 978-3-11-054816-7
e-ISBN (PDF) 978-3-11-054977-5
e-ISBN (EPUB) 978-3-11-054833-4
ISSN 2367-3796

Library of Congress Control Number: 2019945022

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at http://dnb.dnb.de.

Cover image: Sky_blue/iStock/thinkstock
Typesetting: Integra Software Services Pvt. Ltd.
Printing and binding: CPI books GmbH, Leck

www.degruyter.com

Preface

Nowadays, additive manufacturing (AM) and subtractive manufacturing (SM) offer numerous advantages in the production of single and multiple components, offering incomparable design independence with the facility to manufacture components from a wide range of materials, polymers, metals, composites, and so on. AM and SM are used to fabricate products in several industries: aeronautic, automotive, biomedical, and others. Therefore, the progress in AM and SM is very important for the modern industry.

This volume aims at providing recent information on progress on advances in additive and subtractive technologies in nine chapters. Chapter 1 of this book provides information on emerging trends in AM and SM. Chapter 2 is dedicated to the fused deposition modeling using polylactic acid (PLA), thereby improving the performance (state of the art). Chapter 3 describes the development of the basic drill design for cored holes in AM and SM. Chapter 4 contains information on AM of magnesium alloys. Chapter 5 is dedicated to AM for patient-specific medical use. Chapter 6 describes stereolithography and its applications. Chapter 7 contains information on ultrasonic-assisted deep-hole drilling. Finally, Chapter 8 contains information on information and computational modeling for sustainability evaluation and improvement of manufacturing processes.

This volume can be used as a research book for final undergraduate engineering course or as a topic on AM and SM at the postgraduate level. Also, this volume can serve as a useful reference for academics, researchers, mechanical, materials, production and industrial engineers, and professionals in AM and SM and related industries. The scientific interest in this book is evident for many important centers of the research, laboratories, and universities as well as for industry.

I acknowledge De Gruyter for this opportunity and professional support. Finally, I would like to thank all the authors who contributed for this book.

J. Paulo Davim
Aveiro, Portugal
November 2019

https://doi.org/10.1515/9783110549775-202

About the Editor

J. Paulo Davim received his Ph.D. in mechanical engineering in 1997, M.Sc. in mechanical engineering (materials and manufacturing processes) in 1991, Mechanical Engineering degree (5 years) in 1986 from the University of Porto (FEUP), the Aggregate title (Full Habilitation) from the University of Coimbra in 2005, and D.Sc. from London Metropolitan University in 2013. He is senior chartered engineer by the Portuguese Institution of Engineers with an MBA and Specialist title in engineering and industrial management. He is also Eur Ing by FEANI-Brussels and Fellow (FIET) by IET-London. At present, he is professor at the Department of Mechanical Engineering of the University of Aveiro, Portugal. He has more than 30 years of teaching and research experience in manufacturing, materials, mechanical and industrial engineering, with special emphasis in machining and tribology. He has also interest in management, engineering education, and higher education for sustainability. He has guided large numbers of postdoc, Ph.D., and master's students as well as coordinated and participated in several financed research projects. He has received several scientific awards. He has worked as evaluator of projects for ERC-European Research Council and other international research agencies as well as examiner of Ph.D. thesis for many universities in different countries. He is the editor in chief of several international journals, guest editor of journals, books editor, book series editor, and scientific advisory for many international journals and conferences. Presently, he is an editorial board member of 30 international journals and acts as reviewer for more than 100 prestigious Web of Science journals. In addition, he has also published as editor (and coeditor) for more than 120 books and as author (and coauthor) for more than 10 books, 80 book chapters, and 400 articles in journals and conferences (more than 250 articles in journals indexed in Web of Science core collection/h-index 52+/9000+ citations, SCOPUS/h-index 57+/11000+ citations, Google Scholar/h-index 74+/17000+).

https://doi.org/10.1515/9783110549775-203

Contents

List of contributors

Viktor P. Astakhov
General Motors Business Unit of PSMi, 1792 Elk Ln, Okemos, MI 48864, USA

Moisés Batista
Department of Mechanical Engineering and Industrial Design, Faculty of Engineering, University of Cadiz, Avenida de la Universidad de Cadiz 10, Puerto Real, E-11519 Cadiz, Spain

Samad Nadimi Bavil Oliaei
Department of Mechanical Engineering, ATILIM University, Kizilcasar Mahallesi, 06830 Incek Golbasi, Ankara, Turkey

Tianxing Chang
School of Mechanical Engineering, Xi'an Jiaotong University, No. 28 West Xianning Road, 710049 Xi'an, P.R. China

Ngoc-Hung Chu
Thai Nguyen University of Technology, Thai Nguyen, Vietnam

Suman Kalyan Das
Department of Mechanical Engineering, Jadavpur University, 188 Raja S.C. Mallick Rd, Kolkata 700032, India

J. Paulo Davim
University of Aveiro, Department of Mechanical Engineering, Campus Santiago, 3810–193 Aveiro, Portugal

Xuewei Fang
School of Mechanical Engineering, Xi'an Jiaotong University, No. 28 West Xianning Road, 710049 Xi'an, P.R. China
National Innovation Institute of Additive Manufacturing, Buiding A, Door of Metropolis, Jinye Road, 710065 Xi'an, P.R. China

Severo Raul Fernandez-Vidal
Department of Mechanical Engineering and Industrial Design, Faculty of Engineering, University of Cadiz, Avenida de la Universidad de Cadiz 10, Puerto Real, E-11519 Cadiz, Spain

Franck Girot
IKERBASQUE, Basque Foundation for Science, 48013 Bilbao, Spain
Faculty of Engineering, University of the Basque Country, Alameda de Urquijo s/n, 48013 Bilbao, Spain

Ke Huang
School of Mechanical Engineering, Xi'an Jiaotong University, No. 28 West Xianning Road, 710049 Xi'an, P.R. China
2 State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University, No. 99 Yan Cheung Road,710054 Xi'an, P.R. China

Yandong Jing
School of Mechanical Engineering, Xi'an Jiaotong University, No. 28 West Xianning Road, 710049 Xi'an, P.R. China

Theodora Kontodina
International Hellenic University, 14km Thessaloniki – N. Moudania, School of Science and Technology, Greece

Panagiotis Kyratsis
Western Macedonia University of Applied Sciences, Department of Mechanical Engineering and Industrial Design, 50100 Kila Kozani, Greece

Behzad Nasseri
Department of Chemical Engineering and Applied Chemistry, ATILIM University, Kizilcasar Mahallesi, 06830 Incek Golbasi, Ankara, Turkey

https://doi.org/10.1515/9783110549775-205

Van-Du Nguyen
Thai Nguyen University of Technology, Thai Nguyen, Vietnam

Swapnil Patel
General Motors Business Unit of PSMi, 1255 Beach Ct., Saline, MI 48176, USA

Prasanta Sahoo
Department of Mechanical Engineering, Jadavpur University, 188 Raja S.C. Mallick Rd, Kolkata 700032, India

Jorge Salguero
Department of Mechanical Engineering and Industrial Design, Faculty of Engineering, University of Cadiz, Avenida de la Universidad de Cadiz 10, Puerto Real, E-11519 Cadiz, Spain

Karmjit Singh
School of Engineering and IT, Federation University, Mt Helen Campus, VIC 3350, Australia

Ibrahim A. Sultan
School of Engineering and IT, Federation University, Mt Helen Campus, VIC 3350, Australia

Dimitrios Tzetzis
International Hellenic University, 14km Thessaloniki – N. Moudania, School of Science and Technology, Greece

Ana Pilar Valerga
Department of Mechanical Engineering and Industrial Design, Faculty of Engineering, University of Cadiz, Avenida de la Universidad de Cadiz 10, Puerto Real, E-11519 Cadiz, Spain

Prasanta Sahoo, Suman Kalyan Das

1 Emerging trends in additive and subtractive manufacturing

Abstract: The manufacturing sector has experienced a rapid advancement in the last few decades. From the popularization of computer numerical control machines as the face of traditional machining to the development of additive manufacturing (AM), it has been an open field in a series of innovations. Although AM is promising in terms of material savings and generation of complex parts rapidly, it cannot be a replacement for the conventional machining process, which seems better in terms of mass production. Thus, a hybridization of both the technologies seems to offer an optimal solution with respect to increased productivity and efficiency. Besides, improvement in information and communication technologies, Internet of things (IoT), robotics, and so on makes the manufacturing process self-sufficient and fully integrated. Besides, collaborative manufacturing systems are now a reality that responds in real time to meet changing demands and conditions in the factory, in the supply network, and in customer needs. All these have paved the roadmap for the implementation of Industry 4.0 (4th industrial revolution).

Keywords: Additive manufacturing, subtractive manufacturing, 3D printing, stereolithography, fused deposition modelling

1.1 Introduction

In the past few decades, few industries have been impacted by rapid advancement in technologies quite like manufacturing has. The ever-increasing demand for advanced products along with the pressure of cost reduction has led to a competitive attitude among the industrialists, which may be cited as one of the primary reasons for infusion of innovation in the manufacturing sector. Manufacturers have been faced with an “evolve-or-die” ultimatum as customers expect faster rates of innovation. Hence, apart from the traditional machining, things such as additive manufacturing (AM) techniques, smart manufacturing, and agile manufacturing, have been embraced by the manufacturing community, and continuous effort has been put to increase the effectiveness of these techniques. AM is the fast upcoming technology that has already proved its mettle and is responsible for transforming how products are designed and produced. It has gained popularity through other names such as 3-D printing, rapid prototyping (RP), additive layer manufacturing (ALM), and solid freeform fabrication (SFF) and has begun to be incorporated even in our daily lives. Subtractive manufacturing (SM) belongs to more of the conventional manufacturing techniques

https://doi.org/10.1515/9783110549775-001

based on machining of materials. Computer numerical control (CNC) is the modern machine for carrying out SM. As the advancement in the field of AM has been phenomenal in the past couple of decades, this chapter emphasizes more on its current trends and techniques. Figure 1.1 illustrates the basic philosophy of SM and AM.

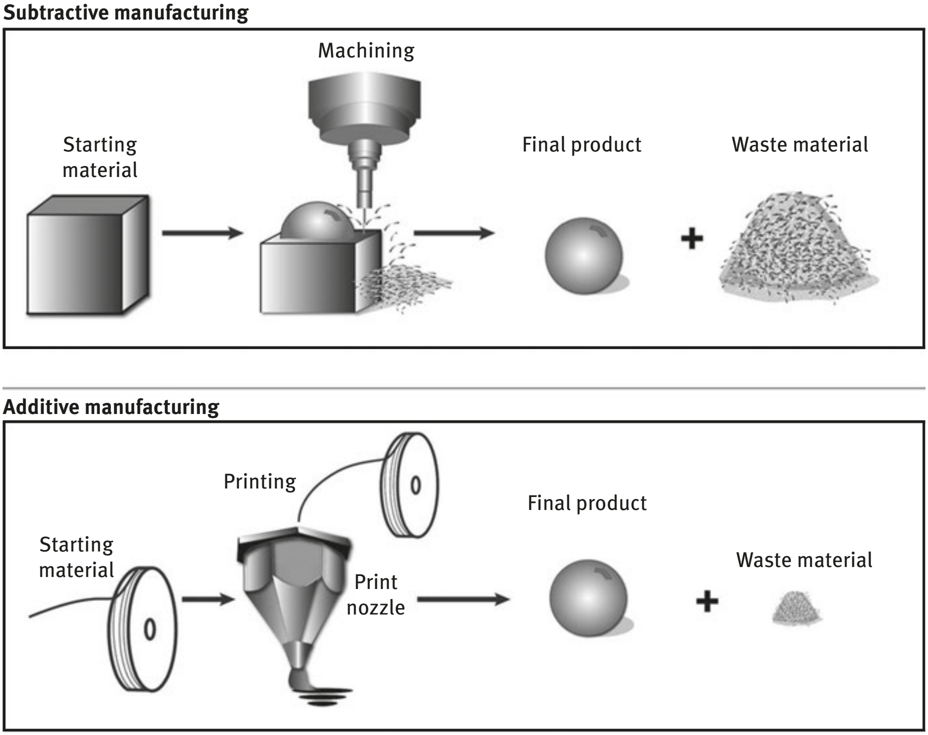


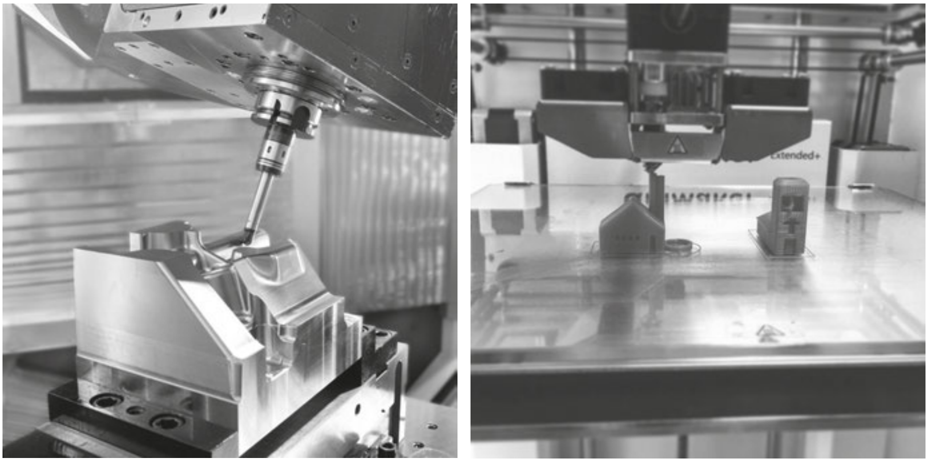
Figure 1.1: Basic principles of subtractive and additive manufacturing (source: GAO analysis).

The basic idea of AM is to first create the CAD (computer-aided design) model of the object to be build. The CAD model is sliced into individual layers. The object is then built by AM progressively layer by layer. Hence, it is obvious that costly jig and fixture, other equipment and processing which are normally required for any conventional production processes are eliminated in this case. According to the joint ISO/ASTM standard [1], AM is defined as the "process joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies," which cuts, drills, and grinds away the undesired excess from a solid piece of material, often metal. AM processes, on the other hand, have some following commonalities, namely a pc to store and process the geometric information as well as to drive the fabricator, deposition of feedstock which is administered as points, lines, or areas to create a part [2]. Some of the advantages of AM include:

i. Complex parts can be fabricated without the need of costly tooling.
ii. There is no issue of tolerances such as circularity, linearity, and perpendicularity, which requires a major share of attention in case of conventional machining.
iii. Components can be produced as per requirement reducing the load on inventory as well as the lead time for critical or outdated parts that need replacement.
iv. Material wastage is very less compared to SM.
v. Easy building of prototypes and optimizing the design.

Due to these host of advantages, AM has found wide acceptance across a variety of domains, such as aerospace and aviation industry, medical and surgical devices, electrical and electronics industry, defense and military applications, automotive applications [3]. Fuel injector nozzles are of complex shapes and require multicomponent assembly, which is now preferably produced through AM resulting in significant cost savings [3]. It is also reported [3] that burner tips for mixing and swirling result in energy savings as well as their service life extends if the same are made of high-temperature materials. Now, with AM it is possible to give complex shapes to high-temperature materials. Automobile sector has been one of the major adopters of 3D printing. Apart from various spare parts of brakes, clutches, and other subsystems of a vehicle, AM has had two major points of influence on automotive applications: as a source of product innovation and as a driver of supply chain transformation. AM has also penetrated medical and dental sector, where various organs, namely, liver, kidney, heart, ear, and nose have been produced by AM. Biocompatibility of the produced organs have been significantly improved. Besides, AM has the advantage of producing individually matched organs that can be derived from the patient's own medical imaging.

The inception of AM was based on production of nonmetallic parts, especially made of plastics. This posed a hindrance in its wide acceptability as most of the practical engineering components are metallic. However, substantial development in AM metal processing techniques over the past couple of decades has changed this scenario. Production of low-cost lasers, cheap high-performance computing devices, and development in feedstock technology (for producing metal powder) have made AM a front-runner production method [3] in today's world. This is also evident from the rapid movement of the commercial AM machines out of the shelves. Although AM technique is found to be a champion among all the production methodologies, some optimization and fine-tuning with respect to material of feedstock, produce tailor-made materials, AM processes, surface finish, properties of the produced part in order to be able to yield defect-free, sound, and reliable AM components. Figure 1.2 shows some actual photographs of parts being manufactured by machining and 3D printing.



(a) (b)

Figure 1.2: Parts being manufactured by (a) machining and (b) 3D printing (creative commons).

1.2 Evolution of additive manufacturing

1.2.1 Development of 3D printing

Modern AM technology or 3D printing, as it is known, was first realized around 1975 [2]. 3D Systems which was founded in 1986 is credited with selling the first commercial AM machine SLA-I. SLA-1 as the name suggests was based on stereolithography (SLA) technique of 3D printing. Progress in laser technology and material research paved the way for the first successful demonstration of this process. According to Bandyopadhyay and Bose [4], "SLA is a system where an ultraviolet (UV) light source is focused down into an UV photo-curable liquid polymer bath where upon contact, the polymer hardens. Patterns can be drawn using the UV source to semi-cure the polymer layer. Uncured polymer stays in the bath and provides support to the part being built. After a layer of printing is done, the hardened polymer layer moves down on a build plate in the liquid medium and the next layer of polymer is available on top for the following layer. This process continues until the part is finished based on the CAD design and is removed from the liquid medium. In most cases, further curing is needed before the part can be touched." The first patent of an RP system (using SLA) was obtained in 1986 [4].

1.2.2 Advancement in other rapid prototyping techniques

Apart from development of SLA-based system, other techniques of 3D printing were also developed parallelly. Advancement in material science and associated technologies led to the development of innovative AM machines that employed materials and methods. Apart from SLS, some of the popular RP systems included selective laser sintering (SLS), fused deposition modeling (FDM), ink jet printing, and laminated object manufacturing.

SLS was developed in the University of Texas at Austin [4]. The material is spread in powder form on the substrate where a laser selectively cures the powder according to the CAD geometry. The cured layer is then lowered for spreading of next layer of powder and the process is repeated until the desired part is produced. The first SLS machine was realized in 1986 [4]. Around the same time, FDM technique was invented in which a thermoplastic is extruded through a heated nozzle turning it to semimolten state, which is then deposited on to the bed by the movement of the nozzle (layer by layer) to produce the part.

In 1994, the first 3D printer using an inkjet approach was released [4]. This technique has lot of resemblance to SLA. Here, the thermoplastic material (often photopolymer) is jetted on the build tray in thin layers. If required, the layers may be exposed to UV light for curing. High-quality wax model could be produced though this technique similar to investment casting.

The preceding text discusses a few of the founding RP systems that were developed around the 1980s. However, many other people around the world realized the significance of these processes and started research in this field. Several enterprises have developed their individual 3D printing equipment based on new technologies. These developments of AM have ushered in a new era in the field of manufacturing.

1.2.3 Transformation from rapid prototyping to additive manufacturing

At the beginning, the capability of RP machines was limited to only producing parts made of plastics and other polymers, and they were unable to handle metals and ceramics. Now, the philosophy of AM is different from that of RP as the parts produced by AM is supposed to be of actual practical use [4]. Some more iterations happened in the field of RP technology before components made of metals or ceramics could be produced. Realizing the importance of metal processing, many companies started their own ventures of developing AM machines that could produce metallic parts. An enterprise of the name of EOS made the initial metal AM machine in around 1994 [4]. The company did experimentation on SLS technique and came up with a direct metal laser sintering machine (DMLS) machine, which had the ability to sinter metal powders. The machine could produce parts made of common metals, such as stainless steel, nickel, aluminum, cobalt, and even titanium alloys. The company continued its research in this direction and went on to become one of the most successful AM companies in the world.

Contemporary to EOS, another AM technology was tested in New Mexico, which was capable of producing metal components. The technology was known as laser-engineered net shaping (LENS®) [4], which employed high-intensity laser for melting and re-solidifying the powder spread on a tray. Both the tray and laser head being a mobile metal can be deposited on the desired locations layer by layer until the component is produced.

Electron beam melting (EBM) is another technology, which was also being developed at around the same time [4]. The process is a modification of SLS, where an electron beam instead of a laser melts the powder selectively on the loading tray. Once the layer is processed, fresh powder is spread to generate the next layer and the process is continued till the object is built. Many orthopedic implants are made out of this technique. EBM has also been employed for the fabrication of complex components for aerospace applications.

1.3 Evolution of subtractive manufacturing

SM is basically machining in which the raw material in the form of a rod or block (near to the overall dimension of the desired object) is chosen, and selective and controlled material removal is done to produce the final object. Due to the philosophy of material removal, these manufacturing techniques are collectively termed as SM. Various cutting machines such as lathe, milling machine, drilling machine, and shaper that are employed for the material removal process are elaborated as follows:

- **Lathe:** A block of material (raw material) is rotated against a harder and sharper object also known as the cutting tool. The raw material is usually moved in the lateral direction.
- **Milling machine:** The cutting tool moves in a rotary manner removing material from the stock.
- **Drilling machine:** The drill bit makes contact with the material while spinning creating hole in the manner.
- **Shaper:** The cutting tool removes material from the raw material while reciprocating against it linearly.

Single or multiple modes of machining may be required based on the complexity (in geometry) of the part. Besides, this philosophy of producing part by machining is applicable to any solid material such as wood, plastic, ceramic, composites, and metal. Early machining were done manually. However, with time the process has developed and currently machining process has been highly automatized by the introduction of computer numerically controlled (CNC) machines. CNC machines use computers to control the movement and operation of the machine tools.

Wide impetus to the machining process was given by the Industrial Revolution in the late 1700s. Since then machining has evolved into a mature and advanced technology. Earlier machining was a very rudimentary with people using their hands to carve out the desired object from the raw material with frequent needs of manual forging and manual filling of metal. During the machine age (late nineteenth to early twentieth century), the traditional machining processes, such as turning in lathe, milling in miller machines, and drilling in drill presses, were developed with manufacturing of the respective machine tools. These processes are very popular and still practiced in many parts of the world even today. Figure 1.3 illustrates some of the traditional forms of machine tools.

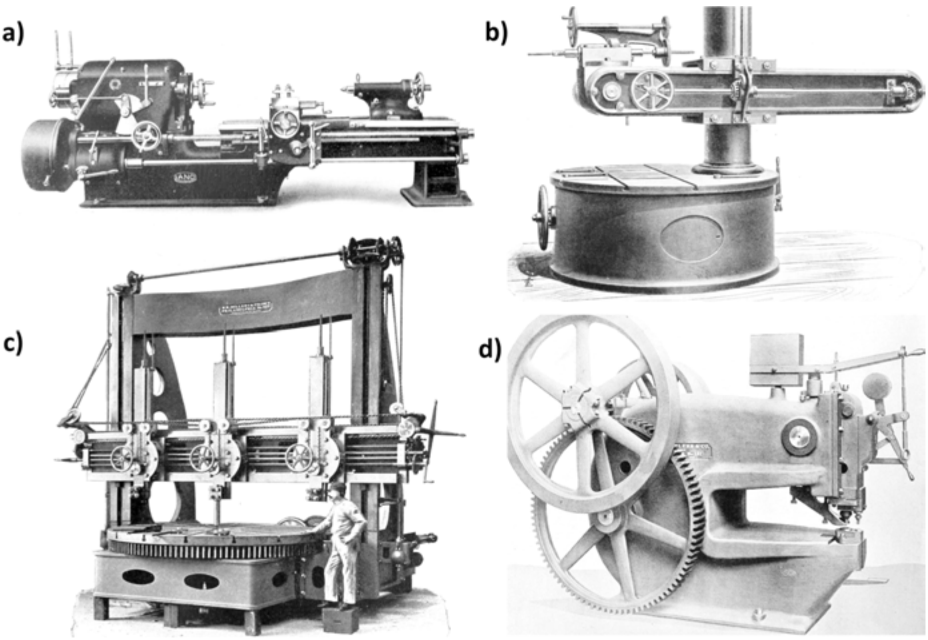


Figure 1.3: Traditional machine tools: (a) lathe (image source: Machine Tools catalogue), (b) drilling machine (source: staticflickr.com), (c) milling machine (source: staticflickr.com), and (d) punching machine (source: Flickr's The Commons).

After World War II, new machining technologies such as electrical discharge machining, electron beam machining, electrochemical machining, photochemical machining, and ultrasonic machining were developed in the arena of SM. The earlier machining processes were differentiated from the newly developed techniques by coining of terms such as conventional and nonconventional machining, respectively. The non-conventional machining was found to be useful particularly when dealing with novel and improved materials which are otherwise difficult to machine through traditional processes.

With the advent of new technological developments, demand for accurate and precision machining began to gather. Besides, the need for faster and bulk production leads to the understanding that some form of automation has to be introduced into the machining process. Post World War II, a numerical controlled (NC) machine was developed by John T. Parsons in association with MIT (Massachusetts Institute of Technology) [5]. The project is required to fabricate aircraft components that had complex geometries and also to find a more cost-effective way of doing it. Gradually with time, NC was infused into the manufacturing sector and it was not long before it established itself as the industry standard.

During the late 1970s, as computer began to be introduced for solving practical problems of mankind in various domains, the idea that computer can also control the machining process was floated. Soon the philosophy of CAD and computer-aided manufacturing (CAM) was developed, which catalyzed the progress of CNC machining to become a reality. The first commercial CNC machine was produced in 1976 and at around 1990 these machines had become the standard for manufacturing industry. The kinds of CNC machines included CNC lathe (illustration provided in Figure 1.4), CNC mills, CNC routers, and CNC grinders which are capable of manufacturing products made of plastic to steel. The initial NC machines were driven by punch codes that had a set of codes, which were known as G-codes. G-codes stand for “Geometric Code” and tell the machine when and how to move besides controlling its machining operation. The early NC models were hardwired and hence it was very difficult to modify the pre-set instructions. However, with the introduction of CNC machines, the

Figure 1.4: Photograph of CNC turning machine (Wikimedia Commons).

computer itself could participate in the operation and control of the machine. With time, G-codes have evolved to become very flexible allowing the operator to do real-time adjustments if needed.

The aim of both CNC and the conventional machine is one and the same, that is, to produce the desired part from a block of raw material. However, the primary advantage of CNC over the conventional machine is the degree of automation involved with the former. The CNC machine can be kept running without any human intervention in case of complex jobs that require long time. Besides, high productivity, speed, and accuracy are the key advantages of using CNC-based machines. For example, in case of conventional lathe, a skilled operator is required for a machine. However, with CNC, a skilled operator can program and operate multiple machines. With advancement in the networking and communication technologies and evolution of Internet, CNC machines can also be operated remotely if needed.

Now, people may argue that SM may seem to hold limited applicability in the era when AM machines are becoming increasingly cheaper and technologically advanced. As SM, although with the latest development is only CNC machining, one that produces part is by removing the material from a larger sized raw material. However, SM allows one to design and manufacture using the end-use materials. SM can handle any materials ranging from polymers and resins, composites, ceramics, wood, metals, and others. Based on the application, a particular material can be chosen and can be worked with to produce the part. SM seems to be suitable to manufacture objects for small and large volume production runs. Moreover, SM can give the desired surface finish to the object and is the preferred manufacturing process when certain mechanical properties are desired.

1.4 Advantages and limitations of SM

One of the advantages of SM compared to AM is that it does not have any layering in the object produced. The layering of the AM process may sometimes affect the microstructure of the final object, thereby also affecting its strength which may be a concern in case of critical components of a system. One can obtain various surface finishes in case of SM, which is possible by choosing an optimal set of machining parameters. The surface finish dictates friction and wear and can be particularly important in case the object is part of a tribological pair when integrated in the system. Besides, SM employs surface grinding as a final step before completing a particular job. Based on the coarseness of the grinder, surface roughness of the object can be varied and the desired roughness obtained. The “stepped surface” observed in case of many AM processes is eliminated in case of SM. However, the philosophy of material removal sometimes puts SM under some limitations, namely undercuts during milling operation are difficult to avoid. Moreover, machining consumes a lot of energy compared to additive process.

One of the disadvantages of operating NC machines is that the operator must have proficiency in G-code programming so that he/she can convert the geometric information of the designed model into machine-executable codes. With the introduction of advanced CNC machines, the tool path can be generated automatically and hence SM prototyping is quite comparable to that made by AM [6].

Subtractive RP can produce parts with high surface finish. Their tolerances regarding this is comparable to components made by injection molding. Thus, the components can be directly subjected to functional testing. Again the development in tool path generation software enables subtractive RP to handle complex geometries previously unimagined. Thus, it can be summarized that SM can handle a wide variety of raw materials. It yields good dimensional accuracy and surface finish with repeatability, which is suitable for mass production. However, some material wastage is also involved in machining.

1.4.1 Rapid injection molding

Rapid injection molding (RIM) is considered to be a part of subtractive prototyping. It is a rapid manufacturing technique to ensure that production is fast and quality is maintained. In RIM, the CAD model of the object is processed based on which the mold is manufactured by machining (milled). The mold is generally made of aluminum which gives an advantage regarding reducing the time for making the mold as well as tooling costs as would have been incurred in case of traditional steel molds. Once the mold is finished, thermoplastic resins are injected in it, which upon solidification produces the prototype [6]. These prototypes can be subjected to full functional tests and can also be tested for proper fittings and assembly. Besides, the molded parts have good surface finish and hence don’t require any post-processing steps. The features of RIM can be visualized as follows:
- Production of prototypes in production-grade resin in 3–5 weeks.
- Any engineering-grade resin of any color can be employed.
- The molded parts are strong and be tested functionally.
- Implement bridge tooling – molds can be used for 1,000s of parts.
- If desired molds can have textures.

1.5 Current state of AM and its impact on industry

AM has proven itself and has become matured enough to be accepted by the industry. Its advantages compared to SM have grabbed the eyeball of many industries. In summary [4], AM process initiates with the production of the CAD model of the component. The CAD model is transformed into STL (STereoLithography or

Standard Tessellation Language) file, which is in general the file type recognized by most AM machines. After that the system splits the model into multiple layers in an orientation, which is easiest to build and at the same time the part remains stable when its manufacturing is underway. Then the desired material in various forms are deposited and binded layer by layer to produce the component. By this methodology intricate shapes can be produced with relative ease and using a wide variety of materials. Because of its ability of producing complex geometries, the potential for the application of AM is huge. Some of the beneficial aspects of AM is presented as follows [7]:

I. Parts can be produced directly from the design without minimal intermediary steps
II. Custom-made parts are possible to be manufactured with no extra tooling or cost
III. The produced part can be put in actual function
IV. Post processing after manufacturing is minimal
V. Manufacturing of flexible and lightweight components with hollow or lattice structure is convenient
VI. Manufacturing waste is minimal; hence, maximum material is utilized
VII. The overall product development and realization time are very less
VIII. Manufacturing can be carried out on demand, thus reducing inventory costs
IX. Excellent scalability

1.5.1 Advantages of AM

1.5.1.1 Limitless design

AM has had significant influence on the manufacturing process of many products across various industries. AM is able to manufacture parts that were impossible to be made through SM. As AM can manage to produce the final object without undergoing much machining and processing, intricate shapes that are otherwise difficult to produce without the traditional methods can be made by AM [4]. This gives the flexibility to the designer, who can focus on the functional aspect without paying much heed to the manufacturing aspects. The designer has only to monitor the overall size of the object and whether it can be fit in the AM machine. Apart from the machine, no major tooling is required for AM. However, for some objects post production machining may be required to obtain the desired surface finish. As AM does not generate much material waste, the problem of disposing the waste material is also not a problem. Statistically it is reported that AM can reduce the material usage by about 75% which in turn can reduce the manufacturing time and cost by around 50% [4]. The enormous savings possible by AM have made the process attractive to manufacture around the world.

1.5.1.2 Versatility in manufacturing

Versatility in building parts is another aspect that makes AM process so lucrative. Reworking on parts is very easy in case of correction of flaws and changing the design for optimal use. This can be very difficult in case of manufacturing methods. Thus, AM can make working prototype very quickly, which can also be tested to see whether it can serve the intended function. Thus, as previously mentioned, components can be manufactured as per requirement. The designer can also modify the design or try a design optimization. Moreover, if a requirement for a custom-made part comes up, it can be delivered very quickly without disturbing the normal manufacturing process [4].

1.5.1.3 Obtaining enhanced performance by alternating material

Nowadays parts made of various materials such as plastics, metals, composites, and ceramics can be made with AM. However, plastics remain the most popular material as they have been the most studied and researched AM material. Work is also underway to investigate whether AM can be used as a material processing technique, so that materials with desired combination of properties can be developed. AM has been employed to bond metals and ceramics to create composited with enhanced wear resistance properties [4]. Through AM it is possible to produce a layer of coating on a particular material to increase its thermal and wear resistance, which may otherwise be very poor. Moreover, in case of a component that has broken or some of its material removed, AM can be used to bond the parts together or it can add material just at the desired location to restore the functionality of the part. Thus, the maintenance cost can significantly brought down by adopting AM as the parts needed can be discarded [4].

1.5.2 Incorporation of AM in modern manufacturing

The versatility of AM has led the modern-day industries to embrace them with open hands. Many companies have already created facilities dedicated to AM. GE Aviation has a facility where around 60 EBM machines and direct laser sintering machines can be installed [4]. AM has found huge application in aerospace industries, which deal with complex part and also require high reliability. AM allows for optimization of components, reducing their weight, lowering material loss, and thus increasing the overall profit. A lot of other aerospace manufacturers have also begun the induction of AM and integration of the same in their production process. Thus, AM has started to get its due attention; however, as of now mainly big enterprises have installed the large AM fabricators, which can give functional parts (mainly metallic) ready for use. Besides, there are issues such as surface finish of the parts as well as the material properties that are being fine tunes. But overall AM technology has matured enough to be able to produce components ready for use.

1.5.3 Growth of CAD: impact on manufacturing

The philosophy of CAD is to make use of computer systems for the creation, alteration, and analysis of a design. Ivan Sutherland is credited with the development of the first CAD software in 1960s, whereas PRONTO is the first commercial CAD software. The present day has seen the growth and commercialization of various CAD packages. Some of the popular CAD software are SolidWorks, Autodesk Inventor, Catia, Creo, and others. In the contest of AM, CAD has found its importance sky rocketed. One of the revolutionary aspects of AM is that it is capable of producing ready-to-use objects from CAD model. Development in CAD now makes possible to virtually design anything. Any theoretical model can be converted into digital form. The CAD file is converted to STL file and the part is produced by the AM method. Due to this people can now design more complex and efficient components. Even at the development phase of CAD, designers still had to keep in mind the manufacturing aspects of the design while designing components. However, that constraint has now been lifted.

1.5.4 Current manufacturing challenges

Although lot of optimism is prevalent about AM, there are major hurdles that have to be crossed, so that the technology receives extensive acceptance. Some of the prominent challenges are mentioned as follows [8]:

1.5.4.1 Deficiency in AM-compatible design knowledge

Although AM is able to convert any product design to reality, a certain amount of rethinking is required to apprehend the full potential of the technology. In case of manufacturing by AM, first of all the model should be oriented in its most stable position. Moreover, in case of overhanging parts, supporting may be required. Thus, the design should have the necessary compatibility to be manufactured by AM methodology. Besides, the design can be made so that unnecessary materials can be eliminated to the best extent possible. Reinforcements if required can also be planned in the design itself as AM doesn’t suffer from the limitations of SM or traditional machining.

1.5.4.2 Higher manufacturing cost

One of the major obstacles for the extensive use of AM is its higher manufacturing costs. The cost structure of AM and SM is significantly different from each other. In case of AM the tooling costs like that experienced in case of SM are not experienced. However, these costs (in SM) can be managed and the process can be made cost-effective if the volume of production is increased. In case of AM, an initial cost estimate is based on cubic centimeters of the product manufactured. The cost factors involved in AM can be listed as follows:
- cost of AM machine
- material cost
- energy cost
- post-processing cost

It has been studied that with polymers and plastics, the volume threshold where AM is profitable is increasing. But in case of metals, AM incurs more production cost compared to conventional machining.

1.5.4.3 Restricted industrial scaling of AM

Even after the adoption of AM worldwide, large-scale production with AM is almost nil or observed in a very few cases. One of the reasons for this is that AM machines are more suited for prototyping. Production in series or large-scale production is still not profitable with AM. Many components are too big to be produced with AM. A handful of instruments can be found around the world, which can handle large components but they too are stand-alone systems working with a single material at a time. GE Aviation is one of the few enterprises that has employed AM for large-scale production of fuel nozzles for turbofan engines. However, adoption among others is very slow. Thus, there is a need to develop the AM machines suitable for large-scale production. For these to happen, the production costs need to be lowered. Besides, the AM system should have features such as process stability, quick changeovers, in-process quality control, and higher reliability. The system should also be easy to maintain and repair in case of breakdown.

1.5.4.4 Threats on cyber security and IP rights

AM systems relying largely on digital and computer-based systems are vulnerable to some risks of which the SM are almost free of. There are risks of the design being stolen as the actual parts are produced from a digital CAD file. There are chances of the design being copied even from the actual model (if it is replicable) after it is produced and sold. Besides, as the data is stored digitally in the computer or sometimes in cloud to have better communication between the supplier and the customer, there looms a danger from cyber-attacks. Detailed discussion regarding this is presented in one of the following sections.

Some of the other general challenges faced in AM [7] lies in the development of a robust, autonomous, user-friendly, safe, and integrated system so that parts can be manufactured quickly and with the necessary accuracy (dimensional). Besides, the surface finish of the finished product should be acceptable and the overall process should not consume too much amount of energy. Variations in the quality of the product from machine to machine as well as from batch to batch are again a challenge and result mainly from the lack of a proper understanding between the AM process parameters and the product quality. In case of metallic objects, prevention of surface oxidation is another factor that should be kept in mind, otherwise the product quality may suffer. Providing inert gas atmosphere is one of the solutions currently in use against oxidation. Apart from this, metals require higher laser power in comparison to polymers, which add to the overall cost of the AM process. Table 1.1 lists some of the technological limitations of AM.

Table 1.1: Technological limitations of AM [8].

Design and engineering	Manufacturing	Service
Lack of design knowledge (e.g., long-term performance of materials and design for 3D printing	High production costs (e.g., material costs and limits on production speed)	Lack of industry-specific testing procedures (e.g., for production processes)
High risk of design pirating through users	Limitations on size (for specific AM technologies)	Lack of structural regulations in supplier networks
	Limitations on product quality (e.g., in range and combination of materials, resilience, and surface finish)	Risk of supply chain disruption
	Dependence on small number of machine suppliers	

One of the promising aspects for AM is that companies that manufacture AM systems are actively engrossed in improvement of their machines. Many technical institutes, R & D laboratories, and government organizations are also showing interest in AM technology and trying to address the limitations of the process in their own way. This way the workforce is getting trained, and the skill gap for AM compatible design is also getting gradually bridged. Next-generation machines are expected to reduce the production cost of AM due to the fact of patent expiration of many related technologies. Moreover, due to improvement in the accuracy of the parts, post-processing needs are also getting reduced.

Manufacturers of AM machines are improving in-process control of the machines as well as incorporating advanced quality diagnostics into the system. These are some progressive steps toward making AM suitable for large-scale production. According to some manufacturers of large AM machines, the material properties of the products obtained from AM are quite comparable to that obtained through SM techniques.

One of the vital needs of AM is the availability of good quality raw materials with desired properties. Low-quality materials result in bad parts unsuitable for the application for which they are made. Polymers frequently used in AM such as nylon, acrylonitrile butadiene styrene (ABS), and polyether ether ketone (PEEK) have been improved with them becoming more heat resistant and displaying more compatibility to the AM process. Parts made with these materials also show improved strength and reliability. Metals such as steel, aluminum, titanium, as well as precious metals such as gold and silver have also been developed to be suitable for manufacturing through AM pathway.

1.5.5 Other issues in manufacturing

1.5.5.1 Projection-based manufacturing issues in large-scale production

Through large volume production, the standard distribution of goods and products can be carried out [4]. Large volume productions require a strong inventory and can yield cheaper products as well as higher production rates. However, this system has some limitations. If a projection-based manufacturing philosophy is adopted, it can result in wastage of goods in case projection is not accurate as demand does not remain constant and are vulnerable to change because of various reasons. This can further lead to loss of jobs. The above problem can be easily solved if parts were produced on demand.

1.5.5.2 Issues related to centralized manufacturing

If a product is mass produced in a particular country, then rest of the world is dependent on that country for supply of that product. Now, if a country gets affected by some unforeseen issues such as natural calamity or war, the supply of the product gets influenced or at worst gets stopped. This has already been experienced in automotive industry when Japan was struck by the deadly tsunami in 2011 [4]. This situation can be avoided if the production process is distributed across various regions and across the world. Now, distribution of the production process is related to the concern about the degradation of the product quality. With AM, however, this issue can be handled as if the CAD model is shared and equipment available, then quality products can be produced.

1.5.5.3 Generalized designs preferred for business

The existing philosophy of production is to manufacture goods that are of interest to majority of the people in the society. Initially a market survey is conducted to note the choices and preferences of the people. After that based on the general choice, the specification of the product is decided. Finally, the product is manufactured and made available in the market. Thus, it may so happen that in many cases the available product does not exactly fit the needs of a particular customer [4]. The manufacturers also try to fit their designed product within the specification given to them and hence end up making products that are not optimal as the information given to them may not be always reliable. Moreover, when dealing with large-scale industrial manufacturing system, it may be really challenging to produce custom-made products as the tooling and other related accessories are fixed and recognized. Hence, through this system of manufacturing, the customer settles for a product which is just adequate but not perfect. Through the advent of CAD and AM, this problem can be solved; as customized products can be produced quite easily, people getting their perfectly suited product is only a matter of time.

1.6 Various AM techniques

The various techniques of AM have been briefly described in this section. Utilizing the techniques wherever suitable, AM has had a great advancement which is continuing with the advent of newer techniques.

1.6.1 VAT photopolymerization

When a photopolymeric resin is exposed to UV light, it gets cured and thus hardens. This technique has been widely implemented to manufacture products in an additive manner [9]. To simply put, a vat of photopolymeric resin is cured by UV light according to the sliced geometry of the CAD model. Subsequently, the next layer of resin is introduced and cured and process is continued until the total model is realized.

1.6.1.1 Stereolithography

In SLA, a vat of resin (photopolymer) is exposed to UV laser due to which the resin gets photochemically solidified based on the layer of the CAD model. Once solidified, the platform with the vat is lowered to the thickness of one layer (around 0.05–0.15 mm) and new layer of resin is spread on top of the previously processed one. Likewise, the process is repeated till the solid object of the CAD model is obtained. The solid object is again cured by UV light so that their mechanical properties are enhanced. Finally, the completed part is washed with a cleaning agent to remove the wet resin from the surface of the object.

1.6.1.2 Direct light processing

Direct light processing (DLP) technique for producing parts is almost similar to SLA method except that the former employs a more conventional source of light such as an arc lamp with a liquid crystal display panel. The panel is fitted such that it covers the entire surface of the vat with resin. During building, the 3D layered image of the object is displayed on the resin layer with the help of the projector. The exposed part of the liquid resin gets hardened. After that, second layered image is cast on the fresh layer of resin. The process is repeated until the 3D model is complete and the vat is drained of liquid, revealing the solidified model. DLP AM is faster and can print objects with a higher resolution.

1.6.2 Powder bed fusion

Powder bed fusion (PBF) employs the principle of fusion (sintering or melting) of material in powder form using a thermal source of energy (usually laser or electron beam). Layer-by-layer sintering is done sequentially to finally give rise to the object. Spreading of powder in thin smooth layers is done by a mechanism using either a roller or blade that is integral to PBF system. Once the part is finished, it is covered in loose powder from which it is taken out and cleaned. Through PBF, plastic as well as metallic parts can be produced.

1.6.2.1 Selective laser sintering

SLS is a PBF process that employs a laser power source to heat and fuse the powdered material (typically nylon or polyamide). Arrangement is made so that the build platform is lowered to a single layer thickness so that the next layer of powder could be spread and processed. Upon completion of the job, the part is cleaned and subjected to post processing if required.

1.6.2.2 Selective laser melting and direct metal laser sintering

Both SLM and DMLS are used to produce metallic parts. SLM is nearly of the same concept as SLS but only the powder is fully melted in case of the former. It is to noted that the metallic powder must be prepared nicely so that the granules are perfectly shaped in order to even out while spreading. As the powder is melted and re-solidified, it allows the formation of new crystal structure in the material. Porosity can also be redefined in the solidified material. Thus, further costly and time-consuming post-treatment steps are eliminated. Also through SLM, fully dense parts can be produced in a direct manner. In case of DMLS, the metallic powder is heated until they reach near melt temperature but not melted. Under this condition the powders fuse together chemically. DMLS can work with alloys, however, the common material used in DMLS is aluminum or titanium powder. Ultra-thin layers of fused powders are produced one on top of each other. Support structures may sometimes be required while fabricating parts by SLM or DMLS based on the geometry of the object.

1.6.2.3 Electron beam melting

In EBM, metal powder is completely melted and fused using a concentrated beam of high-energy electrons. Through local meting and re-solidification, the sliced geometry of the object is obtained. A vacuum atmosphere is preferable so that electrons don't collide with the gas particles. Besides, oxidation can be eliminated if the process is carried out in vacuum. The advantage in using this process is that it generates lesser amount of residual stresses resulting in lesser distortion and warping. Thus, requirement of support structures is less. EBM is also an energy-efficient process and can produce parts faster than SLM and DMLS.

1.6.2.4 Multijet fusion

Multijet fusion is a more cost-effective way to 3D print complex parts very quickly. At first, a thin layer of powder is spread on the platform. Then droplets of the fusing agent along with the detailing agent are deposited from a nozzle based on the required geometry of the part. The detailing agent inhibits sintering and is spread near the edge of the part. After that thermal energy is applied to fuse the powders where the fusing agent was spread. This is repeated layer by layer to give rise to the geometry.