ADVANCES IN ADDITIVE MANUFACTURING PROCESSES

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Advances in Additive Manufacturing Processes

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FOREWORD

When Dr. Jeyaprakash, Prof. Che-Hua Yang and Dr. Muralimohan Cheepu invited me to write this preface, I was honored and delighted to take this opportunity to familiarize myself with this exceptional work.

Additive manufacturing or additive layer manufacturing, also known as 3D printing, has become a transformative tactic to obtain industrial production by creating more vital parts by near-net shapes. Additive manufacturing was initially developed in 1987 with stereolithography from 3D systems for light-sensitive liquid polymer layering using a laser source. After commercializing the additive manufacturing system from 3D systems in the U.S., Japan's NTT data CMET and Sony/D-MEC, CMET called its system solid Object Ultraviolet Plotter. It is also known as Solid Creation System, proposed by Sony/D-MEC. The first Stereos Stereolithography System was sold in 1990 by Electro-Optical Systems in Germany. Later, in the year 1991, it was surprising that three additive manufacturing technologies were commercialized, such as fused deposition modeling, solid ground curing, and laminated object manufacturing.

Consequently, in 1992, DTM part of 3D Systems proposed the novel technique of Selective laser sintering, which can fuse the powder materials using heat from the laser. In 1994, many new additive manufacturing systems have been introduced with better technology within a short period. In 1999, 3D Systems developed a faster and economical technology called Acuta 2100 Thermojet. At the same time, Fraunhofer has developed a controlled metal buildup. After the creation of several technologies each year, the updating and improvements in technologies made the German-based company Trumpf discontinue its TrumaForm LF machine in Q2 2006. The technology was grown up to provide service by 3D Systems Rapid Product Development group in 2013.

Additive manufacturing involves manufacturing the parts by layering with the thousands of layers without any cutting or machining operations. It is capable of taking production to the next level than conventional manufacturing methods. One of the most significant benefits of using additive manufacturing is the more excellent range of shapes that traditional methods cannot make use of. Even with the hollow center, any design can be made with a single piece. Moreover, these parts are more substantial without any stressed and weak sections. Additive manufacturing quickly produces the parts and helps avoid endless meetings with engineers in the parts' manufacturing and design. It can only be done with the assistance of CAD software that changes can be made with one click, thereby obtaining the required models. It may thus provide companies with the manufacturing flexibility to produce complex parts with slashing costs.

The technology for additive manufacturing has advanced to the next level with the transition from analog to digital processes. In recent years, communications, imaging, architecture, and engineering have all undergone digital revolutions. Therefore, it is time to adopt this technology for additive manufacturing to bring digital flexibility and efficiency to manufacturing operations. 3D printing and rapid prototyping are informally used in additive manufacturing, and each process is a subset of additive manufacturing. Finally, additive manufacturing creates a perfect trifecta of improved performance, complex geometries, and simplified fabrication, and it is the future of smart manufacturing.

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PREFACE

It is well-known that the technology is rapidly moving towards 3D printing to ease the manufacturing processes and produce the parts with high quality and high production rate. 3D printing or additive manufacturing is being utilized everywhere in the manufacturing process of parts in order to avoid any difficulties. It is expected that the additive manufacturing processes can bring about another industrial revolution. 3D printing methods mark a revolution in various manufacturing methods that produce large-scale individual parts and involve mixed series production of multiple components.

This book, "Advances in Additive Manufacturing Processes," provides insights into various 3D printing/additive manufacturing processes and the basic knowledge of the techniques and their applications with relevant examples. The improvements and advancements of each method and their achievements with the practical experimental data have been discussed.

Moreover, the recent developments, defects, and challenges are the key topics to explore in the current book. It is advantageous to acquire near-net shapes of complicated parts using additive manufacturing with the desired mechanical properties. It is well known that the additive manufacturing parts' fatigue properties are minimal compared to machining parts. The formation of defects, porosity and the non-fused region affect the mechanical properties of the additively manufactured components, and hence it is essential to diminish such hostile effects. The book is very useful for the current manufacturing industries. It provides recent updates and guidelines for the additive manufacturing processes to be adopted in order to increase productivity and reduce the manufacturing cost.

In this book, eight kinds of 3D printing/additive manufacturing processes are provided, which are the manufacturing industry's significant processes. A detailed description of the processes and their improvements according to the practical applications in current manufacturing industries is given precisely.

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DEDICATION

To the many teachers across five countries I have learnt so much from, and my loving family who unconditionally supported me throughout my busy working life.

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The editor and co-editors would like to thank the National Taipei University of Technology (NTUT), Taipei-10608, Taiwan and Super-TIG Welding Co., Ltd., Busan, Republic of Korea, for the valuable support and extended facility to carry out this book project in a successful manner. In addition to that, the editor(s) are grateful to Ms. Humaira Hashmi, Editorial Manager, Bentham Science Publication, for her valuable guidance and facilitation. The enthusiasm and thoughtfulness of NTUT faculty, students, staff, and community partners over the years have inspired us to make this book resourceful for other academic colleagues.

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CHAPTER 1

3D Printing and Additive Manufacturing

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Abstract: At present, the requirement for new product development and upgrading of the existing product have become inevitable in the manufacturing scenario. The manufacturing sectors are striving hard to sustain in the global market, hence they are continuously seeking rapid manufacturing technologies for developing new products as there is a demand for innovative designs with enhanced features. Conventional manufacturing technologies have certain shortcomings, such as long production times, and are inherent to material wastage due to the subtractive nature of the processes. To meet the demand, it is necessary to accelerate the product development process. The time spent on the design, manufacturing and testing of a product has to be shortened. To emphasize the part representation (or) to rapidly create a system, the prototyping part is 'Rapid Prototyping' (RP), and the technology is 'Additive Manufacturing' (AM); it is also popularly known as '3D Printing'. AM is a novel manufacturing technology as the products are fabricated by adding successive layers of material with the aid of a computer. A Computer Aided Design (CAD) model is created and exported as a Standard Triangle Language (STL) file that is readable by an AM machine. There are many techniques available, which can be categorized according to their raw material. This chapter comprehensively reviews the AM techniques, the applications and the various materials used to produce the AM component.

Keywords: 3D printing, Additive manufacturing, Ceramics, Computer-aided design, Direct energy deposition, Functionally graded materials, Fused deposition modeling, Laminated object manufacturing, Manufacturing, Metals and alloys, Nanocomposites, New product, Polymers, Powder bed fusion, Rapid manufacturing, Rapid prototyping, Selective laser sintering, Solid state sintering, Stereolithography, Sustainability.

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INTRODUCTION

Mass customization is the future of 'manufacturing', and the technique which enables this is known as rapid manufacturing. It is the new order of the day where the engineer does not compromise on the cost and quality, yet achieves customer satisfaction. The best example is designing a disabled-friendly car seat for the entry of physically challenged people who want to enter and exit the car on their own without the help of another person. The manufacturing process here is called rapid manufacturing, and the technology followed to achieve this is called Additive Manufacturing (AM) [1, 2]. There have been numerous cases where AM has played an important role. For instance, in the medical field, a person who has lost a limb can get back the limb manufactured through reverse engineering techniques with the help of a CAD model functional prototyping. Depending on the use of the limb, a proper material will be chosen; for example, silicon material can be chosen for the ear, since it is more flexible. For a better understanding of our readers, the process of generating a customized product for the end-user is known as rapid manufacturing, but the route employed is Additive Manufacturing. Thus, we will see how a process has evolved over a period of time from producing polymer-type prototypes to metal-type prototypes. In the heart of this revolution lies the device 3D printer. Additive Manufacturing (AM) is popularly known as layered manufacturing [1]. AM is a layered built automated fabrication process that is used to build a 3-Dimensional object from 3D CAD data, ushering the fourth generation of the industrial revolution, which integrates computer and physical processes better known as Cyber-Physical integration. AM provides the third vertical that gives completion to the manufacturing process. There are three verticals, such as subtractive vertical, constant volume vertical and additive vertical. In the subtractive pillar, we have conventional and unconventional machining processes like milling, turning, *etc*. In the constant volume, we have metal forming and metal casting, and in the additive pillar, we have joining (welding) and AM.

AM is an evolving technology that arrived on the scene nearly 3 decades back in 1987; during that time, it was popularly known as Rapid Prototyping (RPT). It is called a young technology because the standardization for the process was given only in 2009 by the American Society for Mechanical Engineers (ASME) in cooperation with the American Society for Testing and Materials (ASTM). In the autumn of 2009, only the ASME conveyed a subcommittee 'F-42' and coined the term 'Additive Manufacturing', which was mainly a layer-based technology, and gave 'F2792-12a' standard. But this standard has been withdrawn as of 2015, with no other standardization being assigned to it [1]. Additive manufacturing contains three stages; they are 1) Preprocessing, 2) Processing and 3) Post-processing. Once the 3D image is captured, then it is subjected into slices by the computer.

Finally, the contour information is obtained by using the special kind of software and physical processing layering technique. Here the customer or the end-user can give their input at any time. The slice thickness of a component can be varied in each layer while intra thickness varying is in the early stage of research. We will showyou how a product attains a final shape using a flowchart representation shown in Fig. (**1**).

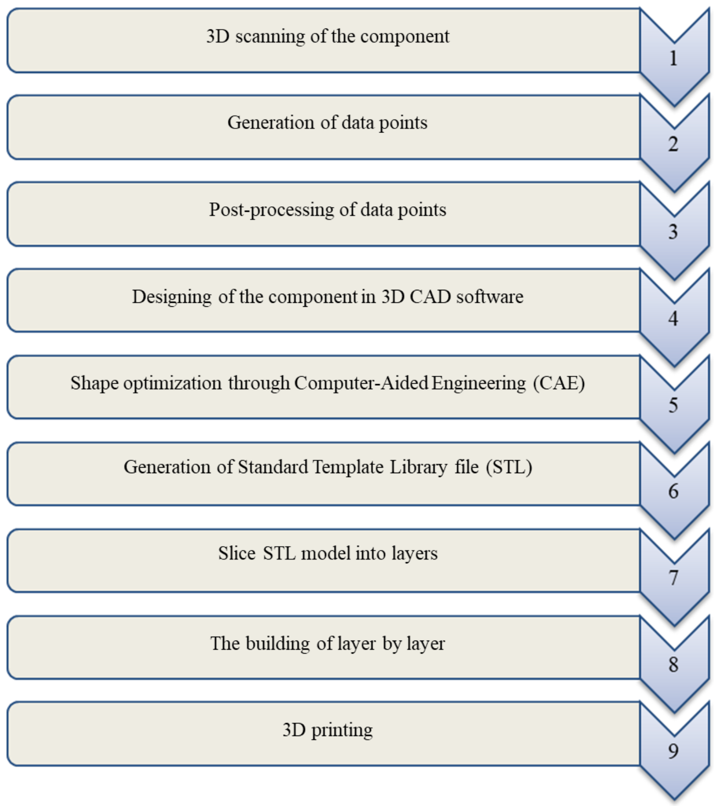

Fig. (1). Process flow in additive manufacturing.

AM is characterized by 'Rapid Prototyping' and 'Rapid Manufacturing', which are two main areas of this technology. Rapid prototyping refers to the production of prototypes intended for the specific application, whereas rapid manufacturing is used when there is a need for the final product. Rapid prototyping has two sub-stages, such as solid imaging and concept modeling. In these stages, the 3D image of the product is captured, and it is followed by functional prototyping; this is applied to allow examining and authenticating one or more critical remote functions of the final product or to give any alterations to the model [3].

CHAPTER 2

Selective Laser Sintering

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Abstract: Selective Laser Sintering (SLS) is a laser-based additive manufacturing technique capable of printing both metallic and non-metallic three-dimensional physical parts rapidly in the layer-by-layer fashion directly from the CAD models. It is an effective method in rapid prototyping, which forms the layer of material by directing a high-density laser into the bed of metallic or non-metallic powders. SLS can be classified based on the laser medium used and the mechanism of printing. Based on the mechanism, it is classified into direct SLS and indirect SLS. The quality of parts in terms of surface finish, mechanical properties, metallurgical properties, and so on depends on SLS's operating parameters, such as laser parameters, feedstock properties, and geometrical parameters. The SLS printed parts can have properties similar to the wrought material.

Keywords: Additive manufacturing, Alloys, Ceramics, Direct SLS, Fusion, Hatch space, Indirect SLS, Layer formation, Layered manufacturing, Laser power, Metals, Optical scanning, Particle sintering, Polymers, Post-processing, Powder bed fusion, Rapid prototyping, Selective laser sintering, Scanning speed, Types of laser.

INTRODUCTION

Advancements in manufacturing requirements have necessitated the need for advanced manufacturing techniques. The need for complex internal part shapes and competing mechanical properties drives the advancements of manufacturing techniques. Owing to these needs, Additive Manufacturing (AM) offers better methods to produce products of complex needs with time compression. The AM techniques work based on converting CAD drawings into the parts directly using layer-by-layer manufacturing principles [1]. Among various AM techniques available, laser-based techniques are the recent interest of the researchers. Selective Laser Sintering (SLS) is the process of rapid heating and fusing powder

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from materials to produce solid parts using a focused laser beam. This technique is used to create layers of the 3-dimensional (3D) part to be made. Compared to conventional manufacturing methods, SLS may cut down the total manufacturing cycle time, cost of manufacturing and increase competitiveness [2 - 4].

The lasers are classified based on the lasing medium. The lasing medium may be solid or gas [5]. Ruby, Alexandrite, Nd: YAG, Nd: glass, Nd-YLF, Ti-sapphire, and Er-YAG are examples of the solid-state lasing medium, and the wavelength ranges from 694 nm to 2940 nm. ArF, XeCl, KrF, XeF, Argon, Krypton, HeCd, Copper and Gold vapors, HeNe, and CO_2 are examples of gas lasers, and the wavelength ranges from 191 nm to 10,600 nm [6]. Semiconductor lasers such as AlGaInP, AlGaAs, InGaAs, InGaAsP, and liquid dye lasers such as Stilbene, Coumarin 102, and Rhodamine 6G, are also available with wavelengths ranging from 403 nm to 1650 nm. Various types of lasers are used in the SLS process. A majority of commercial SLS machines use CO_2 lasers due to their availability at low cost and being capable of delivering higher energy laser beams. SLS was first introduced in 1980 by Carl Deckard and Joe Beaman, and it is a subset of the Powder Bed Fusion (PBF) technique. All the PBF techniques are similar in essential characteristics; however, they use one or more energy sources for initiating the fusion of powder particles on their surfaces. The laser is the primary energy source used by most of the PBF techniques. Initially, the LS technique has been developed to fuse the polymeric materials, and later, the developments resulted in its capability to fuse metal powders. Any material capable of absorbing electromagnetic emission and turning in the form of powder can be processed with SLS. SLS and the Direct Metal Laser Sintering (DMLS) are the foremost commercialized machines worldwide nowadays.

This chapter discusses the process of SLS, layer formation mechanism, and parameters responsible for producing quality products, and attention is given to the different types of materials used in SLS and the properties of printed parts.

THE PROCESS OF SLS

The typical configuration of SLS setup involves high power laser source with a scanning mechanism, a computer control system, a platform to build the part, a roller or sweeper tool to spread the feed material above the platform, and two chambers called powder feed chamber and build chamber, as shown in Fig. (**1**). The powder feed chamber feeds the powder particles progressively while the 3D part is made within the build chamber. Some machines may have two powder feed chambers positioned on both sides of the build chamber. The total setup is enclosed in the environment filled with inter gas to avoid oxidation during part building. Similar to the other AM processes, production using SLS also starts with making a Computer-Aided Design (CAD) model of the part to be produced. Certain medical applications would require converting the scanned data into a CAD model using reverse engineering. The 3D CAD model will then be stored in the standard AM format called stereolithography (STL) format. The format usually contains data in the form of connected triangular to form an object.

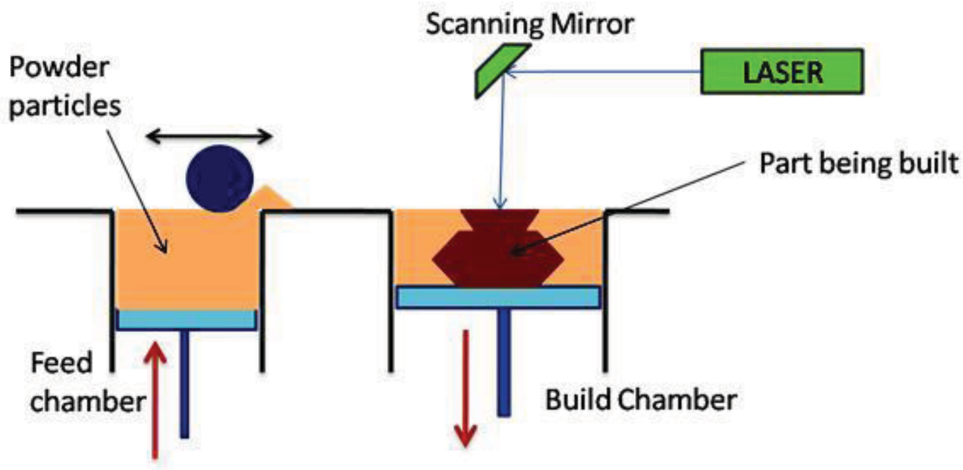

Fig. (1). Schematic of SLS.

Further, complex structures of parts and features of parts, such as color, density, gradient, and so on, can be added to the data [7]. Based on the application and strength requirements, the direction of printing is decided. The model is then sliced into layers of some desired thickness which decides the build time, dimensional accuracy, and path for laser scanning. This sliced data is communicated to the SLS machine, where it stores it in the internal readable format.

After the data is communicated to the computer controller, the SLS process commences. A controlled quantity of powder is fed into the platform by raising the piston inside the powder feed chamber. The feed powder is then spread evenly over the platform using a sweeper tool or a roller. The powder particles over the platform are preheated to a temperature considerably below its melting temperature using heating mechanisms such as resistance, infrared, and feed cartridge heaters [8]. Preheating is done to reduce laser power requirements, porosity, shrinkage, and thermal distortion. This would also improve the laser absorption capability and wettability. Further, based on the CAD model's sliced data, a high-power laser beam is scanned through the cross-sectional area defined by the layer. The scanning system is integrated with a computer control system so

CHAPTER 3

Direct Metal Laser Sintering Process

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Abstract: The chapter presents a comprehensive report of technological developments in direct metal laser sintering (DMLS). The DMLS process is a powder bed fusion process capable of manufacturing three-dimensional complex metallic parts through the layer-by-layer deposition of metallic materials having a wide range of applications in different fields, such as medical, automotive, aerospace, and energy. The present chapter aims to provide an insight on the DMLS working principle, sintering mechanism, and process parameters (*i.e*., laser power, scan speed, layer thickness, *etc*.) that influence the quality of the built part. Also, a comprehensive discussion on process monitoring and control techniques, modeling, and optimization techniques has been presented. Further, an extensive argument is provided on the challenges faced in DMLS concerning various materials (titanium, aluminum, steel, *etc*.), the evolution of microstructure, and mechanical properties experimentally and numerically. The chapter concludes with a detailed discussion on various applications and future research directions.

Keywords: Additive manufacturing, Aluminium alloys, Applications, DMLS process, Microstructure, Process monitoring and control, Process parameters, Sintering mechanism, Titanium alloys.

INTRODUCTION

Additive manufacturing (AM) is one of the evolving technologies in the field of manufacturing processes, wherein the material is added layer-by-layer to fabricate three-dimensional (3D) complex geometries, which is not possible with traditional manufacturing processes. The basic principle of the AM is to melt the material with the help of a heat source and deposit it in a layer-by-layer fashion to generate complex geometries [1]. The direction of layer deposit and layer height has been mathematically calculated by computer-aided design (CAD) models and comput-

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erized control of heat source movement in all directions. Unlike traditional manufacturing processes, additively manufactured components have higher specific strength [2] and supporting lattice structures, are energy-saving [3] and cost-effective [4], and involve near-zero material waste [5] and parts assembly [6]. The molecular time and length scales are not sufficiently small compared to the characteristic macroscopic flow scales. Features of AM have a crucial role in various applications of different industries, such as aerospace, medical, automobile [7], *etc*., that can revolutionize the entire manufacturing sector.

The AM has been classified based on the nature of the material, type of process, type of binding process, and type of deposition techniques [8]. Fig. (**1**) represents the classification of AM based on the type of material and process used [7]. However, AM is capable of using a wide range of materials, such as polymers, plastics, ceramics, metals, and composites. The first AM process was stereolithographic and invented in 1980 to produce rapid prototyping of polymers [9]. Polymers, amongst other materials, have been at the center of attention due to ease of production and availability. Jasiuk *et al*. [10] conducted a critical review on AM of polymers. The authors have presented the different AM methods to fabricate polymer and composite components. Also, material selection for different AM processes has been suggested based on the advantages and limitations of each process. Further, the futuristic directions related to high-speed printing, product and design flexibility, and recycling of polymers and composites, have been discussed. Parandoush *et al*. [11] reviewed AM of polymer-fiber composites. The authors have elaborated on the fabrication techniques that are capable of producing 3D and four-dimensional (4D) polymer-fiber composites components. However, the reinforcement of fiber in polymers enhances the properties of the polymer matrix. Fiber orientation and void fraction of composites are the main concern in the 3D printing of these composites. Besides, the modeling and analytical techniques of fiber reinforcement polymers have been discussed [5]. In industries, polymers are in the form of reactive, liquid solutions or thermoplastic melts enhancing the fiber reinforcement polymer that offers future development of AM technologies. The AM of polymers has extended to the printing of tissues and organs of humans [12]. The AM of printing organs is still in the developing stage. It is evident that comprehensive studies have been carried out on customization of polymers and plastic AM components.

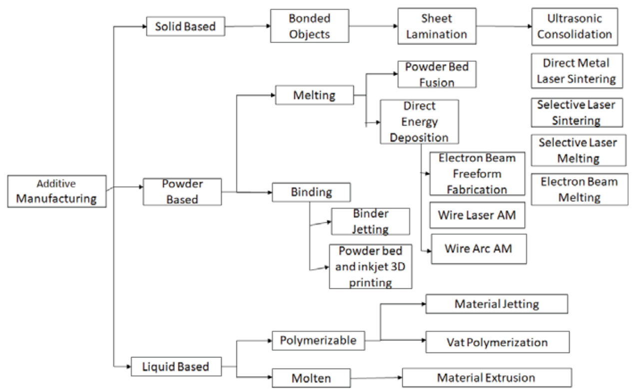

Fig. (1). Classification of Additive Manufacturing (AM).

In recent years, many researchers have attempted metal additive manufacturing. Metal additive manufacturing has been classified based on the power source, material feed system, built volume, *etc*. Further, the material feed system is subdivided into three categories: (i) powder bed, (ii) powder feed, and (iii) wire feed systems where the energy source could be a laser, electron beam, or arc welding [14]. Fig. (**2**) represents the classification of metal additive manufacturing based on the technologies [13]. In recent years, metal additive manufacturing has increased in use by researchers to address various issues, such as thermal and residual stresses, distortion, and surface finish, and its applications in medical field, aerospace, *etc*. Also, many researchers have extended using single metals to the use of multi-metal AM. The following section briefs the history of DMLS.

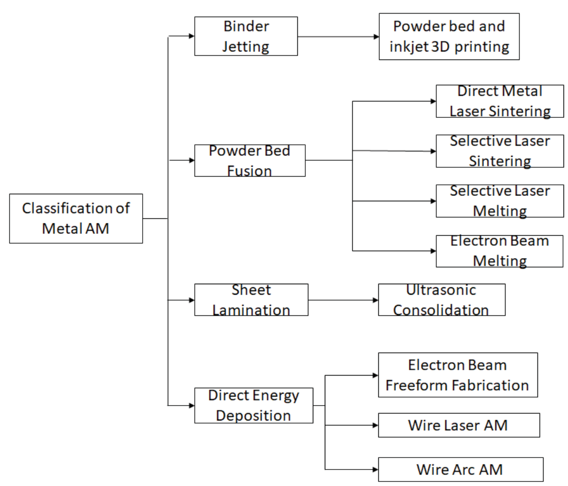

Fig. (2). Classification of metallic AM.

CHAPTER 4

Selective Laser Melting Based Additive Manufacturing: Materials, Properties and Defect Analysis

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Abstract: Our work presents a comprehensive report on selective laser melting (SLM) techniques with a specific focus on the different material families compatible with the SLM process, the mechanical and microstructural characteristics, residual stress and defect analyses. The major process parameters that determine the geometric accuracy and post-treatment techniques that eradicate defects in SLM fabrication are also reviewed. Then, a keyword co-occurrence analysis is performed to determine the future research directions in the SLM. The results showed mechanical characteristaion of SLM, defect analysis of SLM, SLM fabrication of porous implants and bulk metallic glass production using SLM to be the four major domains in SLM literature.

Keywords: Additive manufacturing, Aluminum alloy, Biomedical application, Composite, Developing trend, Heat treatment, Hybrid processing, Liquid phase sintering, Mechanical properties, Mechanical properties, Metallurgical defects, Microfabrication, Microstructural evolution, Network analysis, Powder metallurgy, Powder-bed recoating, Process parameter, Repeatability, Reproducibility, Selective laser melting, Selective laser sintering, Spheroidisation, Titanium.

INTRODUCTION

Selective Laser Melting (SLM) uses a laser with high density to melt and join metal powder in a particular shape traced by the laser source, thus forming the

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final product of near net shape. This process of manufacturing the product into the required shape is also called rapid prototyping, 3D printing, or Additive Manufacturing (AM) technique. This process is part of powder bed fusion (Fig. **1**) and is similar to binder jetting additive manufacturing in which the binder is used to shape the powder particle that is later melted by sintering. In this process, a direct laser source is used to shape the powder into the required final product by direct melting. The major advantage of this process is that it is capable of producing 99.9% relative density of the as casted material with improved mechanical and metallurgical properties without weight addition or reduction. The various metallic materials processed in SLM are titanium, tungsten, aluminium, and copper; this has also opened the gateway for fabricating ceramic and composite materials with a high- density laser source with increased temperature

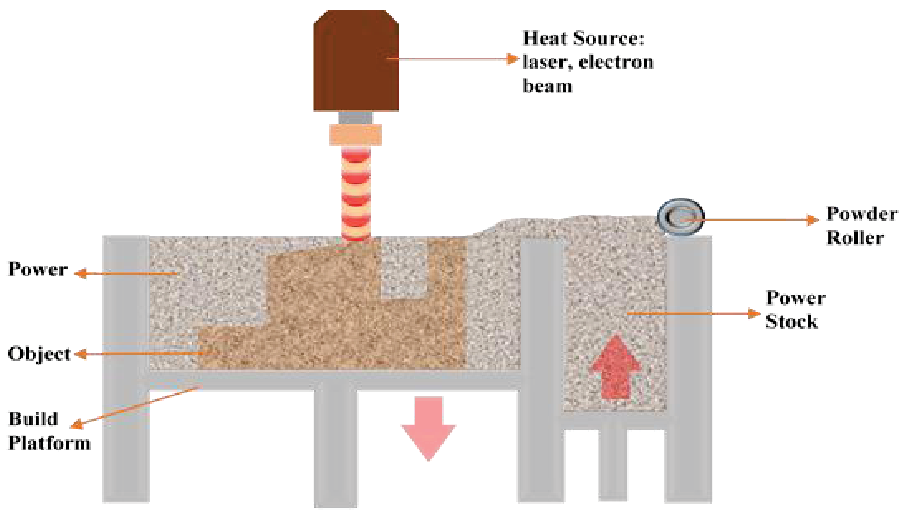

Fig. (1). Powder bed fusion based AM.

range. Yadroitsev *et al*. [1] studied the effects of laser power and scanning speed on single track formation anda reasonable negative correlation was found between optimal scanning speed and thermal conductivity of base material. Yan *et al*. [2] examined the influence of key factors, underlying mechanism formation and fabrication quality of single tracks. In addition to that, hatching distance and scan paths were simulated to identify the formed defects during SLM. Gu *et al*. [3] investigated the balling effects during the printing of stainless steel powder. The result indicates that lower laser power provides balling through coarsened balls possessing an interrupted dendritic structure. A further rise in volumetric density of energy input, lesser scan speed, a rise in laser power or a decrease in layer thickness minimize the tendency of balling. Matthews *et al*. [4] studied the metal powders denudation that is detected near the laser scan path and ambient gas pressure. Results provide new insights into denudation and formation of melt track which is essential for the minimization and prediction of surface roughness and void defects in SLM produced components. Chen *et al*. [5] developed the multiphase flow model to understand the denudation phenomena and physical mechanisms during the laser powder bed fusion process. The balling phenomenon in the SLM process is shown in Fig. (**2**). The SLM process plays a prominent role in bone tissue engineering and biomedical implant. The mechanical and biological requirements associated with bone scaffolds have been analysed. Different materials and processes adapted for scaffold have been deeply investigated [6]. Metallic implants have been noted to be promising and durable for human life. The most prominent metallic material for biomedical implants was found to be Ti-6Al-4V, specifically for biomedical implants. The lattice structure of Ti is used as a bone substile that passes through various design and testing approaches. The porous Ti material performs better than bulk metal though the mechanical strength differs; the elastic modulus is adjusted to match with the cortical bone [7].

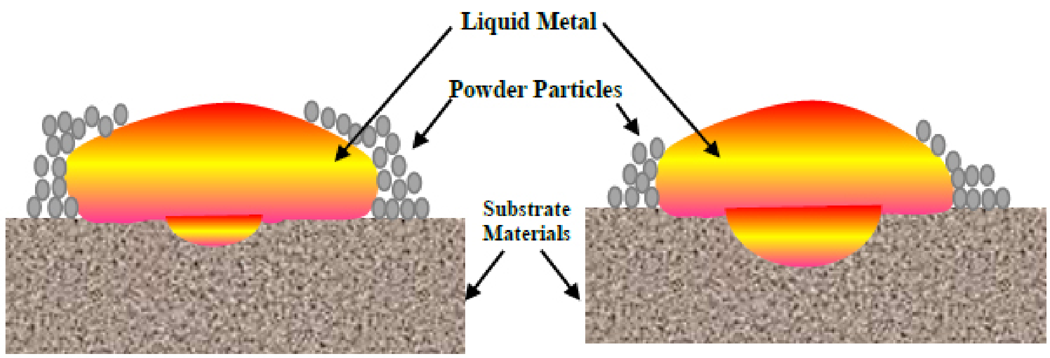

Fig. (2). Balling phenomenon in SLM process.

The research on metallic skeletal endoprostheses produced by SLM has been developed at micro and macro scales [8]. The growth of metal AM research can be partly attributed to the many benefits associated with the process. For instance, AM methodologies do not have the same degree of design constraints as traditional procedures. AM has a much higher degree of geometrical independence that enables mass customization of components. In addition, time, energy and material savings using AM decrease significantly compared to conventional production methodsThe most significant criterion is the overall effectiveness of the equipment (OEE), which needs to be higher than 70% with lower scrap prices at about 1000 ppm [9]. The SLM on NiTi alloy is considered to be a great support for research for understanding the features like shape memory effect and super elastic behaviour [10]. Additive manufacturing technology

CHAPTER 5

Electron Beam Melting

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Abstract: Electron beam melting (EBM) is an effective and competent additive manufacturing process for fabricating three-dimensional metal parts. EBM process uses raw materials in the form of powders. EBM uses an electron beam as the heat source to carry out the bonding process between powders to consolidate them into a required solid part. It involves the use of data from a 3D computer-aided design (CAD) model to create successive layers of raw material. This process requires a vacuum chamber finding EBM as a suitable technique to process reactive materials like titanium alloys. Apart from titanium alloys, EBM also caters to a wide range of powder materials like alloys of cobalt, Inconel, copper, and steel. The parts fabricated using EBM are fully dense and exhibit good mechanical and morphological properties. The applications of EBM include automotive, tooling, aerospace, and biomedical implant industries.

Keywords: Additive manufacturing, Aerospace, Automotive, Beam intensity, Biomedical implants, Cobalt, Electron beam, Hatch space, Layered manufacturing, Layer preparation, Metal alloys, Multi-materials, Nickel, Powder bed fusion, Process parameters, Rapid prototyping, Scan speed, Steel, Titanium, Tooling.

INTRODUCTION

Powder bed fusion (PBF) techniques are gaining a lot of importance in fabricating metallic parts in additive manufacturing (AM). Initial attempts resulted in producing parts of complex features with reasonable accuracy. But the porosity of the fabricated parts was of major concern. Recent advancements in PBF techniques are paving the way for producing parts of denser and rigid charac-

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teristics [1]. Powder bed types of AM techniques are classified into three categories based on bonding mechanisms *viz.,* Gluing, Sintering, and Fusing. Gluing occurs with the help of third-party bonding agents, usually through chemical reactions. The bonds generate in due course of idle time. Sintering is a partial fusion technique in which powders are heated to sintering temperature. After cooling, these half-melted parts get bonded at the peripheries. The fusing is a process that involves complete melting of the powder particles, which forces them into a common localized liquid pool. Upon cooling, this molten pool results in a single solidified structure. The standard classification of the powder bed type of AM techniques is shown in Fig. (**1**). Among these, the electron beam melting (EBM) process finds its suitability in processing reactive materials like titanium alloys. EBM is also called selective electron beam melting (SEBM).

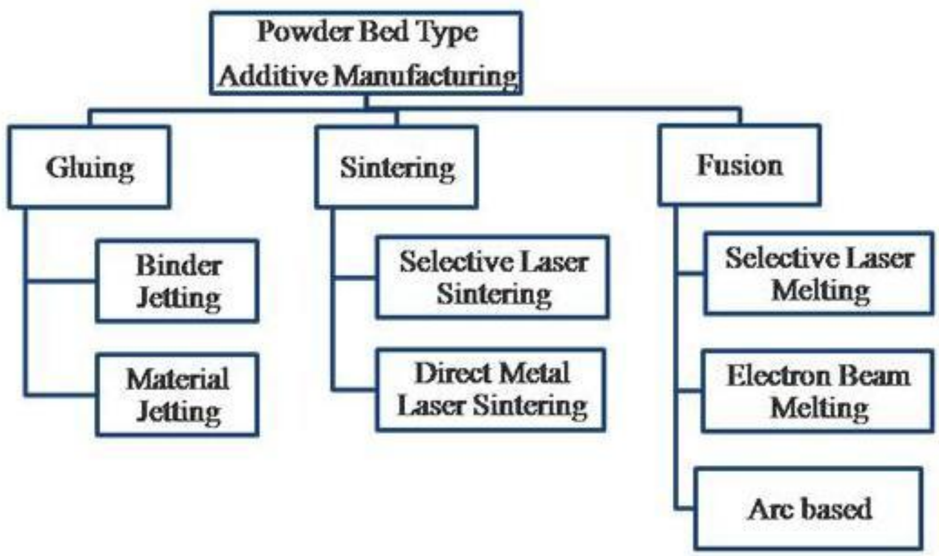

Fig. (1). Classification of AM based on PBF technique.

HISTORY OF EBM

EBM is one of the compelling methods to process metal powders. Initially, it was developed in the laboratories of the Chalmers University of Technology, Sweden. Later during the 1997s, this method was commercialized by Arcam AB, a Sweden-based company.

PROCESS

Electron Beam Physics

The history of the electron beam technique commenced through the experiments conducted by the scientists Hittorf and Crookes. Secondly, they attempted to produce cathode rays within the gases during 1869 and have tried to melt the metals during 1879. Cathode rays have gained much attention and led to the discovery of a specific form of ray, which was defined as “fast-moving electrons” by Roentgen (1895), Thompson (1897), and Millikan (1905). An electron beam is an electron stream that is induced by heat generated through thermionic emission, charged atom or bombardment of particles (secondary electron emission), or strong electric fields (often called field emission). Holes and slits can collimate electrons, and since they are electrically charged, electric and magnetic fields may deflect, concentrate, and energize them. Since the 1940s, electron beams have been used in radiotherapy. A new age of material production began in the year 1948 with the scientist Dr. H.C. Steigerwald Karl-Heinz. He has used an electron beam as a thermal tool to perform vacuum soldering, drilling on watch stones, welding, and melting. Since the results were successful, the developments of electron beam based techniques have emerged faster. He joined Zircaloy of 5 mm thick using soldering operation together in 1958 and thus found the “deep welding effect”. The industrial production of linear accelerators (linacs) made EB to be commonly used thereon during the 1970s.

Process

Any AM process uses the computer-aided design (CAD) model directly in the fabrication process [2]. EBM is part of the AM community of technologies resulting in completely dense metallic components. This is analogous to the more traditional form of Selective Laser Melting (SLM) [3], in which a laser beam is used to produce heat in the place of an electron beam. Both are layer-by-layer AM techniques based on a PBF technique in which powder layers are distributed over a building platform and melted selectively by the heat supply in motion. EBM and SLM, however, show substantial variations in detail arising from the energy source. In EBM, the energy is carried by electrons, and in SLS, the energy is carried by photons, which are basically different. Electro-magnetic lenses can concentrate and transfer an electron beam free of inertia. The electron beam thus hits velocities within the building area of up to 105 m/s, *i.e.* the beam can almost instantaneously bounce from point to point. Fig. (**2**) shows the EBM setup schematic in which a part is built within the machine's building chamber. Making a part is based on the sliced data from a CAD model with constant layer thickness.

CHAPTER 6

A Review on Binder Jetting Fabrication: Materials, Characterizations and Challenges

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Abstract: Binder Jet additive manufacturing is a 3D printing technology that is used for a variety of materials irrespective of the properties and characteristics. A variety of materials that are used include ceramics, polymers and metals. The materials are formed layer by layer by the adhesive bonding between material and binder. Compared with recent developing modern manufacturing methods, binder jetting has the capability of producing quickly integrated complex features for obtaining isotropic properties. Green part manufacturing is processed to obtain the end part. Property obtained through this process is close to the traditional powder metallurgy sintering technique. This article discusses in detail the different materials used in binder jet additive manufacturing, different process challenges involved, binder and droplets, post-processing, characterization, the advantages and applications. Further, the powder characteristics and process parameters are explained.

Keywords: Additive manufacturing, Architectural models, Binder jetting, Binders, Binding, Characterisation, continuous jetting, Curing, Debounding, Demand on droplet, Densification, Depowdering, Filtration, Fusion, Industries, Ink-jetting, Post-processing, Powder, Printing, Sintering.

INTRODUCTION

Due to the substantial growth in the interest of the manufacturing sector towards research and development over the past decade, increasing attention has been paid

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to additive manufacturing focused on binder jetting of metals due to its economic value and high scalability [1 - 4]. The technology of transforming the design into a three-dimensional solid object by adding up layers from the digital file is broadly known as Additive manufacturing (AM) 3D printing. The significance of AM 3D printing lies in ample production with abridged equipment and tooling in design being cost benefit and flexible for the overall industries [5, 6]. Though various systems define the binder jetting terminology in different domains, the ASTM F2792 standard describes the binder jetting as, “an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials”. The technology of binder jetting has influenced to produce real-time functional products rather than making prototyping models alone [7]. Binder jetting is also specified as Binder Jet 3D Printing (BJ3DP) which utilises the droplets of binding material to make the selected powder particles bond and composes powder layers to produce the three-dimensional green product [8, 9]. The technology of metal binder jetting originated in 1993 from the Massachusetts Institute of Technology (MIT). It was identified during the creation of three-dimensional metal powder object through an inkjet-based process. Subsequently, the production across the industries has been reviving the binder jetting technology as it is highly suitable for all manufacturing sectors.

Among the different 3D printing technologies as shown in Fig. (**1**), Binder Jetting (BJ) is unique, since it does not require any heating during the process like other 3D printing additive manufacturing processes [8 - 11]. In binder jetting, the binding liquid is used for selective deposition for joining the powder material together to form the three-dimensional parts. Since the binder jetting does not employ heat during the process, it is applicable for a wide range of materials processing compared to other 3D printing techniques.

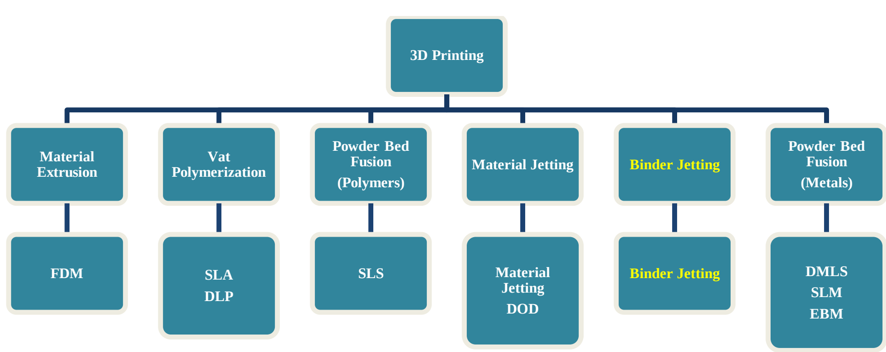

Fig. (1). 3D printing technology.

In binder jetting, the layer of the solid part is formed by making the binder to selectively deposit onto the powder bed at a time. Binder jetting is highly suitable for a wide assortment of materials like ceramics, metals and polymers in shaping complex intricate shapes and ideally suited for high temperature and refractive materials as a very low temperature is used during the process; also, the melting of powder particle does not take place throughout the process and the bonding of the metal powder particle is due to the binder which acts as an adhesive [12 - 15]. Though the parts are bound together by the binder which is the reason for the layer-by-layer adhesion, the part needs to be thermally post-processed by the sintering process to eliminate the binder and generate a fully metal part. The strength, stability and the excellence of the binder jetting components are significantly influenced through the interface between the binder and the powder particle. Whereas, these qualities are not highly imparted in other AM processes based on high energy beams and directed energy deposition [12 - 17]. Also, binder jetting is utilized in various applications, such as in the production of large size sand-casting moulds and cast cores, low-cost 3D printed metal components and fabrication of multi-colour prototype models.

Binder jetting process uses a liquid-based binding agent to selectively join the material in a powder bed, as shown in Fig. (**2**), which influences the part quality, mechanical strength and dimensional constancy [18, 19]. The granular form of materials, such as metals, sand and ceramics, is usually used in binder jetting. Metals including H13 tool steel, titanium, copper, cobalt chrome, copper, and heavy alloys of tungsten and ceramics such as alumina, carbon, natural and synthetic sands, silicon carbide, alone or infiltrated with silicon, tungsten carbide-cobalt, are commonly used in binder jetting [20, 21]. In binder jetting, the type of binders is selected based on the type of powder used and the application and requirement of the patron. Some regularly used binders are Aqueous-Based Binder, Furan Binder, Phenolic Binder and Silicate Binder.

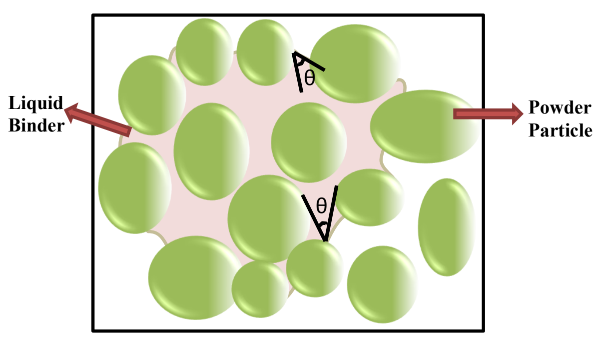

Fig. (2). Local contact between liquid binder and a particle in the powder bed.

CHAPTER 7

Ultrasonic Additive Manufacturing

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Abstract: Ultrasonic Additive Manufacturing (UAM) is an innovative process technology that uses sound to combine layers of metal produced from foil stocks. The variation seen in UAM from other AM techniques is that metals are not melted but joined by ultrasonic welding instead. This technique uses high-frequency vibration to bond the surfaces of metal foils while the metal remains firm. The addition of foils by stacking one on the other by this welding technique leads to the creation of solid parts. This method creates high-density metallurgical bonds without melting the metals. This proves to be advantageous, as it avoids changes in grain size, phases, and precipitation reactions. It also aids in bonding dissimilar metals without creating any brittle inter-metallic bonding. UAM provides a major application of embedding electronics in solid metal parts to fabricate microelectronics systems like micro-processors, telemetry, and sensors.

Keywords: Additive manufacturing, Alloys, Applications, CAD model, Ceramics, CNC, Dissimilar metals, Layered manufacturing, Metals, Material compatibility, Microprocessor, Multi-materials, Rapid prototyping, Sensors, Solid-state, Telemetry, Ultrasonic, Vibration amplitude, Weld force, Weld speed, Welding.

INTRODUCTION

A new additive manufacturing process developed by Fabrisonic is a form of ultrasonic welding and CNC milling hybrid, and the company uses the technique to produce complex and accurate full-metal parts; the process can also include embedded electronics. Fabrisonic is manufacturing parts for aerospace, automo-

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tive, research, and industrial applications since 2011. The system is relatively a high-speed technique named Ultrasonic Additive Manufacturing (UAM) that can produce wholly dense components. Similar to the other additive manufacturing techniques [1], UAM also depends on the 3-dimensional (3D) model prepared in the computer. This UAM method uses metal foil layers of copper, stainless steel, aluminum, and titanium for blending. Multiple metals can be 'printed' together by the Fabrisonic process without unnecessary metallurgical adjustments. The method includes metal trip rolls to print parts using aluminum and copper, which may involve highly complex internal channels with a solid-state welding technique organized in either direction.

The UAM technology of Fabrisonic utilizes sound vibrations to blend layers of metal foils. This method is novel as it allows dissimilar metals to be welded at much lower temperatures. The advantage of this is that it ensures the possibility to integrate electronics into structures. This would not be possible with other 3D metal printing technologies, as very high temperatures are traditionally needed for fabricating a part. In conventional CNC equipment, Fabrisonic mounts its proprietary hybrid 3D printing process.

In UAM, a layer is deposited using 3D printing and machined using milling operation to the required size and finish using the CNC system. The materials used in UAM are in the form of foils. These feedstock materials during the UAM process do not undergo melting since the sonotrode tool used in UAM scrubs the metal to get it attached to the previous layer. A commonly known 3D printer from Fabrisonic uses 6” x 6” x 3” UAM setup to fabricate parts for heat exchanger applications. Fabrisonic claims that heat exchangers account for 30% of its business. UAM has been used in space applications also. For installing bent tubes to the external structure of a space vehicle, NASA has used glues and fasteners for many years. This brought them weight loss in structures but failed to perform well at thermal conditions. Also, these assembling and quality checking operations were done manually by hand; it took a maximum of 9 months to complete the building. After collaborating with Fabrisonic, NASA jet propulsion laboratory (JPL) started improving upon the stated problems, namely vibration, thermal, hermeticity, and burst requirements. The use of UAM has enabled improved performance with a reduction in weight and lead times.

UAM – A SOLID STATE AM PROCESS

UAM is a solid-state additive manufacturing process that uses ultrasonic metal welding (USW) to sequentially bond metal foils together, layer by layer. USW utilizes Computer Numerical Control (CNC) machining to extract material during this additive build-up process to produce the desired geometry. The process flow of UAM is shown in Fig. (**1**) [2]. UAM process is a combination of additive manufacturing and subtractive manufacturing techniques. UAM requires both solid state welding and conventional machining for depositing each layer of material. For machining operation, either CNC or laser machining can be used. This mixture of both additives leads to building up of solid-state fusion, with instantaneous selective subtractive machining offering a range of specific main development capabilities. Along with these capabilities, UAM can also perform solid-state bonding of dissimilar materials thermally and mechanically to each other. Hence embedding sensitive and functional elements within the additively build layers of foils is possible making the structure a dense metal matrix.

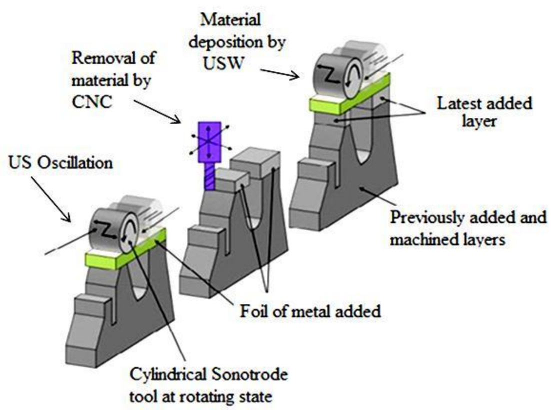

Fig. (1). Schematic representation of UAM.

WELDING OF METAL WITH ULTRASONICS

Since 1950s, the ultrasonic metal welding (UMW) has been utilized in modern applications, including for battery tabs, thin foil wrapping, and even electrical wires in daily welding. By forcing a thin foil of metal onto another metal part, an ultrasonic welding operation begins. To induce scrubbing of the interacting surfaces, ultrasonic vibrations are delivered under a continuous force. In order to allow direct contact between pure metals, the friction created due to this shearing motion takes away the surface oxides. The effect is an atomic bond in a solid-state with minimal heating. The heat and plastic deformation at the interface facilitate the diffusion and recrystallization, resulting in a real metallurgical bond. At very low temperatures and without any special conditions, ultrasonic welding can be carried out [3]. The bonding temperature for both metals is considerably below their respective melting temperature. For example, the peak temperature of Aluminum (Al) is maintained well below 250 °F. The principle of ultrasonic metal welding is depicted in Fig. (**2**).

CHAPTER 8

Direct Energy Deposition

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Abstract: Direct Energy Deposition (DED) method of additive manufacturing (AM) is a new paragon for the production, repairing, and design of the complex components of different applications, such as automotive, aerospace, medical equipment, biomedical products, *etc*. The focused energy source and deposit material (wire or powder form) meet at a focal point where the material melts and is deposited layer by layer at the same time. The laser beam, electron beam, plasma, and electric arc sources are used as a focused energy source based on the type of materials. The demand for the DED process is increasing day by day due to its flexibility for using conductive/non-conductive materials in wire/powder forms. The desired shape and mechanical properties of the manufactured products can be optimized by administering the parameters of DED. A comprehensive review of the DED process is discussed in this chapter, where the deposition mechanisms, the energy sources, the effect of processing parameters, defects, and the mechanical properties, are highlighted in detail.

Keywords: 3D printing, Additive manufacturing, Directed energy deposition, Electron beam, Laser, Metal deposition, Plasma arc, Power feedstock, Steel, Superalloys, Wide feedstock.

INTRODUCTION

The direct energy deposition process (DED) is a kind of direct additive manufacturing process in which raw material and focused heat sources intersect at a common focal point where the material is melted and solidified simultaneously (distance is 1-2 mm between the focal point and solidification position) [1]. The

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melted region is covered in a controlled inert gas environment for reducing oxidation, which is responsible for the microstructural defects affecting job properties, such as finishing and strength. The raw material can be fed either by wire or powder form, or both *via* a feedstock mechanism. Since the process is entirely based on melting and solidification simultaneously, both conductive and non-conductive materials-based products are easy to manufacture using the DED process. The DED setups are controlled by the computer aided designed (CAD) scripted file controlling the right path, deposition rate and energy source. DED process can also be performed by using the traditional cladding and welding technology programs especially implemented for feeding paths. The deposition process is repeated layer by layer until the completion of the final product. Due to the convenient setup, DED process is being widely used in academic institutes and industries to develop prototypes for several applications, such as complex components design, biomaterial components, hard materials, ceramics, composites, coatings, prototypes, 3-D printing, repairing products, *etc*. The DED manufactured products using different materials with their applications are summarized in detail in Table **1**. The commercial DED machines are available by different names on the basis of energy sources and types of applications in the market. The details of these commercial DED machines are mentioned in Table **2**. The details of the different types of DED setups, structure-properties, benefits, drawbacks, and applications are illustrated as follows.

Table 1. Common DED processed materials and applications.

Material name	Application	References
Steels	Hard tools, automotive, marine, prototypes, crankshaft, rails, vessels, driveshafts, mold, die	[2]– [9]
Ti-based superalloy	Engine cylinder head and blocks, turbine blades, aerospace, implants	[10]– [16]
Ni-based superalloy	Orthopaedic implants, gas-turbine engines	[5], [12], [13], [17]– [22]
Ceramics composite	aerospace, automobile, turbine, engines, batteries, and heat exchangers	[7], [13], [14], [23]– [26]
Carbides	Coating on machines tools, turbines, steel, and other products	[12], [17], [18], [27]

Table 2. Some of the common commercial DED AM processes [10].

DED Terminology	Acronym
Direct metal deposition	DMD
Direct light fabrication	DLF
Shape deposition manufacturing	SDM

(Table 2) cont.....

DED Terminology	Acronym
Laser engineer net shaping	LENS
Laser direct casting	LDC
Laser cladding	LC
Laser forming	Lasform
Laser powder fusion	LPF
Laser aided manufacturing process	L-AMP
Laser aided direct-metal deposition	LA-DMD
Laser-based multi-directional metal deposition	LBMDMD

BASIC SETUP AND CLASSIFICATION OF DED PROCESS

The basic DED setup is shown in Fig. (**1a**), where heat energy is inserted from the center and raw materials are fed through the nozzle; an outside nozzle is used for the inert gas to shield the production area. Both the energy source and the raw material nozzles are arranged in parallel to melt the raw material at a focal point, and at the same time, the molten metal is deposited simultaneously. The DED machine moves according to the profiled path mentioned in the CAD file. Thus, the molten metal is deposited directly over the substrate layer by layer.

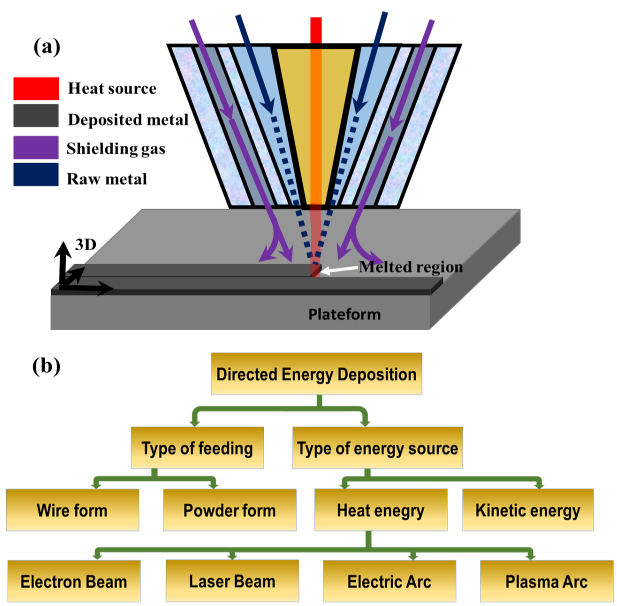

Fig. (1). Details of DED manufacturing process **(a)** Basic mechanism [2], **(b)** Classification based on energy source and feedstock time.

CHAPTER 9

A Progressive Review on Wire Arc Additive Manufacturing: Mechanical Properties, Metallurgical and Defect Analysis

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Abstract: Wire arc additive manufacturing (WAAM) has confirmed its flexibility in meeting the mid- to large-scale component production requirements for the engineering and related sectors. Because of mechanical limitations such as under-matched mechanical properties, the existence of significant residual stresses and the necessary post-deposition activity of the formed component, WAAM currently cannot be used as a fully-fledged manufacturing process. The entire article offers an overview of the WAAM technology including one with a succinct description of the WAAM field history, situation, benefits and challenges. Emphasis has been given, particularly on the measures to limit porosity, tensile strength, microstructural inspections and other important advances in the field of WAAM. The main advantages of WAAM are the integration of the manufacturing process, the fair degree of design flexibility, as well as the resulting optimization ability. Owing to feasibility of large-scale composite materials of significantly higher deposition rates, considerable progress has been made in the setting of the WAAM process. An acceptable efficient heat treatment has been integrated to help reduce defects within the WAAM process and also to obtain the new options that are effective. The integration of materials and the production methods for manufacturing of defect-free and technically feasible deposited parts remains a vital step in the future.

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Keywords: Arc stability, Compression, Corrosion, Deposition rate, ECT, GMAW-AM, GTAW-AM, Grain size, Hybrid AM, Impedance, Inter layer, PAW-AM, PDP, Porosity, Post deposition heating, SEM, Tensile, Tomography, WAAM, XRD.

INTRODUCTION

Wire arc additive manufacturing (WAAM) has demonstrated proven versatility to meet the requirements of engineering and related sectors for medium to large-scale part production. Increased emphasis has been given on measures to reduce porosity, and improve tensile strength, microstructural inspections, and other important advances in the WAAM sector. The key advantages of WAAM are the convergence of the production process, the equal degree of versatility of design, and the corresponding potential for optimization. WAAM's main advantages are the integration of the manufacturing process, the equal level of flexibility of the design, and the optimization capability that accompanies it. Substantial progress has been made in setting up the WAAM process due to the feasibility of substantially higher deposition rates for large-scale composite materials. Heat treatments really help to eliminate defects in the components processed by WAAM. A serious consequence in the field remains for the production of defect-free and technically feasible deposited components. Wire-arc additive manufacturing is one of the strongest absolute technical paths in the current production pattern in various sectors, such as the automotive, aerospace, electrical and electronics industries, due to its material reduction and cost - efficiency [1-4]. The industrial sector has drawn interest in this method. The basic set of WAAM is shown in Fig. (**1**). WAAM is the best choice due to its ability to produce huge metal components with a high deposition rate, affordable equipment costs, high material use, and eco-friendliness. The WAAM cycle can be the root of patent by Baker in the year 1925 [5].

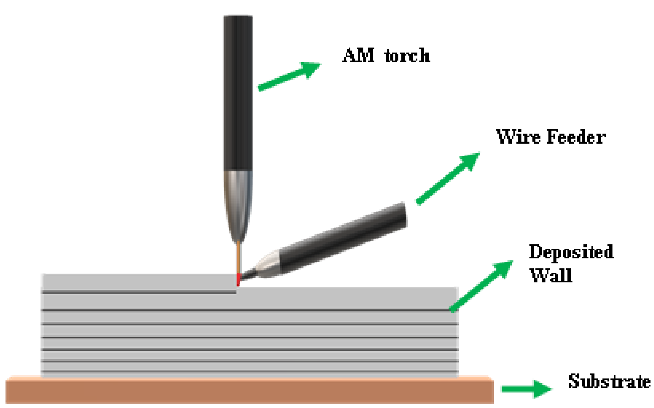

Fig. (1). Schematic diagram of the WAAM process.

Hot forging and heat treatment can significantly change WAAM material mechanical characteristics; YS and UTS have been increased to 922 MPa and 980 MPa, particularly in the as-manufactured region compared to 842 MPa and 945 MPa. In addition, a significant increase in tensile ductility of 14.5 percent after forging and heat treatment compared to 7 percent in the as-manufactured state was observed. Thus, WAAM material showed excellent advantages with heat treatment and hot-forged tensile properties compared to conventional materials. The tensile ductility was observed to be about 8% of the WAAM material, while the forged material has shown less than 10%, and the cast material has shown about 5% [6]. A wire arc additive manufacturing produced part/component showed that part was directly impacted by residual stress and also with distortion [7]. WAAM has been found to be a successful production process for different materials in manufacturing like titanium, aluminum, nickel alloy, and steel. The WAAM method can eliminate production time by 40–60% associated with conventional manufacturing methods, and post-machining time by 15–20% which depends entirely on the component size [8].

WAAM processes are carried out using widely viable wires that are readily available in a spooled form and a wide variety of alloys are used as feedstock for the welding industry. The development of a structurally sound, defect-free, and durable product requires underlying physical processes, feedstock metals, methods of process control, and knowledge of the causes and remedies of the various possible defects. In WAAM, metals are commonly used; however, a particular focus is given on the microstructure and mechanical properties of additive-formed alloys. In the study by J. Wang *et al*. [9], crack-free and versatile composite coating materials were found together with NiTi2 at its initial stage. The majority of fine Ni-Ti dendrites were collected on an arc. The overall mean micro-hardness of 818 HV with 0.2% was estimated to be 60 A, much higher than the uncovered substrate at 2.4. However, the wear resistance was also considerably lower than the uncoated substrate, based on the average wear rate and coefficient of friction obtained by the coating of 60 A. In terms of investment in time and cost, enhanced wear-resistant properties are feasible and effective. The results showed that the low-angle grain percentage increased from 34 to 70%, while the micro-hardness increased significantly. LSP significantly improved its alloy microstructure and average particle size from 59.7 μm to 46.7 μm. Yield strength improved to 178.3 MPa just after LSP, while UTS and EL decreased to 240.3 MPa and 6% [10]. The mechanical properties, which include hardness and tensile properties, have shown significant improvement; also, the travel speed increased from 248 HV to 253 HV for micro-hardness, the UTS improved to 687 MPa from 647 MPa, while the yield strength increased to 400 MPa from 376 MPa. The mechanical characteristics of the components produced by the CMT-WAAM method were superior to those of the casting parts of the Inconel 625

CHAPTER 10

Comparative Studies on FDM based AM Process Using Regression Analysis and ANFIS Model

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Abstract: Additive manufacturing is the method for fabricating the components effectively. The components fabricated by additive manufacturing process have wider applications in various domains. Fusion deposition modeling is one of the additive manufacturing methodologies that has been used for fabricating the components. Generating CAD model occupies the first and foremost step in this process, followed by printing of the designed model through fusion deposition extruders. The preparation of components through fused deposition makes it easier for the complex as well as most intricated shaped components, which is difficult in the case of existing conventional manufacturing practices. This liberty propels the effective utilization of additive manufacturing techniques in various fields ranging from the automotive to aerospace industries. This increasing demand turns the focus towards the selection of precise modeling techniques while selecting the process parameters in the fused deposition techniques. The present work mainly focused on the selection of best models for the fused deposition modeling and the comparative analysis between multiple regression analysis and ANFIS models for the selected parameters.

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Keywords: 3D printing, Additive manufacturing, ANFIS model, Artificial neural network, Comparative analysis, Fused deposition modeling, GRG, Optimization, Part thickness, Prediction, Printing time, Regression models, Response analysis, Surface roughness.

INTRODUCTION

Additive manufacturing (AM) is the most emerging as well as a promising technology in 2020 which is the highlight among all manufacturing methods. AM technique is very well getting adopted in the manufacturing of most intricate as well as complicated structural components mainly used for various industrial applications. The industrial revolution 4.0 is turbocharging the needs and demands for more accuracy in each and every part of the final components, as the conventional methods are failing to meet such demands. AM stands high in all such aspects. AM technique always overcomes issues like wear and tear during machining and also the problem of vibrations which is most predominant while maintaining the accuracy [1, 2].

The AM is a deposition process in which the component is made layer by layer that can be performed using different techniques like fuse deposition modeling (FDM), direct metal laser sintering (DMLS), powder bed fusion (PBF), and so on. The FDM is best suitable for the production of polymer-based products. The FDM process adopts the layer-by-layer printing of melted polymer in the worktable through process-controlled units. The input parameters mainly decide the quality of the components that are manufactured, and so the process is incorporated with many modeling techniques. This indicates that the selection of modeling and simulation techniques plays a vital role in the optimization of parts and products. The selection of modeling techniques also plays a vital role not only in increasing the accuracy of the components but also in reducing the errors in the optimized design [3, 4].

FDM is a method that manufactures 3D haptic physical replicas layer by layer as per the given CAD models. Though the concept was originated in the 70s era, the technological development at that time was not sufficient to support the 3D printing concept effectively. This opens up the door for rapid prototyping concepts to evolve further along with 3D printing; however, it was distinguished based on the materials selection and processing types. This rapid prototyping concept also requires complete understanding of the design and modeling aspects. Further, the knowledge towards development along with experimentation and analysis part may make the rapid prototyping a significant technique [5].

The issue of selection of modeling for the selective laser sintering (SLS) has been handled by many researchers in the previous years and recorded as well. The information clearly reveals that such incorporation has led to achieving more accuracy in the end products. The modeling has been done by considering the response factors, like part shrinkage allowance. The response was made based on the analysis done on the SLS process in stereolithography files. The derived modeling achieved higher accuracy on the selected SLS process. Similar improvement in the part fabrication has also been reported with other techniques as well [6 - 10].

The modeling technique also helps to achieve improvement in the physical properties of the fabricated components. The superior mechanical as well as metallurgical properties can be achieved using 3D printing through optimizing the layer orientation. The end results always surprise the researchers because the selection of modeling technique improves the properties more than the expected levels [11 - 16].

All these studies indicate that selection of appropriate modeling techniques helps to improve the accuracy of the AM part. The modeling methods work very well with any response factors ranging from part layer orientation to part thickness. With the help of this detailed study, an attempt is made to analyse the modeling techniques, such as multiple regression model and ANFIS models, in terms of the response factors, like the thickness of part layers, speed of printing and fill density for the 3D printing of ABS polymer materials.

MATERIALS AND METHODS

In the present work, Acrylonitrile Butadiene Styrene (ABS) is selected as the material to be used in the FDM process. As ABS is a special kind (opaque) of thermoplastic and amorphous polymer, it can be melted within the temperature range of 180 to 220 degrees centigrade. The melted ABS can also be cooled again in a less span of time without any further degradation. This property gives the freedom to the researcher to use it for the preparation of any type of components.

Input Parameters

The FDM technique mainly receives instructions based on the developed CAD models and their respective stereolithography file formats. The selection of these parameters plays a major role in the development of an optimized model for the fabrication of the best components. In this approach, three parameters like the thickness of layers, fill density and speed of printing, are chosen as the major input parameters to optimize the models. The standard L_{27} combinations for 3 input factors at three levels are given in Table **1**.

CHAPTER 11

Additive Manufacturing for Industrial Applications and Potential Quality Challenges

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Abstract: Additive manufacturing (AM), also sometimes referred to as 3D printing, is a rapidly growing manufacturing technology that has been in use for decades already. With the economic and efficiency advantages such as minimization of material waste, precision manufacturing of complex structures and reduced weight, AM has spanned into various industrial applications, including but not limited to aerospace, automotive, healthcare and many other industries that can leverage on the rapid prototyping capability associated with AM. The goal of this chapter is to elaborate on the industrial applications of AM, both current and potential, and to provide a deeper understanding of AM from a quality perspective. The market for AM is expected to grow up to $26.5 billion by the end of 2021. The cost of poor quality in relation to the potential market of AM is expected to be $5.3 billion (or 20% of AM market) in 2021, if the quality challenges are not taken care of. The chapter aims to uncover the advantages of AM over conventional manufacturing techniques and how this change works to the advantage of improved quality of the parts produced. An overview of current quality standards for AM, as defined by ISO and ASTM, is also provided in the chapter.

Keywords: 3D printing, Aerospace, ASTM, Automotive, Cost of poor quality, Healthcare, Industrial applications, ISO, Process capability, Quality, Rapid prototyping, Weight reduction, Waste reduction.

INTRODUCTION

The evolution of technology has taken a big leap in the last three decades. The humankind has seen tremendous growth in the use of cell phones, the internet, electronic vehicles, consumer electronics, smart devices and other similar technologies. One such technology that has been introduced in the late 1980s and has been growing ever since is additive manufacturing, also referred to as 3D printing or rapid prototyping. Additive manufacturing is building a near net shape of a 3D object by adding layers, one on another, using a CAD model. This is just

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the opposite of conventional manufacturing, which is removing layers one by one, otherwise referred to as subtractive manufacturing (ex: lathe machining). Since the advent of additive manufacturing (AM), the technology involved has grown rapidly and is now more efficient and economical. 3D printers, which perhaps have cost several hundred thousand dollars, are now substantially cheap and are available for less than $1000. The complexity of parts made with 3D printers has augmented with the introduction of new 3D printing technologies, and we are now able to print human organs with 3D printers. Though initially, 3D printers were used mainly for manufacturing industrial prototypes, the applications of 3D printed parts have spanned lately to various industries, including aviation, automotive, health sector, consumer goods, electronics, arts, and even the housing industry. With applications covering a wide range of industries, it is imperative to understand the integrity of the parts produced through AM and specifically their quality aspect.

Another essential facet of AM is its versatility to print complex objects. It is crucial for any business to innovate and stay ahead of the competition. With growing technology, the need to deliver better performance in leaner proportions has become an expectation. For example, the televisions and mobile phones we have today are way more efficient than older models, yet they come in sparer sizes. So the companies that make these products rely on swift research and development to achieve this. However, research and development take time not just because of the tiny and intricate parts that need to be designed and manufactured, but also the costly jigs, tools and fixtures that are needed to make them. Several companies invest millions and sometimes billions of dollars in research and development to streamline their research and development. Apple spent a whopping $4.2 billion in the quarter ending in June 2019 alone on research and development, and headed to spend $16 billion in 2019 on research and development, which is enormous for any mobile phone company [1]. This shows how significant research and development is for many organizations and 3D printing can significantly reduce these research and development costs for various companies by printing the parts precisely and quickly, without the need for costly tooling and jigs and the ability to iterate quickly before arriving at the desired output. This would help companies bring out better products to market way faster than the conventional manufacturing methods. There are also other benefits of using AM for industrial applications like cost savings, reduced weight, improved development times and minimized limitations encountered during initial design and prototyping.

The goal of this chapter is to explore the various applications of AM in different fields and also identify the potential applications of AM that could save industries not just millions of dollars in research and prototyping but also help them save a tremendous amount of time and labor involved in the process. The chapter mainly focuses on the applications and how quality is affected in a production environment. This chapter does not intend to elaborate on the technical aspect of the AM technologies used for making the 3D printed parts or provide in-depth details of the materials used for various applications. Instead, the chapter focuses on the current applications of AM in many industries and how the quality of such parts produced can be controlled based on the applications, and also any potential applications that this technology can be used in. The chapter uses some case studies and research performed by experts in the field to demonstrate some differences between conventional machining and additive manufacturing from an ease of manufacturing and product quality standpoint.

The quality of the product plays an important role in the decision-making process of whether bringing a product to market is viable and economical. Quality can be defined in several ways, depending on the user. Some common definitions of quality are fitness for use, ability to maintain product within specifications, degree of excellence and satisfying customer needs. Cost of poor quality, which is also a measure of quality in manufacturing, is the sum of internal and external failures, prevention and appraisal costs, which could go from 20% to 100% of the costs of the products manufactured [2], as depicted in Fig. (**1a**). Several organizations typically have actual quality-related costs that could range from 15-20% of sales revenue; some of them may even be as high as 40% of total operations. But generally, it is estimated that the costs of poor quality in a thriving company are about 10-15% of operations [3].

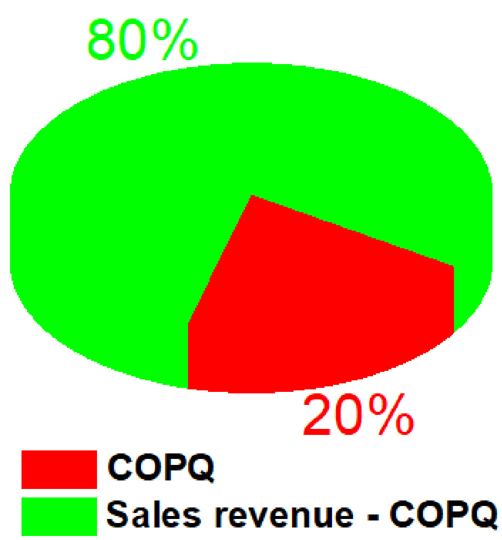

Fig. (1a). Cost of poor quality as a percentage of sales.

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