The role of mechanical testing in additive manufacturing: review

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Abstract. Additive Manufacturing has become a new era of manufacturing technology that goes beyond traditional subtractive manufacturing. It is based on layer-by-layer material deposition technology. Additive manufacturing technology is widely used due to its various advantages such as accurate production in a short time, required product design and complexity, easy operation, rapid prototyping, etc. It is widely used in automobile industry, oil and electric power industry, aerospace industry, biomedical applications and many more. Mechanical testing plays an important role in understanding the complex relationships between basic process parameters, defects, and the final product of the AM process. Mechanical testing such as tensile testing, fatigue testing, torsion testing, hardness and impact tests etc. are crucial to determine various performance parameters of the component of product. Owing to increasing applications of additive manufacturing in various fields it is important to analyse the components produced for their mechanical performance and hence mechanical testing plays a very important role in additive manufacturing. This paper aims to review the various mechanical testing performed in the area of additive manufacture and available published data on the mechanical properties of additively manufactured components. This paper on AM processes discusses the mechanical properties of materials and current research.

Keywords: additive manufacturing, mechanical properties, fracture, fatigue, tensile, hardness test, mechanical testing.

1. Introduction

Additive Manufacturing (AM), also known as 3D printing, uses layer-by-layer material deposition techniques to build parts from CAD-generated 3D models. This manufacturing technology enables the production of jointless products or components with minimal post-treatment requirements and minimal material waste. AM was developed by Chuck Hull in 1983 which later came to be known as stereolithography. Computer Aided Design is used to generate a 3D model of the product to be 3D printed and is then translated into a model data. The printer then slices the data into various dimensional planes which is instrumental in instructing the deposition of material layer by layer. Fig. 1 [32] shows the general procedure followed in producing components through 3D printing. 3D printing has become a popular and viable option in many disciplines and many industries. Compared to traditional manufacturing methods, this method has many advantages such as accurate manufacturing in a short time, required design and product complexity, easy operation, rapid prototyping, and reduced material costs. Significantly accelerate product development and market entry, enabling agile product customization and feature integration faster and at lower cost. ASTM International's Technical Committee has finally properly defined these processes as Additive Manufacturing (AM). According to ISO/ASTM 52900-2015, There are seven additive manufacturing production techniques. Each varies due to materials, layering, and machine technology needed. Fig. 2 shows the types of Additive manufacturing process.

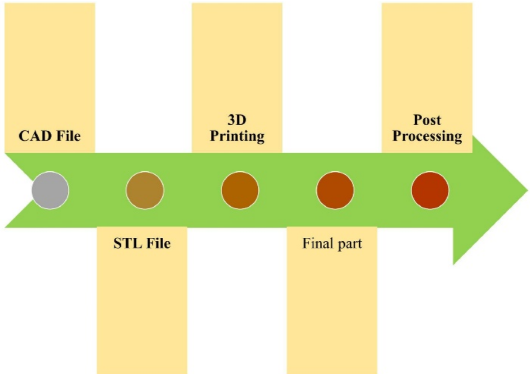

Fig. 1. Procedure followed in 3D printing, adapted from [32]

3D printing components are being increasingly used in various industries and fields. It finds large scale applications in aerospace, biomedical industry, automobile industry, oil and electric power industry. Advantages such as lower material wastage, lower costs, reduced post processing of components and easy manufacturing of very complex geometries makes 3D printing a very popular choice. In order to provide the required reliability in these major and serious applications that can have serious implications due to failure it is very crucial to analyse these 3D printed components for their mechanical performance. For example, in automobile applications there are often sudden impacts on various parts which can be 3D printed, in order to replace the conventionally manufactured parts by 3D printed parts it is necessary that these 3D parts should be more than or at the least equally reliable as the conventionally manufactured parts. Mechanical testing such as tensile testing to determine the tensile strength of the components, fatigue test to determine the lifecycle of components before failure, hardness test, impact test for failure, torsion test to determine the threshold values, vibrational analysis etc. are important to determine the performance of the 3D printed components. This paper summarises the various processes used in AM, materials and finally the types of testing that are critical in determining the performance of the components manufactured through AM.

1.1. Types of additive manufacturing

1.1.1. Powder bed fusion

The powder bed melting method (abbreviated as PBF) is a layered manufacturing process such as direct metal laser sintering (DMLS), selective laser sintering (SLS), selective thermal sintering (SHS), and electron beam melting (EBM). It is a widely used technology. Metal Laser Melting (DMLM). It uses an electron or laser beam to fuse together fine layers of material which are closely packed and spread on a platform and the following layers of material is applied on top of previous layers until the desired geometry of component is obtained. Powder Bed fusion method results in fine resolution and high quality of the component produced [32].

1.1.2. Direct energy deposition

Direct energy deposition technology uses concentrated thermal energy to melt a material by melting it as it is deposited. An electron beam gun or laser mounted on a 4-axis or 5-axis arm melts a raw material or powder of metal wire or filament. The process can be used with a wider variety of materials, including polymers, ceramics and metals.

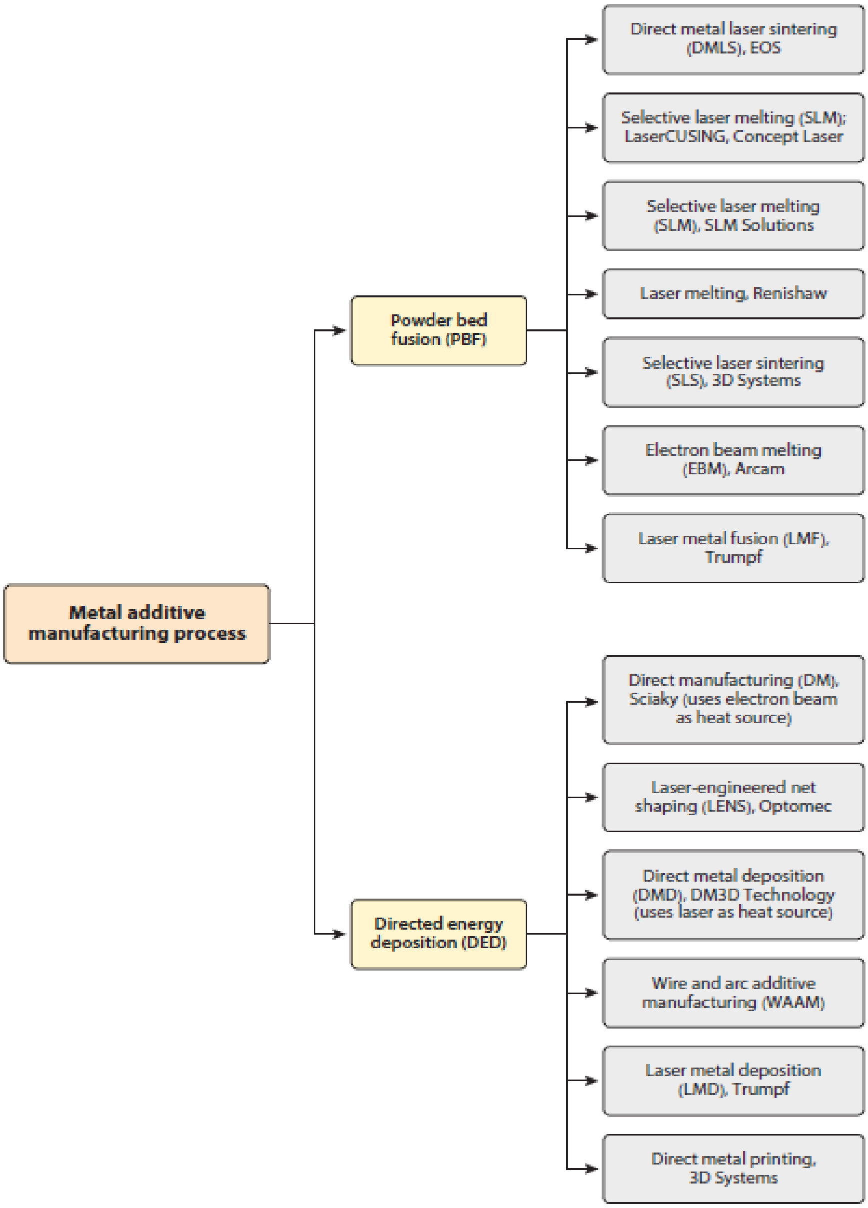

Fig. 2. Summary of metal additive manufacturing processes adapted from [29]

1.1.3. Material extrusion

Material extrusion is one of the most famous AM processes. The rolled polymer is extruded or stretched through a heating nozzle attached to the movable arm. The nozzles move horizontally, and the beds move vertically, so the molten material is stacked layer by layer. Proper bonding between layers is achieved by precise temperature control or the use of chemical adhesives. Benefits of this method are low cost and high speed.

1.1.4. Stereolithography

Stereolithography (abbreviated as SLA) is used to create models, prototypes, and patterns layer by layer by photopolymerization. Through the process of photopolymerization, light connects the molecular chains to form a polymer, forming the body of the model. It is the earliest AM process.

1.1.5. Material jetting

Material jetting is an AM method that uses an inkjet printhead to inject molten wax material onto a build platform The material cools and solidifies, so the layers can be layered on top of each other Printheads typically move the x, y, and z axes back and forth to create 3D objects. The layers of this object will cure when cooled or cured by UV light. Benefits of this method are smooth surface finishing and multi-material printing.

1.1.6. Binder jetting

The binder injection method is similar to the material injection process, except that the printhead alternates between powder material layers and liquid behaviour layers. Inkjet printheads apply a liquid binder to a thin layer of powder. You can build parts layer by layer by gluing particles together. Binder injection technology is suitable for making components with different material types and range of colours.

1.1.7. Sheet lamination

Laminate manufacturing (LOM) and ultrasonic additive manufacturing (UAM) are two methods of sheet laminating. LOM uses alternating layers of paper and adhesive, and UAM uses thin metal plates that are ultrasonically bonded. LOM is great for creating objects that are ideal for visual or aesthetic modeling. Benefits of this method are low cost and high speed.

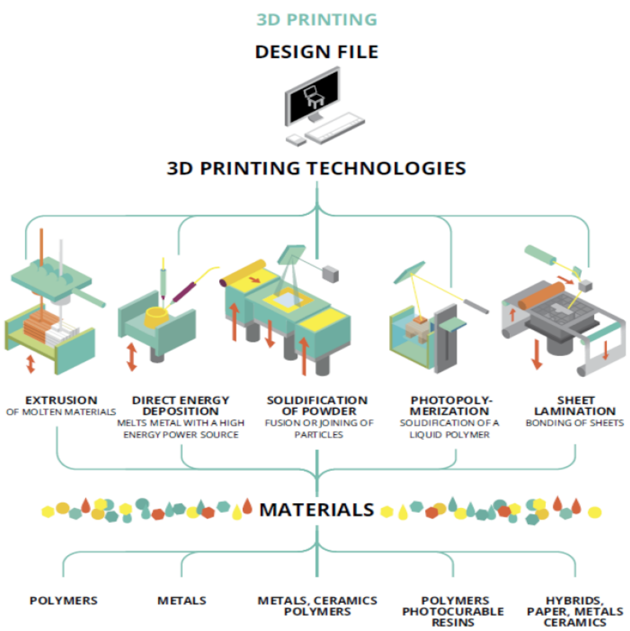

Fig. 3. Materials used in additive manufacturing [30]

1.2. The material used in AM

There are three types of materials available for additive manufacturing: polymer, ceramic, and metal. All seven processes of AM make use of these materials, polymers are most popularly used and certain additive manufacturing techniques allow themselves towards the use of certain materials over others. A huge variety of materials can be utilized for 3D printing, but metals are popularly used due to their extensive use in industrial and consumer appliances. Traditionally, the aerospace industry used advanced and costly materials like titanium and nickel alloys, which are difficult to manufacture and create a large amount of waste. Materials are often manufactured in the form of powder or wire feedstock. Other materials used include adhesive papers, paper, chocolate, and polymer/adhesive sheets for LOM. Fig. 3 and Table 1 shows the materials used in Additive manufacturing.

Table 1. Summary of various materials used in different process

Sr.no.	Material category	Examples
1	Polymers	ABS (Acrylonitrile butadiene styrene)
		PLA (polylactide), including soft PLA
		PC (polycarbonate)
		Polyamide (Nylon)
		Nylon 12 (Tensile strength 45 MPa)
		Glass-filled nylon (12.48 MPa)
		Epoxy resin
		Wax
		Photopolymer resins
2	Metals	Maraging steel 1.2709 (Tensile Strength 1100 MPa)
		Titanium alloy Ti6AI4V (Tensile Strength 1150 MPa)
		15-5ph stainless steel (Tensile Strength 1150 MPa)
		Cobalt chrome alloy, Co28Cr6Mo (Tensile Strength 1300 MPa)
		Aluminium AlSi10Mg (Tensile Strength 445 MPa)
		Gold and Silver
3	Ceramics	Silica/Glass
		Porcelain
		Silicon-Carbide

2. Challenges for mechanical property characterization

AM offers the opportunity for a rapid transition from design to product, especially for parts that are difficult or impossible to machine, but predicting mechanical properties remains a challenge. The difference between the AM process and the traditional process is that not all materials are melted and homogenized. The AM process of depositing material layers creates anisotropy and residual stress in the part. This is a big challenge. Researchers need to establish standardized methods for determining material properties based on specially designed AM treatments. Peer-reviewed literature is beginning to emphasize the complexity of associating mechanical properties with various process parameters. This issue is important to AM's success as a major manufacturing process, but there is not much literature available in this area. Research is moving towards a better understanding of raw material microstructure, material fusion and process parameters. Researchers try to find out the correlation between raw material, microstructure, material fusion process parameters and mechanical properties. Modelling is used to understand the relationship between anisotropic properties and AM products. Much work needs to be done to facilitate current research towards industry-related AM component testing. In this article, we will review the various mechanical tests performed on the samples created by AM. Table 2 shows Summary of various testing methods for AM components.

3. Types of testing

Mechanical properties can be categorized into static properties and dynamic properties. Static properties deal largely with tensile, torsion, hardness and impact properties of material. Dynamic properties deal largely with high and low fatigue cycles and creep cycles. Before employing the additively manufactured components in applications, a thorough round of testing is crucial to carry out on the component to ensure that each component meets t- he safety performance and quality standards. A wide range of testing is performed which is as follows.

Table 2. Summary of various testing methods for AM component

Sr. No	Name of testing	Applications
1	Chemical Analysis	Various AM technologies use the powder form of material for manufacturing; hence it becomes essential to understand and test the chemical properties of these powders about specific requirements
2	Mechanical Testing	The performance characteristics of the components can be determined using mechanical testing. These mechanical testing are performed according to the ASTM standards to determine various factors. Widely performed mechanical tests are- Tensile, hardness, Fatigue, Vibrational Analysis etc.
3	Metallurgical Analysis	To understanding the effects of build direction, process variables and design, metallurgists utilize techniques ranging from optical microscopy and SEM-EDS analysis to electron microprobe and advanced surface analysis techniques. For Examples: 1) Post-processing assessment 2) Porosity evaluation 3) Characterization on the interface layer 4) Particle shedding analysis 5) Microstructural characterization
4	Powders Evaluation	The product quality and operational efficiencies are highly dependent on the characteristics of additive manufacturing powders. 1) Particle Size Distribution 2) Morphology 3) Flow, quantitative shape analysis 4) Powder imaging, density
5	NDT	1) Computed tomography 2) White light interferometry 3) Surface profilometry 4) Dimensional validation

4. Overview of mechanical testing used for AM component

Different types of mechanical testing used to predict the performance of AM components

4.1. Tensile testing

Additively manufactured components find a wide range of applications in industries like aerospace, defence, automotive, healthcare, oil and are exposed to various loading conditions. Tensile testing becomes crucial to determine the behaviour of these materials and the subsequent components under the action of load. This testing will provide insights into the mechanical performance of a 3d printed material. Tensile testing is most often performed per ASTM standards. In the tensile testing of 3d printed materials force, displacement and strain are measured and stress-strain characteristics are plotted. Generally, properties like ultimate tensile strength, elongation and elastic modulus are determined to understand the mechanical behaviour under loading conditions.

4.2. Fatigue testing

Generally, the purpose of fatigue testing is to determine the expected life of a material that is repeatedly loaded, but fatigue strength and crack resistance are also commonly required value. Fatigue test is used for the determination of the maximum load that a sample can withstand for a specified number of cycles. These properties are very important in any industry where the material fluctuates rather than the constant force. Most fatigue studies of AM materials are empirical.

Defects play an important role in controlling the fatigue behaviour of AM materials. Almost all AM Metal fatigue data is generated under simple geometry and constant amplitude loads.

4.3. Vibrational analysis

Throughout the printing process, there are vibrations in the printer which depends upon various factors such as the structure of the printer, nozzle types, processing speeds, orientation of product etc. The vibrations produced in 3d printers are forced vibrations. Neglecting these vibrational properties can lead to catastrophic failure of components produced through 3d printed technology and hence it becomes essential to control these vibrations to obtain better mechanical properties of printed components. Vibration analysis/testing was sued for metallic as well as for non-metallic materials also.

Table 3. Summary of various Mechanical testing methods for AM component

Machine types	Materials	Test	References
EOS/laser-melted PBF	Ti-6Al-4V	Tensile	4
Renishaw AM250/laser-melted PBF	Ti-6Al-4V	Tensile	5
SLM250/laser-melted PBF	Ti-6Al-4V	Tensile	6
EOS M270/laser-melted PBF	Ti-6Al-4V	Tensile	7
SLM250HL / PBF	TNM (Ti- Al-Nb-Mo)	Tensile	8
EBM TiAl	EBM TiAl	Tensile	9
EOS M280 IN718	EOS M280 IN718	Tensile	10
SLM	IN718	Tensile	11
Arcam A2X	Ti4822	Fatigue test	12
Laser melting/PBF	Ti-6Al-4V	Fatigue test	13
EBM	Ti-6Al-4V	Fatigue test	14
PBM/SLM	Ti-6Al-4V	Fatigue test	15
SLM 250 HL	stainless steel 316L	Fatigue test	16
SLM	316L, 15-5PH	Fatigue test	17
FDM	Acrylonitrile butadiene styrene (ABS)	Fatigue test	18
FDM	Polymer Matrix Composite Materials, CARBON FIBER NYLON	Fatigue test	19
FDM	Polyethylene terephthalate Glycol (PET-G)	Vibration analysis	26
FDM	ABS (Acrylonitrile butadiene styrene) plastic	Vibration analysis	24
FDM	Polylactic acid (PLA)	Vibration analysis	33
EOSM250	4340	Hardness and Tensile	21
Arcam S12	IN625	Hardness and tensile	22
SLM	Al-Si-10Mg	Hardness and tensile	23
SLM	CoCrMo	Hardness and Tensile	13
SLM	AZ91D	Hardness and Tensile	14
Arcam A2X	Ti4822	Fracture toughness	24
SLM/SLM MTT250	Ti-6Al-4V	Fracture toughness	25

5. Conclusions

This article reviews the latest techniques of additive manufacturing for with the focus on the major processes, microstructures and mechanical properties. The most commonly used AM techniques which are powder bed fusion, direct energy deposition, metal binder jetting, and sheet lamination, are presented in this article. For each of these techniques, the materials are discussed with respect to their mechanical properties. Table 3 outlines the mechanical properties that are typically generated in the mechanical characterization of materials based on their respective application. Following this scope of study, this review article outlines the available published data for materials used in AM for currently available AM process categories. Albeit the scope of already studied and published mechanical properties has not covered the complete stretch of those shown in Table 3, a part of the mechanical properties reported for the metallic systems approach and sometimes surpass the properties obtained on analogous materials which are conventionally processed. Comparatively less published articles and data are available on standard samples for vibrational analysis, hardness, low cycle fatigue, fatigue crack growth, fracture toughness, and multiaxial testing. However, these goals can be achieved through a more detailed understanding of the fundamental processing-structure-property relationships possible with this new emerging technology.

6. Future scope

There is a substantial scope of investigation on several topics. The various AM processing parameters such as parts microstructures, mechanical properties and their interrelations are still not fully conceived. To enhance the understanding, theoretical studies with the help of AM process modelling can be useful. These theoretical studies could include heat and mass transfer, melting pool prediction, residual stress and distortion evolution, atomistic diffusion, densification, phase change, etc. These models are important to fully understand the relation of structure-property. They can also be used to prognosticate as well as optimize the physical and mechanical properties, and at the same time generate strategies for AM materials design or inverse design. Another potential research direction of AM systems is production efficiency. Higher energy power or faster scanning speed will improve the production rate, but the product quality might get compromised because of variations in microstructures. To address this problem, optimization of process parameters is required for the design and application of AM techniques. Finally, the fabricated material property database and the standards are still being developed. It is still an ongoing effort to establish a comprehensive database to ensure the quality consistency of AM products.

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