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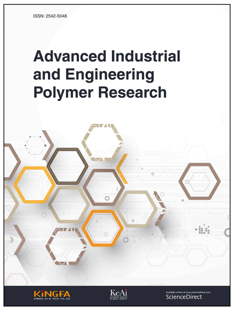

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Mechanical Properties of 3D Printed Parts: Influencing Parameters, Sustainability Aspects, Global Market Scenario, Challenges and Applications

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3D Printed Parts and Mechanical Properties: Influencing Parameters, Sustainability Aspects, Global Market Scenario, Challenges and Applications

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3D printing has evolved as a disruptive technology for fabrication of industrial components, however due to the intrinsic nature of the process, the mechanical strength of the parts developed by 3D printing is a subject of research. The economic and technical advantages offered by 3D printing makes it as a potential replacement for the conventional manufacturing processes, particularly for developing complex and optimized products. The current paper is structured to focus on the various processes of 3D printing used for the development of industrial products, the various process parameters involved in each process and their effect on the mechanical properties of these parts particularly fatigue, tensile, bending strength, etc. primarily focusing on polymeric materials. Further an important aspect of 3D printed parts i'e tribological properties have been highlighted. A systemic literature review related to these aspects has also been presented. A section highlights the various applications of these 3D printed parts particularly in medical, aerospace and automotive. A section also highlights the sustainability aspects of these 3D printed parts. The paper also highlights the possible future research areas, recommendations and challenges involved in developing 3D printed parts.

Keywords: *3D Printing; Mechanical Strength; Additive Manufacturing; Fatigue Strength; Friction; Wear; Polymers*

Abbreviations

AM	Additive Manufacturing
USD	United States Dollar
FDM	Fused Deposition Modelling
FFF	Fused Filament Fabrication
MSME	Micro-Small and Medium Enterprise
AI	Artificial Intelligence
ML	Machine Learning
SLA	Stereolithography
SLS	Selective Laser Sintering
SLM	Selective Laser Melting
ASTM	American Society for Testing and Materials
STL	Standard Tessellation Language
LOM	Laminated Object Manufacturing
PVDF	Polyvinylidene Fluoride
PLA	Polylactide
ABS	Acrylonitrile Butadiene Styrene
PEEK	Polyether Ether Ketone
SEM	Scanning Electron Microscope
HDPE	High Density Polyethylene
HIPS	High Impact Polystyrene Sheet
CF	Carbon fiber
CFRTPC	Continuous Fiber-Reinforced Thermoplastic Composites

1. Introduction

The main objective of the additive manufacturing (AM) is to reduce the process time and process steps. This can be done by rapid prototyping technologies. AM uses 3D modelling software like CAD for developing the design and hence the product within the least possible time [1][2][3]. Product is manufactured by adding successive layers of material on each other by using the data from the designing software [4][5], [6] [7]. AM can be broadly classified into two types: Single Step Manufacturing and multistep manufacturing [8]. The single step involves the fusion of material[7] to attain the basic geometry while as the multi-step uses the adhesion principle to attain the basic geometry and process is completed in multiple steps. Figure 1 shows a representative image of a part printed through 3D printing showing the layered manufacturing.

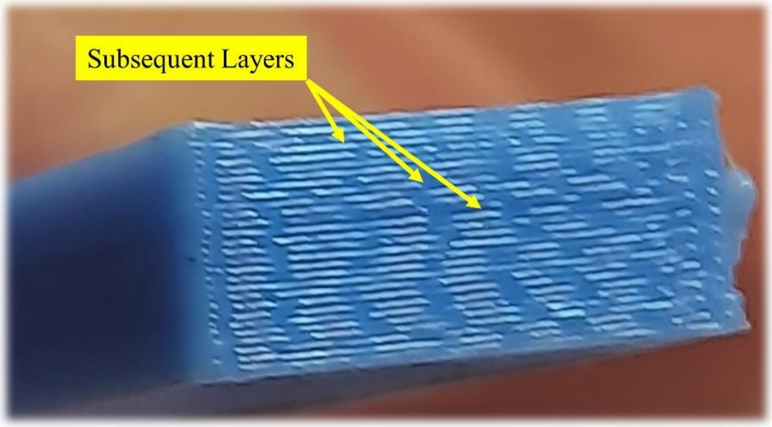

Figure 1: Representative image of a 3D printed part showing the layered structure

The various AM techniques are SLS (Selective Laser Sintering), FDM (Fused Deposition Modelling), SLA (Stereolithography), LOM (Laminated Object Manufacturing). The technology is being up-graded frequently to optimize the manufacturing process and to obtain the desired the geometrical properties of the final product[9]. Almost all the technologies of AM are also known for its material saving property. It is compatible for printing polymers, alloys, metals, bio-medical materials[10]. Researchers are using AM to perform the interdisciplinary studies on materials by combining them with an intention to obtain the clustered mechanical, optical and physical properties in the final product [11][12] [13]. It has been proven better for reducing the lead time in critical replacement parts and shortening the supply chain [14]. From the economic point of view, it is expected that the growth of AM industry is expected to increase by 15.8 billion USD over next few years [15]. Nowadays, large companies such as General Electric Aviation and Siemens are switching to AM for manufacturing parts. However, industries like MSME (Micro, Small & Medium Enterprises) hesitates to work with AM due to large investment and lack of operating knowledge. Recent research has been done on increasing the efficiency of AM by working on supply chain management. Modified supply chain, also known as hybrid chain has been proposed where the parts of the product were manufactured by external AM centers and combined at the head center when the order for the product is received [16]. The review deals with the mechanical and the tribological properties of 3D printed parts, hence the emphasis has been put on developing a systematic literature survey of effect on mechanical properties of 3-D printed parts. It has been observed that the mechanical as well tribological properties depend on various parameters like infill material and printing pattern. Not only the printing parameters but also the process chosen has its effects on the materials properties of product. Research has been done to produce the composites with reinforcements like thermo-plastics and nano materials[17]. Further work is continued in enhancing the surface and morphological properties of AM products. The mechanical testing of 3D printed materials enables us to design and analyze the product as per our need. Quality of products manufactured by AM can be modified and enhanced as per the industrial requirement. It has been employed to develop the product especially for Aerospace and defense applications. Hence, the mechanical characterizations like Tensile test, Hardness test, creep test define the product's behavior when subjected to mechanical loads under real life situations[18]. Some 3D Printed Parts Printed by Fused Deposition Method are shown in Figure 2.

Figure 2: Various 3D Printed Polymeric Parts (Representative Image)

Additive manufacturing enables the users to print the parts of some the components of machine that need to be fixed. This reduces the human intervention and dependence on the service providers particularly for consumers from remote locations. The open access availability of various design related software tools related to 3D printing further helps the end users to use the technology with ease. This reduces the time and money of the user. AM has enabled mass customization of products in a short period which is not possible by any conventional way of manufacturing [19]. AM has reduced the supply chain by manufacturing the parts or products on demand. Thus reduced the cost of transportation and saving the time by avoiding the stockpiling. The labor cost is eliminated in the AM, which indirectly brings the price of the part down. Unlike the subtractive manufacturing were the material is cut down to bring the product into the shape, here the material is added as per the geometry thus reducing the material wastage [20] [21].

In spite of the fact that the setup cost if the 3D printing machines is high, however due to the aforementioned benefits the overall cost of the products developed through AM is considerably lower as compared to conventional manufacturing processes. Some important differences between the AM and Conventional manufacturing are briefly given in table 1:

TABLE 1: DIFFERENCE BETWEEN CONVENTIONAL AND ADDITIVE MANUFACTURING

Conventional Manufacturing	**Additive Manufacturing**
Material is cut to attain the proper shape and size	The material is added to attain the proper shape and size
Very difficult to manufacture complex geometries	Complicate geometries can be easily manufactured
Low manufacturing volume	Manufacturing volume is enhanced as various non-essential processes are eliminated
Its featured to consume more time	The time is reduced significantly
The product cost is high	The product Cost is minimized due to optimized processes.
Material wastage is the cause of concern	Less to no material wastage is observed

With the feature of instant redesigning and printing, it has become possible to optimize the material usage, reduce the total weight of the product without degrading the mechanical or tribological properties. Above all, the thermal, mechanical and other performance of product with complex geometries has enhanced by applying the optimization techniques on printing parameters and product design which is not possible by the conventional way of manufacturing.

For industry 4.0, AM is considered one of the key player for the implementation of mass customization under the economically feasibility condition [22]. The amalgamation of AM in AI, ML and Cloud have made it possible to apply the concept of digital twins [23]. The concept of digital twins can help in overcoming the various problems in printing which include monitoring and control, process simulation which can affect the product quality and enable the real-time correction.

This primary objective of the work is to highlight the mechanical properties of 3D printed parts with a focus on polymer based components. Apart from discussing some introductory sections related to 3D printing literature pertaining to study of these properties has been included from prominent databases. The paper also brings forth a discussion on some important aspects such as sustainability, tribological properties, global market scenario and potential application areas have been included apart from the mechanical properties which are not available in any review reported thus far.

1.1 Brief History of AM:

The development of Additive manufacturing started back in 1987 in a "watershed" event in the United States. Stereolithography was the first AM technology which was accompanied by the development of new methods like Laminated Object Manufacturing in 1991 and Selective Laser Sintering in 1992[15][24]. In 1993, an indirect method of tooling was introduced by Soligen known as Direct Shell Production Casting and Quick Cast. Due to the introduction of these two methods, AM became more popular. It was General Motors in 1991 which were first to adapt AM by using SLA-250 [25]. With the passage of time AM kept on improving. In year 1994, Kira Corp introduced paper lamination. Ink jet printing came into existence in year 1996 with 3D printing technology. Work on thick metal sheets started after SLS came into existence in year 1999. Thus, AM started its operations for aerospace companies. Boeing was the first company to work with AM for fast manufacturing of electrical boxes and brackets [15]. With the advent of New technologies like fused deposition modelling, the development for low cost readily available 3D printers started. These printers were easily available and were easy to operate. The Recent developments of AM material characterization can be seen in Figure 3 wherein it is clear that a lot of focus is being laid on studying the mechanical properties of these 3D Printed parts. Also amongst the mechanical properties, the studies related to tensile testing are more as compared to other mechanical properties.

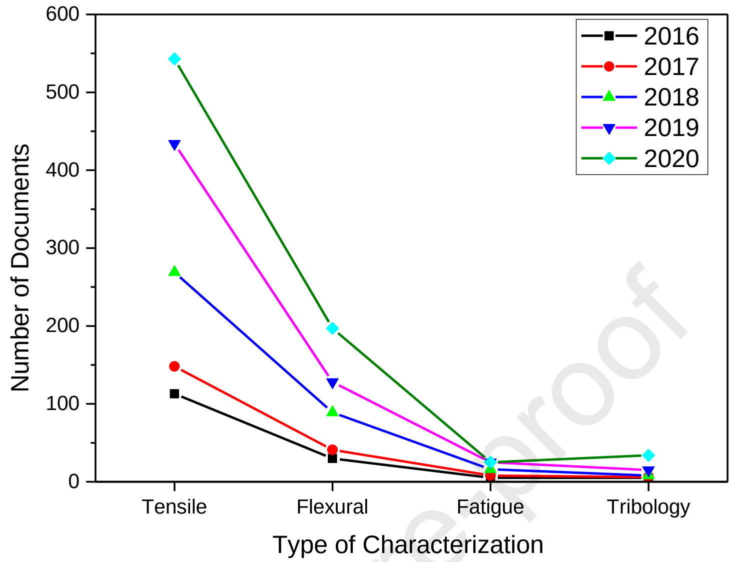

Figure 3: Number of Papers published in Scopus related to Mechanical Characterization of 3D Printed Parts for the past 05 Years (Keywords used: *3D Printing + Tensile Strength, 3D Printing + Fatigue Strength, 3D Printing + Fatigue Strength and 3D Printing + TRIBOLOGY)*

1.2 AM Materials:

For an Additive Manufacturing Process, the AM materials are generally classified as Amorphous, Semi-Crystalline and Thermoset in accordance with the process category [26]. Depending upon the process, plastics are categorized as amorphous polymers, semi crystalline polymers and thermoset. Due to large viscous softening temperature, the amorphous polymers are good for material extrusion. For semi-crystalline polymers, due to small temperature range, hence they can be used in powder-based fusion. Thermoset polymers are mostly used in material jetting [27]. During the thermoset process, main emphasis is given on resin viscosity. The resin viscosity is kept low for perfect jetting [28].

Metals have been processed by AM with powder-based techniques like powder bed fusion and direct energy deposition. Binder jetting is also used for metal printing. Researchers have published data for AM of metal alloys like TI6Al4V [29] [30], stainless steel [31][32] etc. Metals like gold, silver have also been manufactured using selective laser melting[33]. The AM of metals is less in comparison to other alloys, plastics due to thermal residual stresses and non-equilibrium microstructures. The internal defects of a material can be responsible for fatigue generation and surface roughness; this can be corrected by post processing of the product. Polishing is generally used to overcome the surface roughness. Other techniques like buffing and chemical etching can help in reducing surface roughness and lowering the levels of stress concentration [34].

Nowadays focus is laid on generating functionally graded materials with high entropy, high strength. One such category of materials is High Entropy Alloys. They are the combination of five or more elements of equal percentage with equal atomic mass[35]. They possess the properties like high strength, corrosion resistance and oxidation resistance, hence their application vary from nuclear fusion tanks [36], cryogenics [37]and bio-medical [38]. Researchers [39][40] have studied the microstructure properties of additive manufactured super-alloys and it was observed that the microhardness of super-alloys manufactured by additive manufacturing is 13% higher than that of manufactured by conventional casting methods. With the growing demand in the market, AM materials are also taking a leap to meet these demands. New materials with reinforcements are introduced by researchers, which are reinforced with certain materials for better mechanical or surface properties [41]. Some important Additive manufactured materials with the process involved is shown in Table 2.

TABLE 2: MATERIAL PROPERTIES OF ADDITIVE MANUFACTURED MATERIALS

Author	**Material**	**AM Process**	**Investigation**
[42]	Aluminum-scandium Alloy	Laser printing	Enhanced Static Mechanical properties, hypereutectic Al-

			Scandium composition with grain refinement.
[43]	AZ31, Magnesium Alloy	Selective Laser Melting	Appreciable porosity in the range of < 5%
[44]	Ti6Al4V	Direct Energy Deposition	More elongation in transverse direction, High ultimate tensile strength of 1060 MPa (in average) in comparison with the prior studies on Ti6Al4V
[45]	α+β titanium alloy	Laser Melting deposition	High yield strength (895,971MPa) and elongation (160.8%, 11.8%) are seen for α+β titanium alloy for longitudinal as well as transversal directions respectively.
[46]	AISI 420 stainless steel	Laser Rapid forming	Laser Rapid forming can produced purified AISI 420 Stainless Steel.
[47]	300M Steel	Laser Solid Forming	Uniform microstructure after heat treatment.
[48]	Inconel 718	Laser Solid forming single direction raster scanning (SDRS), cross direction raster scanning (CDRS)	Ductility of CDRS specimens are more in comparison to SDRS while as ultimate tensile strength remains the same for both the processes.
[49]	Beta Ti-24Nb-4Zr-8Sn alloy	Solid Laser Melting	Nearly 99% density is achieved.

2. Additive Manufacturing Technologies:

Additive manufacturing is also known as rapid prototyping (RP). RP was employed by the industries for creating the prototypes before the final commercialization takes places but soon, it was used to generate the final product hence the name was replaced as additive manufacturing. It was ASTM which suggested to change the terminology [4] [7]. The AM works by adding layers of material of small but finite thickness constantly until the product of required dimensions is obtained. Every AM process starts by creating a geometric model using modeling software which than converted into the STL file format. Here the slicing of the CAD model is done. Now the STL file is transferred into the AM Machine which then manipulated for proper position and size. The layer thickness, printing speed and print orientation is set to the machine. Printing size is mostly automatic in itself. AM machine used the data that is previously fed to it.

Post processing is one of the important aspects of AM. It is done after the completion of printing. It involves removing support features. Surface finishing and painting is also done in this stage. Heat treatment for perfect body shape and reducing porosity of the product is also achieved. It is important to know that there are various AM machines which are directly compatible with the modeling software, hence the slicing with STL format is neglected. Maintenance is the main concern for the better operation of AM machines. 3D printers need to be carefully monitored as they are expensive and fragile. They require regular checkups and cleaning. Thus, it is necessary to keep them away from the dirty and noisy environment. The detailed structure of various AM technologies is shown in figure 3.Some important AM techniques are discussed below:

2.1 Stereolithography: It came into existence in year 1986 [50]. Charles Hull is known as the father of this technology. It is considered as one of the oldest AM techniques. It uses UV light or a beam of laser for generating product, hence the raw material must be curable by light/laser. Such materials are known as photo polymers or photo resins which are treated by photo-polymerization. Since AM works layer by layer manufacturing, hence after the creation of first layer the table or bed is lowered up to the height equal to one layer. The polyresin is spread and cured again. This process continues till the final product is made [51]. The heat treatment is necessary as only 95%

of material is cured through photopolymerization [52]. SLA process is usually slow, expensive and comes with small range of input working materials. It mainly encounters with some errors like warping [53]. This is due to the shrinkage of acrylate resins. There are two reasons of shrinkage, one is due to bond between high dense polymer and less dense polymer. The second is due to the expansion of polymer during the photopolymerization (due to rise in temperature). Hence SLA needs post-processing. Some common post processing techniques with SLA are photocuring and heat treatment of products [54].

2.2 Selective Laser Sintering: SLS works with the powder-based input material which is treated with a beam of laser in order to get their particles sticked at the surface. Before the sintering process, the bed or the platform is heated up to the temperature slightly less than the melting temperature of powder material. This process is necessary in order to avoid the distortion and increase the bond strength with the previous sintered layers[55]. The laser beam is guided to the required path with the help of scanning mirror to generate the layer. After the first layer, the platform is lowered up to the height equivalent to the thickness of one layer. The powder is spread all over the bed and laser sinters the material to form the second layer. This process continues till the product with accurate dimension is made. The particle size of the powder plays an important role in SLS as the strength and density of the manufactured part depends on it [56] . Research has shown that residual stresses in the manufactured parts by SLS can be reduced by using the laser operations in an optimized way [57]. There are various methods and strategies on which SLS works. Some common strategies or methods are meander, Stripe, Chessboard and spiral. For smaller cross-sections and homogenous build area meander is used while as chess-board and stripe is used for large cross-sections. Spiral method is employed for in homogenous buildups [58]. In order to get the perfect mechanical and structural properties, parameters like laser exposure time, contouring method, up-skin and down-skin parameters need to be controlled as they effect the properties like fatigue strength, hardness and roughness[59].

2.3 Fused Deposition Modeling (Material Extrusion): It is considered as one of the important techniques of AM. Developed by Stratasys to manufacture the products of thermo-plastic materials like acrylonitrile butadiene styrene polycarbonate and polylactic acid [60][61]. The process uses solid raw materials in the form of filaments. The process uses solid raw material in the form of filaments. These filaments are fed to the extrusion chamber where they are heated till it starts to melt. Now this melted filament is extruded layer by layer on the platform till the product is completely manufactured [62]. Sometimes the product has overhanging, thus they require support during the printing process. The support needs to be printed as per the requirement. It must be noted that the material for support should be easily breakable and soluble in water. FDM has various printing parameters like printing speed, print orientation, infill percentage, layer thickness and extrusion rate. It has been seen that all these parameters effect the mechanical as well as structural properties of the product[63] [64][65]. FDM is considered as one of the simple technologies of AM. It is fast and easy to operate. The products are manufactured at low cost as compared to other AM technologies but there are certain drawbacks like poor mechanical properties, rough surface texture. Hence the products manufactured by FDM need post-processing [66][67].

2.4 Laminated object Manufacturing: LOM uses thin sheet of raw material, which is treated with blades or laser into the required shapes. After the laser treatment, each layer of sheet is glued together by a hot roller. There are two ways of LOM. First one is form-then-bond and other is bond-then-form [8]. The bond-then-form is popular with printing ceramics and metal-based materials. The processed products require high temperature for post-processing. It finds its applications in paper industry, foundry shops and electrical industries. Some important fabrications include optical fibers[68] , PVDF films [69] , Nickel Titanium switches [70]. There are several drawbacks like poor surface quality, post-processing requires lot of time and least dimensional accuracy.

2.5 Selected Laser Melting: This technique was first developed by M. Fockele and D. Schwarze with an aim to produce metallic parts form the metallic powder. It is categorized under the powder bed fusion process that requires high density laser energy to melt the powder in a desired shape and size [71]. Like any other AM process, it also uses STL file of the drawing for layer by layer manufacturing. Once the first layer is completed, the printing platform is lowered for second layer. This process continues till the product takes its shape and size. The SLM process requires controlled atmosphere inside the chamber. Nitrogen or Argon gas is used to maintain the inertness of the chamber so that heated metallic products will not oxidize [72]. The application domain of this technology is diverse ranging from automotive to aerospace, medical to dental, heat exchangers to pumps, etc.

3. Effect of Process Parameters on Mechanical Properties:

Additive manufacturing technology is widely used in our day-to-day life. Its importance in our day-to-day life has been growing rapidly. From aerospace to medical science, it has shown its tremendous success. The product quality has been the main concern. To attain the perfect quality, one needs to explore all the process parameters associated with the material printing. Some important mechanical properties and their variation with the process is discussed below:

3.1 Tensile Strength:

Tensile strength is an important property for mechanical parts. Researchers have reported the effect on the tensile strength of PLA based specimen with the change in parameters like infill percentage, part orientation and the layer thickness [73]. Figure 4 shows a typical tensile test specimen of a polymeric 3D printed material.

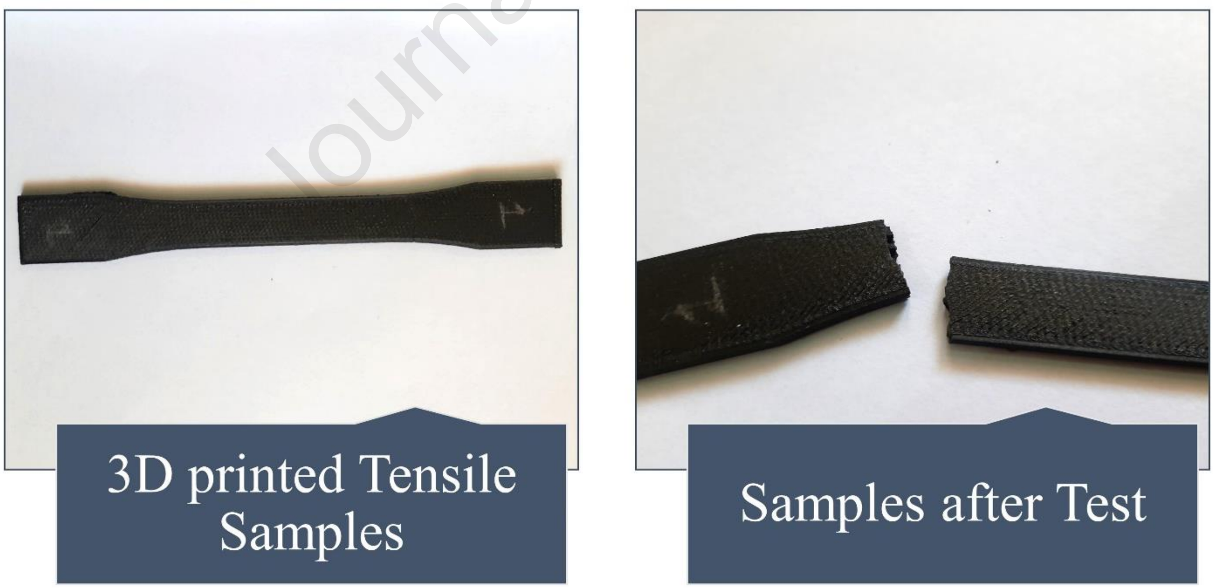

Figure 4: A typical tensile test specimen of a 3D printed part (before and after the test)

Significant change in the tensile strength was observed while altering the above-mentioned parameters in fused filament fabrication or fused deposition modeling. The highest tensile strength was observed at 0.3mm layer thickness, 0º orientation and 80% infill percentage [73]. Investigations have been performed to study the effect of process parameters like layer thickness, air gap, part orientation and raster angle on the tensile behavior of materials printed [74]. The observation of the study was that part orientation has the most effect on tensile property. Further, the maximum tensile strength was reported for build orientation 0º, raster angle 50º, negative air gap of -0.0025, raster width 0.2034m and layer thickness 0.127m. [75] reported the effect of printing speed, raster angle and layer thickness on the tensile properties of ABS with FDM. Maximum Tensile Strength was reported with 0.1 mm layer thickness, +30/-60 raster angle, 40 m/s printing speed. [76] Reported the influence of raster angle on the tensile strength of FDM printed PLA. The results showed that the specimens of raster angle 0◦ and 90◦ showed least tensile strength. Printing patterns also play and important role in determining the mechanical properties of printed materials. Researchers have investigated the effect of infill percentage and infill pattern on the tensile properties of ABS specimens [77]. Figure 5 shows the SEM fractographic images after a tensile test of a polymeric sample manufactured through 3D printing. The cross sectional view also depicts the interlayer bonding between the various layers of the sample.

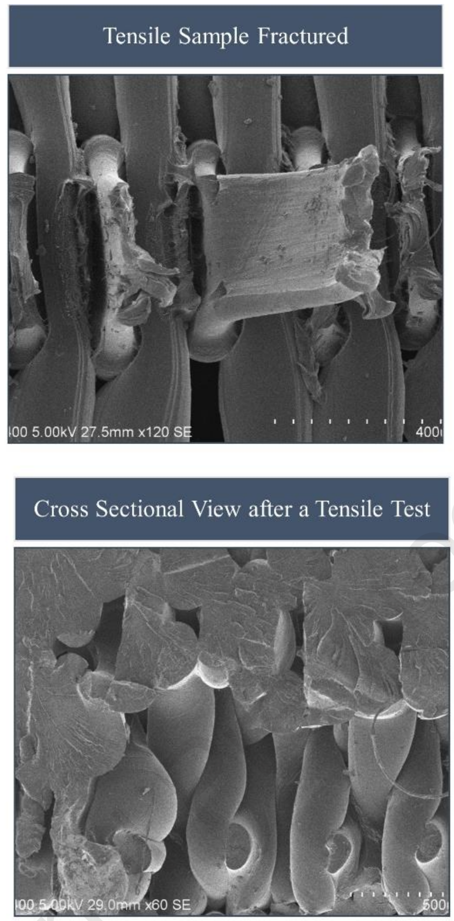

Figure 5: SEM Fractography of a 3D printed polymeric sample after a tensile test (Cross sectional view)

It was seen that, with the increase in infill percentage, the tensile strength also increases further observations reveal that rectilinear pattern has significant role in enhancing the tensile strength of 3D printed specimens. Effect of Extrusion temperature has been explored by [78]. The author explores the tensile properties of carbon fiber PLA specimens and post-process the results using ANOVA. Observations reveal that the interaction between the extrusion temperature and infill pattern has the significant effect on the tensile properties. The interaction between extrusion temperature and infill percentage has significance on the tensile properties of carbon fiber PLA. [79] has developed a relationship between the process parameters like bed temperature, layer thickness and nozzle diameter w.r.t tensile and flexural properties of solidified PLA. It has been verified by the author that with the increase in layer thickness the tensile strength decreases while as flexural strength increases. Bed temperature is helpful in increasing both tensile as well as flexural strength. With nozzle diameter, the tensile strength increases while as flexural strength first decreases then increase with increase in nozzle diameter. The recent studies on the performed-on AM materials to study the effect of process parameters on the tensile properties are shown in Table 3.

TABLE 3: VARIOUS STUDIES CARRIED TO STUDY TENSILE BEHAVIOR OF 3D PRINTED PARTS

Author	***Material used***	***AM Process***	***Tests Performed***	***Major Observations***
[80]	Pure ABS and PLA. Blends of ABS and PLA.	Fused deposition Modeling	Tensile Test Flexural Test.	• Pure PLA has better tensile strength than pure ABS. • The specimens with equal concentration of ABS and PLA show much better tensile and flexural properties.
[81]	PLA	Fused deposition modeling	Tensile Test	• Print orientation has more effect on tensile strength and less on Young's modulus. • As the number of layers increase, the young's modulus as well as tensile strength decrease.
[82]	Polyamide 12 (PA 12) + Various concentrations of	Selective Laser Sintering	Tensile Test	• SLS manufactured PA 12-20HGS60 and PA12-20HGM composites had higher

	Hollow glass microspheres (HGMs)			tensile stresses as compared to other. • Polymer additives alter the crystallization temperature, which alter the process parameters of SLS for near-net-shape of SLS components.
[83]	PLA	Fused Deposition Modeling	Tensile Test	• Anisotropic behavior of FDM 3D printed material is observed. • The specimens with defects show lower tensile properties.
[84]	Nano clay/HDPE nanocomposites	Fused Deposition Modeling	Thermal Tests Tensile Tests	• The tensile, flexural strength are showing the increasing trend with the increase in NC concentration. • Melting flow index decreases with the increase in NC concentration.
[85]	Clear V4 resin	Stereolithography (SLA)	Tensile Tests	• Mechanical properties like tensile strength, maximum stress and young's modulus are isotropic for SLA.

[86]	PLA	Fused Deposition Modeling	Tensile Test Bending Test	• As the layer thickness increases, the tensile bond strength increases and then decreases peaking at 0.4mm • While the flexural and tensile strengths decrease.
[87]	Inconel 718	Selective Laser Melting	Tensile Test	• As the aging temperature increases, the tensile strength also increases. • Moreover, the strain hardening rate also increases with the aging temperature.
[88]	ABS, HIPS, Polycarbonate, T-Glase, Nylon, Semiflex, Ninja flex	Fused Deposition Modeling	Tensile Test	• The tensile strength of a 3-D printed material largely depends upon the weight of the specimen.
[89]	Polyurethane Elastomers neat, And compounded Polyurethane Elastomers with diluent and photo initiators	Digital Light Processing	Tensile Test	• Self-healing property has been enhanced by DLP • The tensile properties are good. The healing efficiency is 95% at 80 °C for 12 hours.

[90]	ABS-HIPS ABS-PLA PLA-HIPS PLA-HIPS-ABS	Fused Deposition modeling	Tensile Test	• Multi-materials have evolved as a better choice for the functionality of materials by 3D printing. • Multi nozzle system proves to be time consistent for functionally grading of material.
[91]	continuous fiber-reinforced thermoplastic composites (CFRTPCs)	Ultra sonic assisted Laminated Object Manufacturing	Tensile Test	• The study showed that unidirectional printed specimens have high tensile strength and tensile modulus. • Also, Post processing like hot press treatment have enhanced the mechanical properties of specimens.
[92]	CF-PLA	Fused Deposition modeling	Tensile Test	• For tensile test, maximum strength is displayed 80% infill
[93]	Methacrylate Methacrylate+Lignin	Stereolithography	Tensile Test SEM	• Lignin concentration enhances the tensile strength as well as young's modulus.

				• The trend is seen in both posts cured as well as non-post cured samples. • With the increase in Lignin, the roughness also increases.

3.2 Fatigue Behavior: To study the fatigue behavior of materials manufactured by AM, Researchers did series of experiments on PLA processed by FDM process [94]. It was observed that under cyclic loading, the specimen prepared with 45º print orientation has highest fatigue life in comparison to those built in X and Y direction. Further Research was expanded by Letcher in 2014 [95] were they also explored the effect of print directions on the fatigue life cycle. The author prepared the specimens of PLA in three directions, that are: 0º, 45º and 90º. It was seen that printing orientation definitely has its effect on the tensile as well-as fatigue properties of the specimen. The PLA printed 90º direction showed the minimum resistance to fatigue while as specimen printed with 45º had the most resistance towards fatigue. The layer height thickness has also a significant impact on the fatigue properties of specimens. [96] has investigated the effect of layer thickness on the fatigue behavior of PLA specimens. It was seen that with the increase in the layer thickness, the fatigue endurance limit was enhanced and the no. of loading cycles until the material failure has been heightened. Apart from the above two parameters, researchers [97] have investigated the impact of raster pattern, infill density, nozzle height and printing velocity of the fatigue behavior of PLA specimens. The optimized data set of parameters was given for enhanced fatigue limit. Hexagonal raster pattern with 0.5mm of nozzle diameter and layer thickness of 0.3mm provided the better results. Other polymeric materials like ABS and ABS plus processed by FDM have also been explored. Researchers [98] [30] have conducted and series of experiments to check the influence of parameters like printing angle, temperature during the printing process on the ABS processed by FDM. The results depicted the strong dependence of fatigue life-time on the above-mentioned parameters. presented a comparative study of fatigue behavior was presented between the PLA and ABS specimens printed by FDM process subjected similar loading conditions [98] .

It was recorded that the fatigue lifetime of ABS was less than that of the PLA samples. Fatigue limit of the specimens printed in the vertical directions have higher values of fatigue strength.

3.3 Tribological behavior: In the present situation, polymeric materials are replacing metallic materials due to high strength, self-lubricating properties and light weight. Due these advantages the polymeric materials find itself in almost all the engineering application. Self-lubricating polymers find their applications in mechanical systems were no external grease or lubricating oil is acceptable. One such example is the sliding shoes in textile drying machines. Offshore oil extraction plants require bushings which do not corrode with the harsh environmental conditions of ocean. This need can be full filled by polymer composite bushing. The load bearing capacity can be enhanced by fiber reinforcement [99]. Hence, it is necessary to evaluate the tribological properties of polymers and the effect of various additive manufacturing process parameters on the tribological properties of polymers and polymer composites. Researchers conducted an experimentation on ABS and PLA specimens with an aim to study there tribological behavior [100]. It was observed that the PLA and ABS exhibit almost similar tribological properties when prepared under same printing conditions. Figure 6 shows samples printed by 3D printing process for a typical pin on disc tribological test.

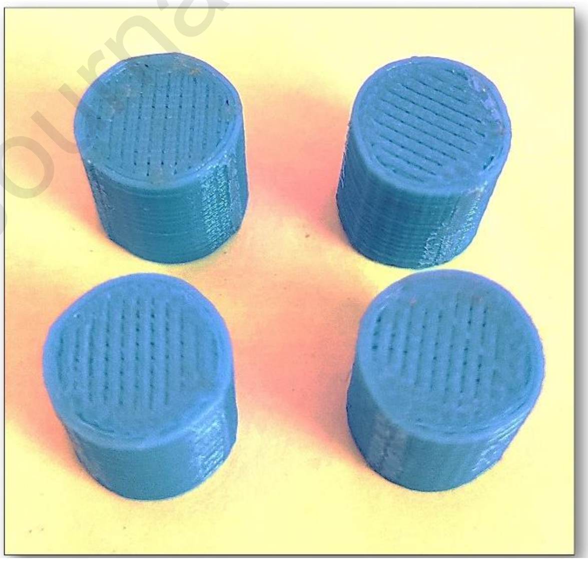

Figure 6: 3D printed pins for a typical tribological test

The PLA printed with and 45º infill angle show more wear than the PLA printed at 90º, the opposite of this true for ABS. Hence from this we can say that different kind of polymer materials show different tribological behavior with the change in printing parameters. reported the dependence of friction behavior of 3D printed ABS on the raster gaps was reported by investigators

[101]. For positive raster gaps, friction behavior showed momentous increase. Similar kind of research shows that wear rate increases in 3D printed ABS with the positive gaps employed during the manufacturing process [102]. Researchers have observed that wear rate in inversely proportional to raster angle and air gap. While as wear rate is directly proportional to infill density and layer thickness [103]. For coefficient of friction, Researchers [102] has reported that parameters air gap, raster angle and infill density have strong impact on the coefficient of friction while as it is least affected by infill density. Surface Roughness has shown tremendous dependence on the process parameters like layer thickness [104]. Srinivasan [105] investigated the effect of process parameters on the tribological properties of ABS printed with FDM. It was seen that layer thickness and infill density are the important two parameters for altering the wear strength of ABS. Figure 7 shows the wear morphologies after a typical pin on disc tribological test of a 3D printed polymeric sample. The different wear modes can be seen in the direction of sliding such as ploughing marks, cracks and delamination. Also the cracking at the interlayer boundary can be seen.

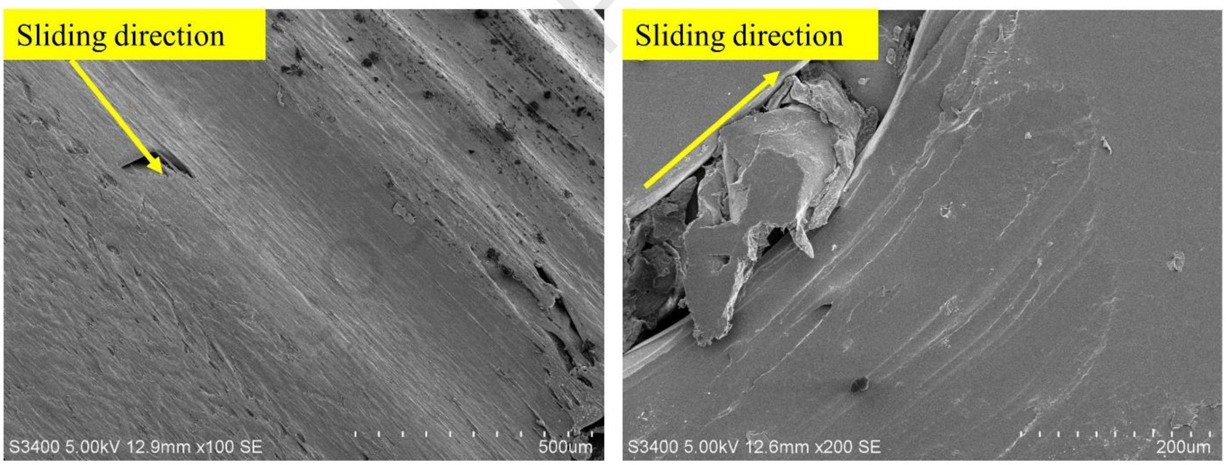

Figure 7: SEM images showing wear morphologies of a 3d printed part after a typical pin on disc sliding test

The minimum wear strength was recorded on higher value of infill density and minimal value of layer thickness. Hence, to design the materials for tribological applications of polymer composites, it is necessary to study the process parameters of printing in order to maximize the required tribological characteristics.

3.4 Compression and Bending behavior:

Compression analysis of additively manufactured lattices is currently emerging as the new domain of research. The AM technologies have opened the door for printing the complicated structures, which have the positive impact on mechanical properties as well as on the material usage. The recent work in the field of AM and compression is to enhance the compressive behavior. Figure 8 shows the typical samples for a bending test.

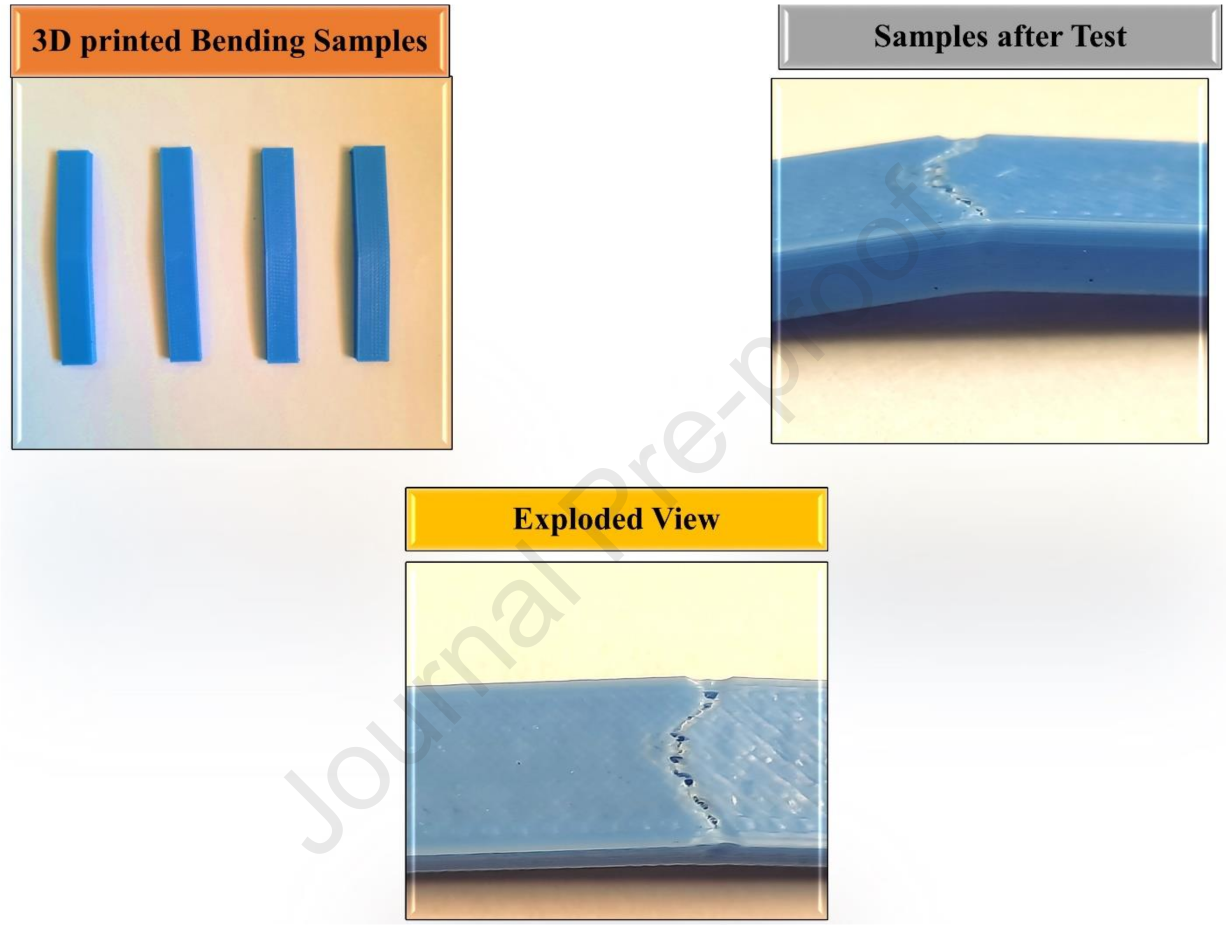

Figure 8: 3D Printed Samples for bending test (Before and after the test)

Generally, it is observed that AM manufactured parts show high stiffness than conventional manufacturing. Recent work by the researchers suggest that in FDM process, the effect of infill has a significant role in enhancing the compressive behavior. The high infill percentage can reduce the early breakage between the consecutive layers [106]. The stiffness values are also high in AM manufactured products. AM has been extensively used for developing scaffolds which can bear the compression easily as the geometries are regular with zero discontinuities [107]. To develop the efficient scaffolds[108] or the structures for aerospace applications researchers are optimizing the cell size, shape [109]. In order to improve the compressive behavior of AM manufactured lattices, the researchers have developed an interesting method of variable-density for each unit cell, ratio of cross-sectional circular radius of the edge to the length of the cube edge (r/s) is taken as variable [110]. For a similar arrangement of cells, the relative density plays a key role in compressive behavior. As the relative density increases, the yield force of the structure also increases. Researchers are also investigating the effect of process parameters of AM on the compressive behavior. [111] Has reported the impact of cell size on the compression behavior. The results display that with the decrease in cell size the compressive properties decrease. In addition, other parameters like cell shape, size; the porosity of the lattice has also the significant impact on the compressive behavior of lattices. For example, porosity plays an important role in determining the yield strength and compressive modulus [112]. Volume fraction is also the important parameter for compressive properties of the lattices. As the volume fraction increases, the compressive strength increases [113]. Strut diameter has an important role to play in the compression. Researchers have observed that in AM manufactured lattices, elastic stiffness and peak strength increase as the strut diameter increases [114]. The AM material have emerged as the key players in the sensors and actuators. From the application point of view, Bending plays an important role for any pneumatic based actuator that work under different pressure conditions. Researchers have addressed and informative review based on the sensors and 3D printing where we can clearly see that people have been constantly working to develop 3D printed strain sensor onto a bending actuator [115]. At the optimum printing parameters, researchers have enhanced the bending performance up to 20% with extrusion based FDM in comparison to the conventional injection molding [116]. Figure 9 depicts the ductile fracture mode of a 3D printed sample after a bending test. The propagation of crack along the interlayer boundaries can also be seen.

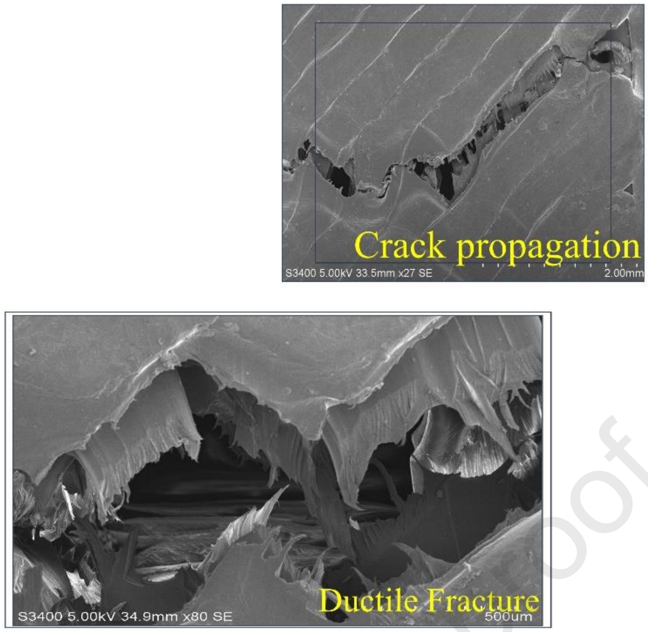

Figure 9: SEM fractographic images after a bending test for 3D printed polymeric sample

Since the AM technologies are also used to print the concrete, therefore research needs to be focused on the bending behavior of 3D printed concrete to provide better beams and columns. Researchers have observed the anisotropic behavior of 3D printed concrete reinforced with fibers [117]. The addition of fibers have significantly improved the flexural properties of 3D printed concrete thus eliminating the negative effects of 3D printed due to the interfacial combinations of layers.

4. Effect of Thermal Gradient on Inter Layer Bonding in AM Products:

The temperature phenomenon has been identified as one of the important parameter for FDM printed process, which effects the strength, and various other properties due to the quality of bonds between the layers [118]. Quality of bonds between the layers can be described on the bases of two mechanisms that are: thermal fusion and polymer inter-diffusion which severely depend on area of contact between the two layers and thermal energy between the molten polymer [119]. The effect of temperature on the inter-bonding between the polymers can be seen in Big area additive manufacturing where the layer time is long which can reduce the temperature of polymer below the glass temperature which leads to weak bonding between the surfaces, hence the strength is affected [118]. To overcome this problem, Researchers have developed a novel method of preheating the bottom layers above the glass temperature with the help of infrared radiations. The strength is enhanced remarkably [120]. The effect of temperature difference can be largely seen in materials with high melting point like PEEK that undergoes a large temperature difference from extrusion to deposition. Recent numerical and experimental investigation conducted by the researchers show that enhancing the reheating temperature among the layers deposited can improve layer to layer bonding and hence the strength of PLA and PEEK [121]. Several other researchers have depicted the relationship between the bond quality and mechanical properties of polymeric materials such as polyamide (PA) 12 for FDM/FFF [122]. With the increase in temperature, the viscosity decreases, which further enhances the bonding quality of material. In addition, crystallization behavior of extruded material also depend upon its temperature. The voids on the surface of printed material are significantly reduced as the platform temperature and the extruder temperature is increased [123].

5. Global Market Scenario of 3D Printing

3D printing is considered as the method for rapid prototyping. Recent developments in the field have made significant improvement and now it's been directly used for manufacturing process. The 3D printing process has evolved as one the best method and hence people are trying to manufacture things at home due to the availability of economical 3D printers. Staples in U.S and Walmart in U.K were the first (in year 2013) to sell home 3D printers. This was followed by amazon, as they started the separate section for 3D printing services filament, software, books and other required parts. Researchers have shown the various advantages of using 3D printing which range from flexibility to designing of high-end complex end products [124]. Since 3D printing can be very helpful in customizing of end products, Hence the desirability for the product and willingness to pay good amount of money is observed [125][126]. It has been observed that 3D printed products can reach the customer at very optimized or low cost due to the reduction of transportation cost as the products can be made at nearby location. Further, the costly warehouse or the storage of final or semi final products can be avoided which can account for low cost for the customer and good profit for the manufacturer [127]. 3D printing has developed in such a way that even the medical field is amazed by its work. From bio engineering (cell development) to prosthetics, it has left its marks in this domain. It has been studied that the share of 3D printed medical equipment will be 1.9 billion U.S dollar by 2025 [128]. Jet engines developed by General Electric using 3D printing process were expected to reach the mark the mark of one lakh by the end of 2020 [128]. From the materials usage point of view, it has been seen by a research group of Airbus that the raw material usage can be reduced by up to 75% when 3D printing is employed rather than conventional manufacturing process [129]. Weight reduction of 3D manufactured aircraft parts has been reported by researchers which can help in dropping the fuel consumption worth 2.5 million U.S dollar [130], Hence we can also say that it has contributed to lowering global carbon dioxide emission. There are more than 100 3D printed parts used in super hornet jets employed for air cooling ducts [131]. Further the technology is also used in some advanced aircrafts like Lockheed Martin F-35 [132]. 3D printing has significant role in packaging and food industry. Reports given by Lipton et al and World economic forum, which gave insights about the circular economy and 3D food printing. This report gave the approximate data of the plastic use in packaged food, it was seen that around plastic packaging worth of 80-120 billion USD is annually lost annually [133][134]. This problem could be tackled by developing multi-use (recyclable) packaging plastic material developed by 3D printing technology which can increase its market leverage. To cater the needs of modern world like going green, energy storage devices play an important role. Thus, efficient method like 3D printing for economically sustainable manufacturing is exploited. To classify battery as printed, at least one of the components must be manufactured by 3D printed technology [135]. With the advancement in 3D printing, energy storage batteries are widely manufactured by 3D printing [136]. By 2023 it's amused that the global market growth of 3D printed is estimated up to 26 U.S billion dollar [137]. 3D printing has expanded its wings into the construction segment. 3D printing construction is the new and booming field these days. It involves collaborative work of mechanical engineering, software engineering, civil engineering and architectural engineering [138]. Study shows that 3D printing construction is 3 times faster than conventional method for building 200m^2 house [139], Hence responsible for reducing time and manpower. The research has been limited to small structures however the results are applicable for massive construction purposes. From the environmental point of view, it has a potential to reduce 50 % environmental pollution generated by conventional construction [140]. Current construction industry is largely dependent on manpower, which account 25% of the total construction budget which may include even unskilled laborers [141]. This flaw can eliminate by taking 3D construction printing as an important issue. This sector is last one to adopt 3D printing technology, however recent advances in this field has encouraged lot of agencies to sponsor construction printing. Current market study shows that by 2023 the market revenue by construction 3D printing is going to increase by 314.0 million USD [142], with the deployment of around 7000 construction machines or robots by 2025 . From the above literature, it is clear that 3D printing has been adopted by almost all around the world. From medical to aerospace to construction market it will dominate all related markets in the upcoming years. Further research is needed to overcome the gap between the 3D printing technology, human interaction and resources.

6. Sustainability Aspects of 3D Printing

The true meaning of sustainable development is an approach to economic and technological development along with creating a balance in environment and society. Whenever a product is to be developed a lot of phases have to be encountered like the design, the process, the use, the disposal and effective ways to reuse it. A new technology needs to undergo evaluation on the grounds of sustainability at each phase to act as precaution against its negative influences. As the literature of the technology of printing in three dimensions i.e 3D Printing or manufacturing with addition i.e. Additive manufacturing technology suggests several research operations have been done for its evaluation. Some of them have adopted qualitative vs quantitative approach [143], some have introduced sustainability orientation in firm's [144] while some may have linked the AM with sustainability through design [145]. AM may be treated as novel in many aspects like little to no material wastage [146], reduced demands for cumulative energy [147] and inventory [148]. Nevertheless, some of its current negative impacts on environment like non-recyclable waste [149] and hazardous powder emissions [150] are still putting challenges to the researchers. It may not be reasonable to draw conclusions over sustainability of this technology over the few negative points. Researchers concluded in their work that AM is case specific as far as the environmental impact is considered [143]. The firms mostly concentrate over the few attributes before starting a new line of production, which are the processing speed, the cost incurred, the flexibility and the quality. In a survey, around 80% firms were found adopting AM for the purpose of innovation by Forbes (2019) report. Talking about the AM in the firms both the developed and developing countries show different attitude towards adapting 3D printing at factory level. Where the countries like India focuses on long term promises and countries like U.S.A wants short term profit as was founded in a study by researchers [144]. More and more firms are adopting AM for creativeness, innovation and customization very few visualize its environmental and social impacts [151].On the other hand this fact cannot be ignored hat AM can prove to be sustainable for not only economy but environment and society also. Out of multiple benefits of AM, we will discuss some of the pioneering ones including; Economic Benefits, Environmental Benefits and Social Benefits. Figure 10 depicts the various benefits of 3D printing process from sustainability point of view

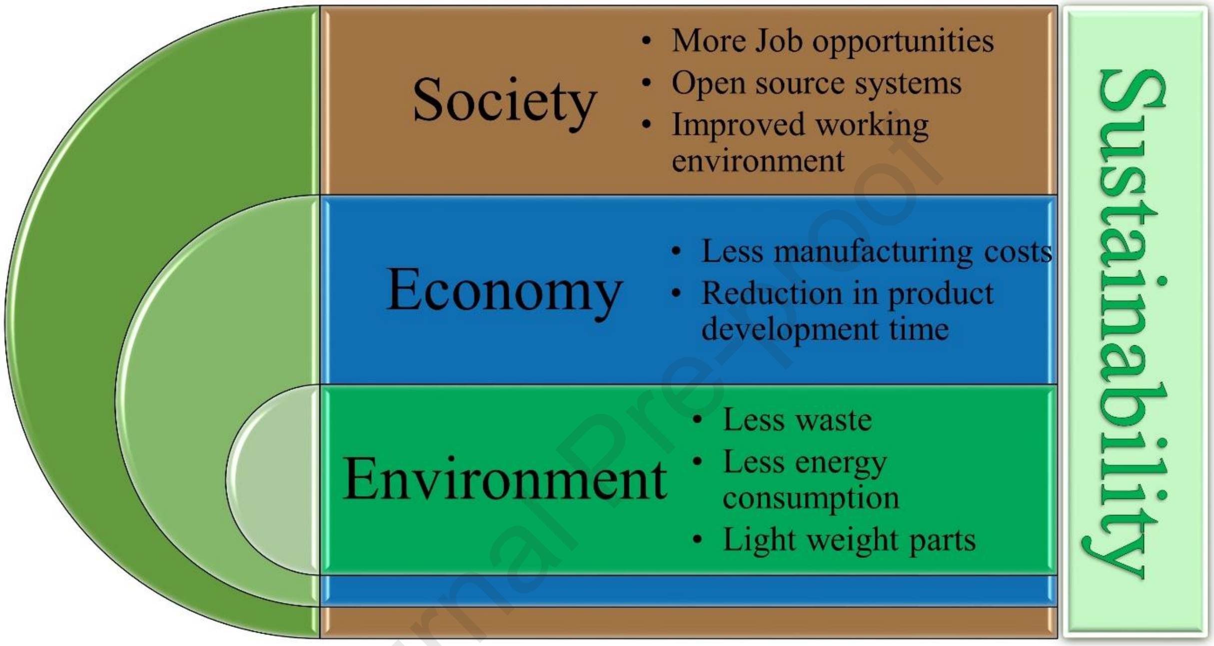

Figure 10: Sustainability aspects of 3D printing Process

A) ***Economic Aspects***

As per the current financial crises of the world there is a requirement of new manufacturing systems which will sustainably help to promote economy globally [152]. AM is definitely going to attract the firms owing to its production system with some of the attractive features viz cost reduction [151], reduced life cycle of product [153] and high customer satisfaction and involvement [154]. AM is allowing nozzles, which were previously being made in several parts to be built as one unit, reducing 75% of manufacturing cost. In addition, the printed parts are lightweight which requires much lesser fuel for flying [155]. Inventory costs are also being minimized due to small batch production and the tool-less attribute of the said technology [127]. AM helps in bypassing the intermediate costs including the tariffs and transportation charges with its unique characteristic of being portable [156]. AM is giving power to the customers so that they can print out the product in a relatively convenient manner and hence increasing the life cycle of the product [153]. Also with the introduction of IAD (innovation as data) in AM high level of customer satisfaction and involvements are achievable [154]. One of the big hurdle which is on the way of adopting AM despite of its functionality and versatility, is the high investments made by the owners in the already existing conventional manufacturing systems [144]. It will be a huge step to replace the conventional systems with the AM, but its adoption in the future will be unavoidable.

B) ***Environmental Aspects***

The firms nowadays may be adopting the technologies mostly for the economic benefits but being environmental friendly will pay in a long run for sustainability [157]. AM with less processing steps no doubts, can be considered greener because it helps in reducing energy demands, wastes and CO_2 emission [151]. Studies have suggested that utilization of the AM on mass level will help to reduce the energy demands not only because of the reduced manufacturing stages but also with the few to none post processing stages [156]. It has also brought down the high buy-to-fly ratios (material in finished product: material wasted in making the product) in aerospace manufacturing, saving a lot of materials energy. Other studies indicated up to 40% of wastes can be reduced while 95-98% unfused material can be reused [158]. Further other material inputs like lubricants, coolants or some other environmentally hazardous substances can be avoided [153]. Even in the construction industry AM has shown more than 50% lesser environmental impact with lower potential to generate small particulate matters and Ozone depletion [159].

C) ***Societal Aspects***

AM being highly automated is making a huge change in the field of labour structures by making localized production possible for the consumer nations. For developed countries, automation may be beneficial but underdeveloped may face insecurities of unemployment [160]. On contrary the creation of job opportunities by adopting AM makes this topic debatable [144]. From technical perspective, this technology is helping with giving more health and work friendly environment by reducing the prolonged exposures of labors to the impure air and water. By having properly designed work areas not only the fatal injuries are avoided but the labors are also prevented from other serious health issues like cancer [161]. The democratized production system of AM is providing the high utilization of materials by giving equal opportunities to the consumers in the market and society globally. This open-source system will help to tide over not only the technological but also the cultural and educational gaps between under developed and developed countries.

7. Waste Reduction by Additive Manufacturing

AM has turned into the potential key player for minimizing the material wastage as it uses the only material required for printing the object and some support structures. Technologies like binder jetting can help in reducing the waste by just recycling the excess amount of powder. At large-scale manufacturing, people are currently working towards attaining the sustainable goals for manufacturing which can achieved by recycling the waste material [162]. To avoid material wastage, big manufacturing houses are promoting the new renewable materials that are environment friendly [163]. Each AM technology add material rather than conventional manufacturing in which material is often cut to attain the perfect shape and dimension. Thus preventing the excessive material usage. Projects like “Million wave” which started back in 2018 aimed to print prosthesis by the plastic waste from ocean [164]. AM has also helped the astronauts at international space station for recycling of plastic into the spare parts [164]. Also, in the entertainment sector, AM has used recycled PLA for printing furniture and toys under the project “The Robotic Playground” [164]. Similar kind of project “Print your city” with an aim to print urban furniture by AM from the plastic waste [164]. On the large scale development, AM has worked on the development of house module known as “Tera” with the plastic waste and basalt [164]. With further advancements in the domain, “deciduous”- The AM manufactured pavilion. The project was the result of recycled 30000 discarded water bottles. This project gained a lot of appreciation at Dubai International Financial Center [164]. From this section it is evident that AM has been constantly developed to meet the needs of modern era, taking every aspect in consideration. The manufacturing wastage through AM is reduced largely in comparison to traditional manufacturing methods. It has also taken lead in recycled material as the input material. Thus, in future AM may become an efficient method of reducing the wastage and global carbon emission.

8. Potential Applications

The application arena of 3D Printed parts has moved much beyond the rapid prototyping to a variety of applications ranging from medical to space applications [165][166][167][168]. Figure 11 shows the various application areas of 3D Printed parts. Apart from rapid prototyping, 3D printing has evolved as an efficient technology for reverse engineering and for maintenance of critical components. 3D printing has a potential in the medical science in the development of medical devices of complex shapes, developing implants, exoskeletal parts, orthopedic and dental materials, tissue engineering [169] and models for anatomy [170]. The customization of products which is possible in case of 3D printed parts also widens the scope of these parts for a wider customer base including fashion industry. The ability of 3D printing to develop complex 3D printed parts has led to use of this technology in jewelry. The various intrinsic advantages of 3D printing such as shortened product development time, ability to print complex shapes, little or no post processing, less manual intervention and less involvement of jigs and fixtures makes 3D printing as a future technology for development of various industrial products. However, the cost of the raw material and the machinery is limiting the widespread use of the 3D printed parts particularly the metallic parts.

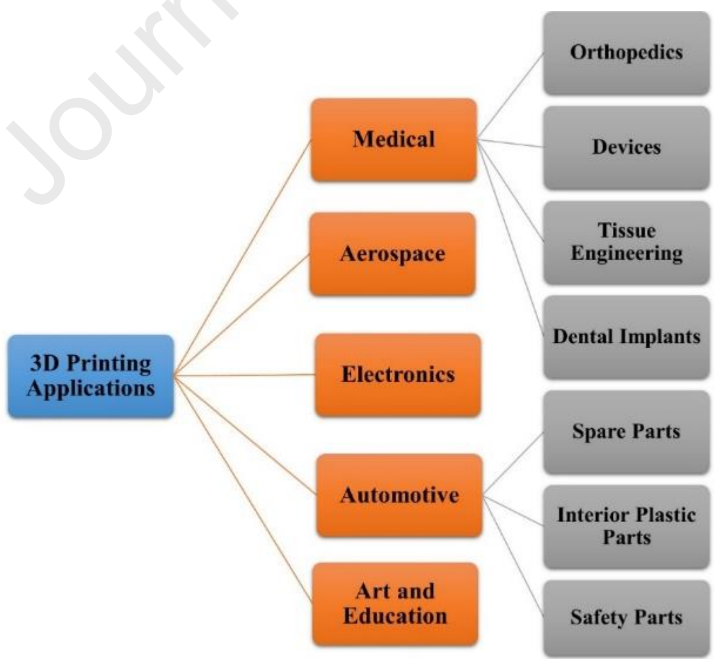

Figure 11: Applications of 3D Printed Parts

AM has been expanding its domain in almost all of the sectors. For Automotive sector, the global market share of AM is U.S $ 1.61 billion for the year 2020 and it is expected to grow up to U.S $ 4.89 billion in 2027 [171]. For manufacturing complex parts of car, AM can be the best candidate as the process works by material optimization and waste reduction. In 2014, Local Motors manufactured a 3D printed car [172]. Further, driverless and recyclable 3D printed bus has also been introduced. Later on many companies like Ford adapted AM for manufacturing engine parts and prototypes [173]. Companies like BMW and Audi for engine part manufacturing and various testing tools adapted it [174]. It proved to be cost effective and time efficient process [175]. Aluminum metal matrix has been widely used for automobile applications with selective laser sintering method. Components like exhaust, pumps and valves are being easily manufactured using Aluminum metal matrix and selective laser sintering [176]. Other components like car roof and frames of windshields can be manufactured by carbon fiber using additive manufacturing [177].

AM has been widely used in medical sector. Its market share is predicted to increase from US$89.3 million (in 2019) to US$348.1 million up to 2027 [171]. The domain of AM in medical sector ranges from the diverse areas of cardiothoracic surgery to neurosurgery [178][179] and orthopedics to plastic surgery [180][181]. A new area of AM is the bio printing where the generation of skin and other tissues are taken into the consideration. New research focused on the developing new organs by bio printing which definitely make our life much easier [182]. AM has shown tremendous growth in prosthodontics where dentist can scan, prepare and print the teeth. This method can save money as well as time [183]. AM has been employed in printing crowns and dentures which are removable partial as well as complete dentures [184]. The method have shown its importance as the time consumption is optimized, cost is reduced and mechanical properties are enhanced [185]. Maxillofacial surgery has attained tremendous advancement with the application of AM. Occlusal splints, which is manufactured by conventional milling process, are quite expensive. On the other hand, AM Occlusal splints are cost effective. Their mechanical properties are less in comparison to conventionally manufactured splints but the wear reduced remarkably [186]. In orthopedics, the most important application of AM is the domain of developing scaffolds of defined porosity, pore shape and size. The traditional methods of manufacturing of these scaffolds are space holder method, freeze-casting method. The main disadvantage with these methods are that they cannot control the pore shape and size at micro and macro level however, the AM inspired methods can control the pore shape and size whether the porosity occurs in random or in a gradient way [187]. Methods like laser sintering and laminated object manufacturing are used to develop the customized prosthetics from metals, paper and plastic [188][189]. Orthopedic implants by AM are biocompatible and possess geometric freedom. The AM orthopedic implants have less stiffness and mismatch at the juncture the surface roughness and elasticity can be controlled as per the requirement of part [190].

9. Challenges

The 3D printing is not gaining widespread usage in the industrial sector primarily due to some barriers as depicted in the Figure 4. The initial cost of the machinery, cost of raw materials and non-availability of skilled work force is restricting the use of 3D printing for a variety of industrial products. However, apart from this there are many issues such as poor dimensional accuracy, poor repeatability of material properties, which do not give the designers and material scientists a good confidence in the process yet. The poor mechanical properties of the developed parts and a poor surface finish is also limiting the use of 3D printed parts for various critical applications. However, these challenges can be overcome by studying the effect of various process parameters affecting the mechanical properties and developing more insights into the process so that the processes can be more efficient in developing products with superior properties. Various challenges and barriers of AM are shown in figure 12.

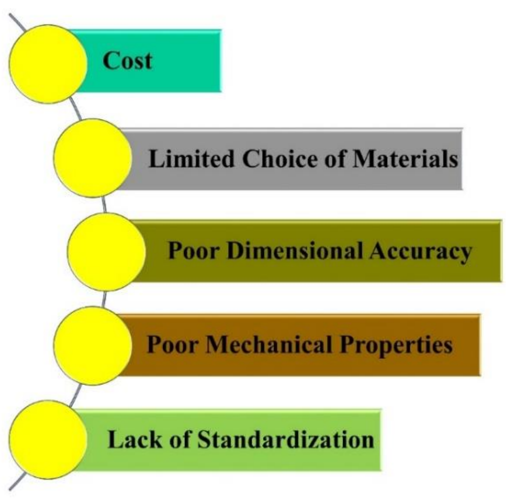

Figure 12: Challenges and Barriers to 3D Printing

The printing time is also considered as one of the challenge for additive manufacturing. AM processes are usually slow and time consuming. Unless the printing time is reduced, the AM cannot take the place of conventionally manufacturing. Cost of AM setups are high but this might not be the problem after several years. Small customized 3D printers have been made available at the local market but for large scale manufacturing setups, the cost remains high. Not only the setup but also the raw materials such as filaments are expensive. The cost of each filament for 3D printing ranges from 25-50 depending upon the specification of the filament. Anisotropy of additively manufactured structures are one of the main challenges in the present scenario. This may result in varying mechanical properties under different conditions of loading. The appearance of 3D printed objects are not fine enough as they might display the layer-by-layer printing pattern from the side view. This defect may be no matter in applications like scaffolds but in case of buildings and toys were the appearance is much important, it matters a lot.

10. Conclusions

Additive Manufacturing is an evolving technology and has the potential to present an alternative to the conventional manufacturing technologies. The AM technologies apart from having the capabilities to handle complex geometries, are material and energy efficient. Amongst the different technologies, the Fused Deposition Method (FDM) is the most commonly researched technology. The various process parameters have a significant effect on the mechanical and tribological properties of the 3D printed parts. Involvement of a variety of parameters in each 3D printing technology and their dominant effect on the properties of the parts it becomes imperative to devise standards for printing for a particular application. Depending on the target application, an optimized set of parameters can result in a 3D printed part with better strength to weight ratio and other desired properties. Based on the waste reduction, less labor costs and other benefits, 3D printing has evolved as a sustainable alternative to conventional processes, which is reflected in the current global market share and the future market projections. Also based on the favourable properties offered by the 3D printed parts, these parts are finding applications in almost every field of engineering.

11. Future Recommendations

Based on the studies presented in this paper and the aforementioned discussion, a lot of work can be undertaken to widen the material options, improve the mechanical properties of these 3D printed parts. The processes can be optimized to arrive at the best parameters for improving the mechanical properties such as tensile strength, fatigue strength and the tribological properties. The effect of various parameters affecting the friction and wear behaviour of these parts such as load, speed, sliding distance, etc. can also be studied. Also, 3D printing can be employed to develop composite materials and reinforcing theses 3D printed materials with various reinforcing agents such as nanomaterials resulting in improved properties of the developed composites. Since 3D printing can handle part complexity in a better way, it can be used to develop different surface textures for various friction and wear applications and in robotics applications for grasping. Some in depth studies can be devoted to assess the environmental impacts of these technologies and also using the potential of these technologies in the area of medical science. Due to the ease in handling complexity, the technology of 3D printing can be exploited in mimicking natural systems and designing nature inspired products. Further, mathematical models can be devised to predict the mechanical behaviour of these parts. Much attention is needed to develop a better understanding of the mechanisms and theories related to these parts which will help address the challenges faced such as the issue of interlayer bonding, thermal stresses, poor dimensional accuracy and cost of the initial machinery so that the disruptive technology can be exploited at a larger scale. This shall help in making the products greener and efficient and hence achieving the larger goals of sustainability.

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