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Review Article

Retrospective investigation on emergence and development of additive manufacturing

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The ability to obtained personalized and complex-shaped products with lower cost of development, less energy consumed during manufacturing, less material waste while facilitating in making the products on-demand are the unique benefits associated with additive manufacturing (AM). This work is a review comprising of the details on the early development of AM including key developments over the years, followed by discussion on the advantages offered by AM in relation to the traditional manufacturing methods. The purpose of this work is to help the researchers in the area to have an idea of emergence of the AM technology and gather the information associated since the creation of first three-dimensional (3D) object till the advancement in the field in recent years. Discussion on some recent research developments therefore are made part of this study work in order to clearly have an idea of currently conducted work by the researchers in the development of materials, enhancement of material properties and study of effect of various factors, additives, orientation, machining parameters, etc. on the behavior of additively manufactured material.

Keywords: Additive manufacturing, 3D printing, ABS, PLA, FDM, Mechanical property

1 Introduction

AM is basically a process in which materials are joined or fused together under a computer controlled system to form a 3D object. This manufacturing process creates 3D object by reading instructions from computer aided design (CAD) or additive manufacturing file (AMF) by successive adding material layer by layer. Since the process involves the creation of required 3D object by adding layers of material in succession the object so formed is often termed 3D-printed objects. As the name suggests AM binds together the material while processing whereas in traditional methods of manufacturing materials are removed while processing. One can easily find that AM process has less wastage of material during manufacturing and is called additive in nature. Conventional manufacturing on the other hand is subtractive in nature with high wastage of materials. The major advantage of AM over conventional manufacturing is that the AM process doesn’t demand special new tooling every time to make a part. Also, AM is incredibly resource-efficient. The only material that is consumed by the process is that used for the actual assembly of the product. This results in waste prevention and saves manufacturing time. Further, companies can produce customised goods at a large scale with minimum wastage of product[1].

In manufacturing industry AM is continuously growing as an advanced manufacturing technique to form intricate objects with small or no material wastage. The reports on recent industry trend indicate that AM represented around $1.6B in revenue in the year 2012 with expectation to grow double by 2017 and to more than six times by 2022. The business of AM material is expected to grow over 250% in 2022 to that in 2012[2].

At present the materials suitable to undergo 3D printing or additive manufacturing are polylactic acid (PLA), nylon, high density polyethylene (HDPE) and acrylonitrile butadiene styrene (ABS) but ABS is the most common among the materials used in industries[3]. ABS is a terpolymer produced when polymerizing styrene with acrylonitrile in the presence of polybutadiene. The proportions include acrylonitrile 15% to 35%, butadiene 5% to 30% and styrene 40% to 60% with chemical formula as $(C_8H_8)_x$-$(C_4H_6)_y$-$(C_3H_3N)_z$). ABS material exhibits good impact resistance, toughness, electrical properties, resistant to aqueous acid, flammable in high temperature and can be easily recycled[4].

Based on state of the material and fundamental process of adding up material-layers, various AM

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processes have been developed. Figure 1 may be referred to get aware of the major AM processes.

In SL, a laser light is used to accurately map cross-sectional area of design from bottom in process to solidify the material layer-over-layer on a platform submerged under photopolymer resin filled in translucent tank. The process in DLP is similar to that in SL with the difference that it uses digital light projector for beaming the entire layers all at once. SLS process can produce solid parts layer by layer through scanning the cross-section of design using a laser to sinter fine layers of powdered material. FDM, a trademark of Stratasys[2], is also referred to as fused filament fabrication (FFF) where parts are produced in layers using filament of solid thermoplastic material fed to a heated movable nozzle where it melts and finally reaches the precise location by moving nozzle following a pre-determined path. Material jetting process dispenses a photopolymer resin out of hundreds of tiny nozzles in a print head assembly allowing jets of material to deposit build material solidified using ultraviolet light. But it requires base support which is printed simultaneously and is easily removed during post-processing[5]. Work has also been done in printing large format parts using polymeric pellet-based additive manufacturing (PPBAM)[6].

2 Early Developments

The first attempt contributing to AM was the experiment to create solid objects using photopolymers involving two laser beams of different wavelength intersecting in the middle of a vat of resin to solidify the material in the year 1960 at Battelle Memorial Institute[2]. The first patent was filed for the method to produce a 3D-object using Holography on a similar dual laser beam approach by Wyn K. Swainson[5].

Hideo Kodama was among the first to invent successfully an approach for the single-beam laser curing when working at Nagoya Municipal Industrial Research Institute, Japan and published his work-findings in the year 1980 describing the technique to locate 3D-data. He discussed the importance of an x-y plotter device and optical fiber in delivering a spot of UV-light[7]. He further extended his work in developing an automatic method in the year 1982 to produce a 3D-model making use of photo-hardening technique. The work by Kodama is referred to be the first evidence of working AM techniques[8].

Alan Herbert conducted experiments and succeeded to generate solid objects using photopolymer and published his work in 1982 describing the phenomenon of directing a beam of Argon Ion laser through an x-y plotting device on the surface of a photopolymer in order to generate the desired object[9]. Charles W. Hull was granted patent for the apparatus developed to produce solid objects by Stereolithography in the year 1986. Hull made use of a computer-controlled light-beam in order to photo-hardening the successive cross-sections to produce the required object[10]. Jean-Claude Andre also filed a patent in 1984 for the apparatus developed to fabricate a replica of an industrial part. His apparatus was based on the approach involving single-beam laser[2].

It was the year 1987 when additive manufacturing (AM) first emerged commercially with stereolithography (SL) from a company named 3D Systems. It was considered as processes that solidify

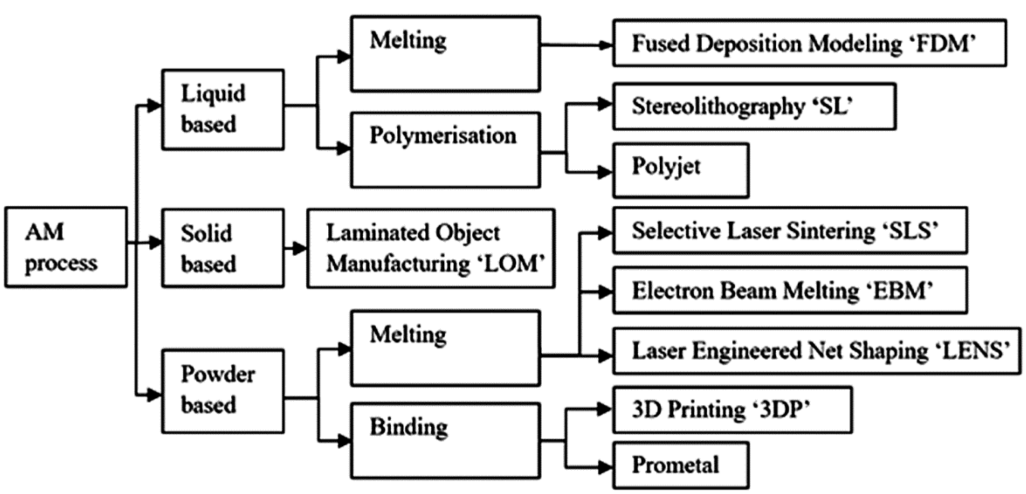

Fig. 1 — A broad classification of AM processes.

thin layers of ultraviolet (UV) light sensitive liquid polymer using a laser[2]. In 1988 S. Scott and Lisa Crump invented a technology called fused deposition modelling and patented the same in 1989 as a technology for 3D printing. Here a material in the form of wire was fed continuously to a nozzle, where it melted down and extruded out of a nozzle and create a 3D object layer by layer. It was first commercialized by his company Stratasys in 1992. Stratasys, in the year 1996, further develop an extrusion process similar to FDM process that can deposit wax material layer by layer to create 3D object using an inkjet printing mechanism[2]. Some key developments noticed in the area of additive manufacturing over few decades are tabulated below in Table 1.

3 Importance of AM

AM has its scope in every major manufacturing-industries from automotive to aerospace, defence to consumer products and medical as well. Important applications of AM include development of full-

Table 1 — Some key developments noticed in the area of additive manufacturing over few decades[2].

Year	Key development	Developed by	Country
1960	First experiment to create solid objects using photopolymers	Battelle Memorial Institute	Ohio
1980	Invention of an approach for single-beam laser curing	Hideo Kodama	Japan
1987	SLA-1 was the first commercially available AM machine that employ stereolithography (SL)	3D System	US
1988	Commercialization of the first-generation acrylate resins	3D Systems and Ciba-Geigy (in association)	US
1990	First Stereos stereolithography system made available for purchase	Electro Optical Systems	Germany
1991	Commercialization of three AM technologies namely,		
	fused deposition modeling (FDM),	Stratasys,	US
	solid ground curing (SGC),	Cubital,	Israel
	laminated object manufacturing (LOM).	Helisys.	US
1992	Two new AM techniques are available, namely,		
	Selective laser sintering (SLS)	3D Systems	US
	Soliform stereolithography system	Teijin Seiki	Japan
1993	Commercialization of direct shell production casting (DSPC) which uses an inkjet mechanism	Soligen	Germany
1994	Introduction of new AM systems, namely,		
	ModelMaker (deposits wax materials by inkjet print head)	Solidscape	US
	Solid Center (first non-stereolithography system)	Kira Corp.	Japan
1996	Introduction of the Genisys machine, with an extrusion process developed at IBM’s Watson Research Center.	Stratasys	US
2000	Development of Direct Metal Deposition (DMD) process to produce and repair parts using metal powder.	Precision Optical Manufacturing (POM)	US
2000	Introduction of a machine named Prodigy, which prints part in ABS plastic using FDM technology	Stratasys	US
2001	Perfactory machine was introduced which employ digital light processing (DLP) technology with acrylate photopolymer to solidify entire layer at once	Envisiontec	Germany
2008	Offering of “creator” tools to facilitate in printing custom products	Shapeways	Netherlands
2009	Establishment of ASTM Committee on AM Technologies to form standards on testing, processes, materials, design (including file formats), and terminology.	ASTM	Pennsylvania
2011	Release of the specification for Additive Manufacturing File (AMF) format replacing the old STL file format and a standard terminology for coordinate-systems and test-methodologies	ASTM	Pennsylvania
2014	Release of first peer-reviewed journal, 3D Printing and Additive Manufacturing.		
2014	Multi-Jet Fusion polymer-bed fusion technology	HP	US
2015	Introduction of first ever standardized bio-link ‘non-cellulose alginate’ derived out of seaweed material.	Cellink	Sweden
2018	Development of novel platform ‘G3DP2’ to print transparent glass	MIT	US
2019	Expiration of many key patents from leaders in 3DP system manufacturer across the globe.		

functional prototypes, machine-assembly models, patterns for prototype and metal casting, visual aids, etc.[11]. The AM technique is important in today's world of advanced manufacturing for having advantages in the ways listed below in Table 2.

Researcher believe that AM might not completely replace the conventional manufacturing methods like injection molding and die casting, but will continue to produce prototypes layer over layer[12]. Near-impossible shaped prototypes that are not possible to be produced using traditional manufacturing technologies are possible to be modelled and developed with new AM technologies within a short period. It is very evident that role of AM will only continue to grow[2].

4 Mechanical Properties

Any part manufactured by AM process is expected to have high tensile, wear and fatigue strengths with high modulus. Parts made of injection moulding show superior mechanical properties but they are often characterized by residual stresses that get setup in the parts during manufacture. Residual stresses, if not taken care of, may become a common reason for failure of the injection moulded parts under considerably lower forces. However, by adding fiber-reinforced composites in printed thermoplastics, mechanical properties can be significantly enhanced though the addition of fibers results in composites susceptible to fracture during extrusion[13,14]. It was evident that the tensile strength, modulus of elasticity, plastic strain and impact strength of FDM printed parts were around 48%, 50%, 48%, and 78% lower in value as compared to one produced through injection moulding[15].

It was observed that mechanical properties can be enhanced by adding organo-montmorillonite (OMMT) in polymer compared to the material produced through injection moulding[16]. The printing parameters like layer thickness, part orientation and raster width were observed to have little effect on mechanical properties while raster angle and air gap between successive rasters (or infill) were found to significantly affect the performance of 3D printed parts[17-21].

Tensile test was conducted to determine the tensile properties of test-specimens of standard dumbbell-shape under standard conditions. Tensile properties vary with the factors such as specimen preparation, speed and environment of testing. Such factors needed be controlled where precise test-results were desired[22, 23]. It was also observed that tensile strength can be enhanced by increasing the raster angle during 3D printing of parts and reaches a maximum at a raster orientation of 0^{o} [17]. Wear strength can generally be obtained using a pin-on-disk apparatus; a laboratory procedure for determining the wear of materials during sliding[24]. Fracture and fatigue strengths of material were desirable for variable loading where a part need to be designed to sustain against structural failure[25] though the fatigue strength for a 3D printed specimen with infill below 100 % was a lower value and such specimen may be treated as intrinsically notched specimen[26].

Investigation made on FDM printed PLA specimen revealed that the material toughness can be enhanced greatly by layups orienting alternatively by 90^0. Such oriented layups results in properties like strength and stiffness to be nearly isotropic. It has also been observed that depending upon the layer stacking scheme and the loading direction, the materials behavior can be switched from ductile to brittle. PLA composites when printed with the raster angles of $\pm45^0$ show the maximum modulus and strength[27, 28]. In

Table 2 — Advantages associated with AM.

Advantages offered by AM	Description
Product design made simpler	Objects that have their surface comprising of different merging complex curves can easily be created.
Low-quantity economy	The process allows very short runs, as a result single part can be printed cost-effectively.
Significant weight reduction	3D objects with higher strength-to-weight ratio since AM systems cure, extrude, melt or sinter the material.
Lesser time and expenses incurred	Significant reduction in time and expenses incurred in realization of new and existing products.
Reduced assembly	The part with complex curves created through AM in a single piece can replace what is traditionally an assembly of many pieces.
More product designs to choose from	AM facilitates the industry with compressed production schedules, more product designs in selecting a better products.

PLA specimens with layups of 0^0, 45^0 or 90^0, those oriented by 90^0 show fatigue transition life while the rest exhibit no fatigue life[21].

Tests conducted to study the tensile and flexural behavior of ABS and PLA, the two commonly used polymers, revealed that PLA material was superior than ABS in having better tensile and fracture strengths. Tensile strength was larger by 7% and fracture strength was larger by approximately 9% than that for ABS. PLA was found having a higher value for Young's modulus. In flexural test, results show that flexural modulus for PLA was higher than that for ABS by upto 33%. PLA can also bear a flexural stress higher by around 22% when compared with ABS[29]. The strength of PLA can further be increased by reinforcing pure PLA with carbon fibres. Continuous reinforcement of carbon fibre may increase the tensile as well as bending strengths of PLA up to 37% and 109%, respectively[30]. Blends of ABS and PLA in various composition were tested for superior mechanical strength and it was found that the blend of 80% PLA with 20% ABS outperformed the one with PLA alone in having superior tensile properties[31]. PLA-wood composite, on the other hand in another tests, show reduction in cohesion of deposited material-layers and an increases in ductile behaviour of the base material[32].

5 Recent Research Developments

Raney *et al*.[3] study the effect of mesostructure on the monotonic tensile behavior of ABS specimens with ASTM D638, a technical standard developed and published by American Society for Testing and Materials, fabricated using FDM process. The tests were conducted based on two criteria - orientation of the specimens and the infill-percent during printing. The tests results show a loss of material strength during the process of printing compared to traditional methods. For printed ABS specimen a maximum material strength was observed around 92% (of actual value for the material) with 5% of certainty. The bonds across the layers were found 79% stronger compared to that along the layers.

Quan *et al*.[13] investigated additively manufactured specimens of ABS and short carbon fiber with ABS (CF/ABS) fabricated using FFF process for three print angles of 0°, 45° and Z-direction. More fabrication-induced pores were observed for solid cubical specimen with print angles of 0° and 45° during the study contributing to lower initial modulus and yield stress whereas inter-yarn adhesion was observed for 3D braid performs when infused with silicone matrix for a print angle of 45° resulting in improved initial modulus but lower structural ductility. Also it is found that the specimens with print angle in Z-direction show high structural ductility and high ultimate strain due to inter-yarn slippage characteristic. It is observed that specimens with CF/ABS have high initial modulus than that with ABS whereas 3D braid performs with CF/ABS have low ultimate stress and strain than that with ABS.

Zixiang *et al*.[16] tested samples of material prepared by melt-intercalation of ABS- nanocomposites and OMMT using FDM process. It was found that the addition of 5% OMMT by weight can increase the tensile strength by 43%. The flexural strength, flexural modulus and dynamic mechanical storage modulus of the ABS were also significantly increased. It was also observed that the addition of OMMT result in a reduction in the linear thermal expansion ratio and the weight loss in a thermogravimetric analysis[16].

Some researchers created samples with ABS based polymer matrix composites and polymer blends with different build orientations (XYZ and ZXY) through a FDM based technique called material extrusion 3D-printing (ME3DP). The work was extended to analyze the effect of additives on mechanical property anisotropy to ABS material. It was observed that the mechanical property anisotropy decreases for ternary blended ABS with styrene ethylene butadiene styrene (SEBS) and ultra-high molecular weight polyethylene (UHMWPE) in terms of relative ultimate tensile strength (UTS) to a difference of 22±2.07 % as compared to 47±7.23% for parts made of ABS material. The effect of build orientations on mechanical property anisotropy was also measured for different polymer blends. Mechanical property anisotropy was the lowest in terms of UTS for the ABS blended with UHMWPE and SEBS in the ratio 75:25:10 by weight. An improvement was found to the amount of elongation prior to rupture for the specimen of ABS blended with SEBS in the ratio 80:20 by weight with XYZ build orientation. The results of the work with ternary blend of ABS:UHMWPE:SEBS also show improvement in mechanical property anisotropy with the failure occurring in the raster instead of that raster-raster boundary[17, 18].

Sukwisute *et al*.[33] used a reactive DC magnetron sputtering technique to deposit thin films of chromium nitride (CrN) on ABS substrates and investigate the effect of sputtering power on the material hardness and wear resistance. This work employ a nanoindentation hardness test to measure hardness and Young's modulus and a pin-on-disc method to measure the wear resistance of the material by keeping the total pressure at 4×10^{-3} mbar, nitrogen partial pressure at 30% and sputtering time of 2 hours for the study. The investigation revealed that the work successfully enhanced the hardness from 6.65 to 9.58 GPa and Young's modulus from 30.87 to 44.25 GPa for CrN coated ABS samples. The highest hardness of 9.58 GPa (as that of steel) was achieved at sputtering power of 175W leading to the highest wear resistance of the CrN coated ABS surface. These results indicate work's potential and promising future additively manufactured ABS products with steel like wear resistance[33-35].

Some investigation has been conducted to compare the critical strain energy release rates of single-edge notch-bend (SENB) ABS specimens with varied crack-tip/laminae orientation angles fabricated using FFF process and study the influence of layer-orientation on the fracture properties. The study reached to an interesting conclusion that the inter-laminae fracture toughness is lower in magnitude by nearly one order compared to cross-laminae toughness. Also in studying ductile and brittle fracture of additively manufactured ABS specimens it was found that the direction of crack-propagation governs the elastic-plastic response of material. The inter-laminae fracture was observed of brittle behavior whereas cross-laminae fracture was observed of ductile behavior indicating the elastic-plastic response of the material affected by the crack-tip/laminae orientation angles[36-38]. On studying crazing, tests conducted on FDM printed and compression molded specimens of ABS show that crazes initially started from internal voids and propagate through the specimens to reach out the surface to cause failure[39]. In a three-point bending experiment to study notch-strength and crack behaviour on FFF printed ABS specimens with notches of varying geometry, it showed linear mechanical-response till specimen-breakage unaffected by laminae orientation angles when no stress concentration was there. Crack path, though, were affected by build orientations[40]. Among non-Destructive tests to study crazing, print defects and crack behaviour, x-ray Interferometry is generally employed[41].

When conducting tension, compression and fracture tests on the specimens cut out of PLA blocks manufactured by FDM process with deposition of a polymer filament in one direction, it was observed that the mechanical response of material was orthotropic in nature and this orthotropic mechanical response was characterized by a significant tension-compression asymmetry. It was also found that the material of specimen was tougher under the loading in the extrusion direction than that in the transverse direction. Under tensile loading in the out-of-plane direction the failure behavior of the material was observed relatively brittle whereas in in-plane tensile loading the failure behavior of the material was observed more ductile[42, 43]. Researchers also studied the effect of crack on fracture properties of material under Flat, Edge and Up orientations of material-layers. Study showed that the fracture properties of printed material were sensitive to the crack length as well as the orientation of material-layers. It was observed that the fracture load in Flat orientation was higher than in Edge or Up orientation but was lower compared to same for original material. Under Flat, Edge and Up orientations stress intensity factor (SIF) was also observed high for printed material. This study show that the increase in crack mouth opening displacement result in higher fracture load in Flat orientation than that in Edge and Up orientations. SIF was observed increasing with the increase in crack length[44, 45] though the mechanical and the cracking behaviours were not affected by the printing direction[46]. Under three-point bending and tensile tests, specimens with Edge and Flat orientations offer highest strength and stiffness while specimens with Up orientation exhibit lowest mechanical properties[47].

It has been found in a micro- and macro-scale based study to measure the effects of printing parameters on ABS printed specimen using FDM process that thermal conductivity reaches a highest value of 0.25 (±0.05) $Wm^{-1}K^{-1}$ for a layer thickness of 0.4 mm with a material fill density of 100 %. Another significant outcome observed during this study is that while thermal performance can be kept intact the print times for the specimen can be shorten by 80%[48]. In a thermomechanical study, the blending of ABS with short carbon fibers (ABS/CF) and glass fibers (ABS/GF) when tested for heat dissipation show a high increase in mechanical stiffness compared to unblended ABS specimens[49]. Correctly selected print infill, and infill grid pattern[50] was seen to contribute to the enhancement of Tribological properties. Table 3

Table 3 — Parameters, procedures or additives to enhance mechanical properties of printed ABS/PLA specimens.

Material property of ABS/PLA	Gets improved by
Tensile strength	Reinforcing thermoplastics with fibres[13] increasing the raster angle or having layups oriented with ±45^0 [17, 28] adding OMMT[16]
Toughness	Printing specimen with layups orienting by 90^0 alternatively[27]
Wear resistance and hardness	Coating with thin films of CrN [33]
Fatigue strength	Increasing print infill[26]
Flexure strength	Reinforcing with carbon fibres[30] adding OMMT[16]
Thermal conductivity	A layer thickness of 0.4mm with 100% infill for ABS[48]
Mechanical stiffness	Blending with CF and GF[49]
Tribological properties	Increasing print infill, having infill grid pattern[50] Blending ABS with 20% CFPLA Lower layer thickness

lists the ways of improving various mechanical properties in printed ABS and PLA material.

Zhang *et al.*[35], Ramezani *et al.*[51] and Hashemi *et al*.[21] have their research to study the parts mechanical properties that are additively printed by material layers of different raster orientations. Zhang *et al.*[35] found that mechanical properties and dimensional accuracy of additively manufactured ABS specimens are significantly affected by the residual stresses induced during layer over layer process of their fabrication. This work carried on the samples produced with raster angles of 0^o, 0^o/90^o and ±45^o also characterizes the material properties in three ABS variants, namely, ABS (unreinforced), ABS reinforced with carbon nanotubes and ABS reinforced with short carbon fibers. It was observed that shrinkage and deformation were significantly reduced in the samples of ABS reinforced with carbon nanotubes and short carbon fibers as well. Process parameters like print speed and raster angle were also observed to have influence on the shrinkage and porosity of the material. A faster print speed resulted in the increased porosity, residual stress and shrinkage. These properties were found affected greatly with the raster angle as compared to the print speed[35]. Ramezani *et al*.[51] additively printed parts of ABS through arburg plastic free forming (APF) on a free former-Arburg machine by keeping a 100 percent infill degree so that the results can be made comparable to parts produced with injection molding process. Parts are printed in two ways – one with 10 unidirectional thin layers (raster orientation of 0°, 90°) and two, 10 thin layers with orientation of 90° between them (raster orientation of 0°/90° and 45°/−45°). Researchers also have observed that in order to avoid any unwanted dispersion in results it is important to maintain a preparation protocol of storing all the specimens at some constant temperature before conducting tests under conformity of an international standard, released by International Organization for Standardization, ISO 527-2. The researchers compared obtained values of UTS, strain before failure and the elastic modulus of the test specimens produced by APF with those produced by injection molding process. They observed that strain to failure significantly affected by raster orientation independent of the printing direction. The value of UTS for the specimens criss-cross printed in raster orientation −45°/45° through APF found to be 32.4 MPa, very close to the UTS of 35.4 MPa for the specimens produced by injection molding process. Among the APF classes, specimens with 0° raster print was observed to have overall poor properties. The study revealed that the interfacial bonding in APF is stiffer for two adjacent beads than the droplets of same beads in succession[51-53]. Hashemi *et al*.[21] studied the strain-life fatigue parameters for the polycarbonate and PLA specimen printed with different raster orientations. This study revealed no transition fatigue-life in some builds; and in some builds, fatigue-life were found to be approximately 20-400 cycles with high plastic strain. In all the builds, fatigue-life is found to be affected largely by the fill density in printing.

In a biomedical area, to check for the feasibility of FDM printed synthetic trabecular bone, tests performed on specimens of PLA blended with hydroxyapatite (HA) revealed that inclusion of HA improve the mechanical properties and scaled-up blended models were comparable to the presently used polymeric-foam synthetic bones[54].

Table 4 — Effect of reinforcements and layups for ABS/PLA printed specimens.

Reinforcements / Layups	ABS/ PLA	Effect(s)
CF or Carbon-nanotubes	ABS	Improved initial modulus with reduced shrinkage and deformation[13, 35]
CF/45^0/Silicone matrix	ABS	High initial modulus with poor structural ductility[13]
CF/90^0	ABS	High structural ductility with high ultimate strain[13]
OMMT	ABS	Improved tensile strength, flexural strength, flexural modulus and dynamic mechanical storage modulus with lower linear thermal expansion[16]
SEBS and UHMWPE	ABS	Decreased mechanical property anisotropy[17, 18]
Deposition of thin layer of CrN	ABS	Improved hardness, wear resistance and Young's modulus[33-35]
Criss-cross layups (−45°/45°)	ABS	Very high UTS, high residual strength[51-53, 59]
90^0	PLA	High fatigue transition life[21]
HA	ABS	Improves mechanical property in blend so as to be used as bone material that can be printed through FDM[54]

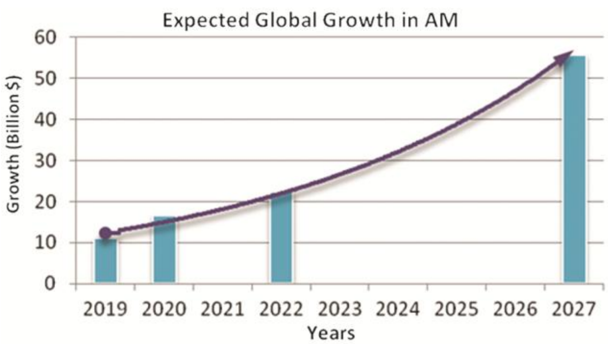

Fig. 2 — Expected growth in AM worldwide[60, 61].

The AM printed components are being used in vast application domains with their mechanical properties depending on their material and the method of printing[55] and wear characteristics depending majorly on build orientation[56]. Nozzle design for 3D printing process is a crucial step. A small change in nozzle parameters affects printing of the components to a large extent. Nozzle design makes direct impact over print-time, geometrical variations, surface-texture of the print[57].

The wear characteristics for the materials (metals like steel, nickel, aluminium and polymers like ABS, PLA, etc.) of additively printed specimen vary based on their quantum differences. Research comprising of detailed study on microstructure and composition of surfaces in contact with appropriate wear testing techniques is required to determine the wear behaviour[58]. Table 4 can be referred to note the effects of reinforcements and different layups[59] in printed ABS/PLA specimens. Figure 2 depicts the expected global growth in AM industry based on current industrial practices[60, 61].

6 Conclusions

A lot of research work has been carried out till date in the development of polymers and materials to suit AM process. Work has also been conducted in the measurement and enhancement of the mechanical behavior of additively manufactured material under tensile, flexure, wear and fatigue conditions when the material specimen kept in various positions, manufactured with different print angles under varying print speeds. In order to have improved mechanical property anisotropy researchers have also tested ABS/PLA with some infill or reinforcement of short carbon fibers/carbon nanotubes, SEBS, UHMWPE or OMMT or polymer filament in various proportions. It has been found that the steel like hardness and wear strength can be achieved with ABS when coated with thin films of CrN. For notched-specimens with variation in crack-tip and laminae orientation angles to study the influence of layer-orientation on the fracture properties by determining inter-laminae and cross-laminae fracture toughness. The mechanical properties of specimen of ABS/PLA prepared by injection moulding generally come superior when compared to specimen fabricated through AM process in all the tests conducted by researchers. This is in accordance with the nature of injection moulding process which produces parts with greater material compaction and enhanced crystalline structure resulting in enhanced mechanical strength. It can be concluded that raster angle, raster direction, layer thickness, print speed and build orientation are the parameters influencing the wear performance of additively fabricated parts. It can also be concluded that the direction of propagation of crack governs the elastic-plastic response of additively printed material. Work has been done and is still being conducted to improve upon mechanical property anisotropy but not enough studies took place, except the few, to study thermal properties of material under varying conditions.

Research is still required for enabling the ease in fabricating objects of steel through AM with the mechanical properties as good as that fabricated through conventional methods. It has been felt that a lot of effort is still required to make the AM process even more economical relating to conventional manufacturing process.

7 Future

The manufacturing industry has experienced the accelerating progress of AM over the last decade. The AM industry has seen an impressive progress, but it has certainly witnessed a little of what is possible. The expected global growth in AM industry based on current industry practices has been already discussed in Fig. 2.

Studies are revealing that only 29% of industry is currently employing 3D-printing to fabricate parts. It is believed that the next big change will be the additively manufactured parts that will go into final products assembly. There is expected to be seismic shift of obtaining a part from traditional to additive manufacturing. This is where research are being conducted and where future opportunities in AM will surely develop. The next big thing will be the 3D-printing of parts required. Siemens is predicting 3D-printing to be cheaper by 50% and faster by 400% in next 5 years[60].

The AM industry is expected to continue strong growth in the years to come. In industry AM is a strong force within digital manufacturing focusing new applications and markets. The AM market, is expected to reach $55.8 billion by 2027 which will be nearly 5 times over the current market. Studies are revealing that 40% of manufacturers expect 3D-printing budget to increase by 50% within a year. It will be no surprise to know that 93% of manufactures are expected to use 3D-printing tools for production in the next 3 to 5 years[60, 61].

The future of AM is looking bright and it is strongly believed that there exists considerable opportunity for AM industry to engineer higher performance AM parts by exploiting design principles to fabricate tailored fracture and failure behaviors in the near future.

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