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A review on polyjet 3D printing of polymers and multi-material structures

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Abstract

This article investigates the state-of-the-art of polyjet 3D printing of polymers and multi-material structures, with an emphasis on its applications in a range of industrial domains, including aerospace, architecture, toy fabrication, and medical field. While significant research and development in the field of additively manufactured (AM) multi-material and reinforced composite structures have been carried out during the previous decade, the need of the hour is to utilize a single manufacturing platform which would not only help to govern the composition, shape, and characteristics of multi-material 3D printed objects at the microscopic level but would also help industries to replace the conventional AM manufacturing methods and optimize their mechanical performance. Significant advancements in polyjet 3D printing of fiber-reinforced and functionally graded structures with numerous modifications in material composition are reviewed, which may revolutionize the industrial sector. Numerous polyjet printing parameters such as accuracy, printing speed, photo-curing effect, build orientation, layer thickness, print angles, and post-processing are comprehensively discussed, and best outputs to optimize the mechanical performance and enhance the accuracy of the polyjet 3D printing products are highlighted. FEA (finite element analysis) models and analytical relations for multi-material 3D printed structures are presented to predict and enhance the overall performance of polyjet fabrication. Along with the benefits of polyjet manufacturing, a few of the limitations and challenges of polyjet AM are addressed which would benefit the reader to conduct further research in this field and enhance fabrication quality significantly. Vivid comparisons with other multi-material AM fabrication techniques such as FDM, SLA, and SLS with their brief discussion, merits, and demerits are done.

Keywords

3D printing, additive manufacturing, photopolymer jetting, polyjet, multi-material structures, FEA

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Introduction

AM (additive manufacturing) also known as rapid prototyping has become an indispensable part of our society.[1] With the advancement of the fourth industrial revolution, high demands for customized 3D printed products have increased. The technological advancements in FFF (fused fabrication filament) have made it possible to fabricate multi-colored composites structures with diverse materials. Photopolymer jetting, also known as polyjet 3D printing[2] involves depositing the substrate in the form of droplets to produce thin layers accompanied by eventual curing of the deposited layers to form three-dimensional parts. The polyjet model comprises a build platform over which the print head traverses to and fro along the *X*-axis and *Y*-axis and deposits the thin layers of thermoplastic resin. The UV (ultraviolet) chamber is equipped with a UV lamp that cures and hardens the accumulated layers using UV light. A three-dimensional model of the object generated using CAD software is transformed to an STL file to slice the three-dimensional structure into digital layers which are then transferred to the polyjet printer through custom machine software. Polyjet printing employs photopolymer materials to build the model and includes another gel-like substance to serve as a support structure. As the supporting materials are soluble and fusible, removing the supports is a simple and damage-free process. Photopolymer jetting performance is assessed at a large scale for producing high-quality components. The first multi-material 3D printer, Fab@Home, was built in 2006. The idea was immediately embraced by numerous industries, resulting in the development of several multi-material 3D printers. Objet merged with Stratasys in December 2012, with a market capitalization of US $ 3.0 billion. Stratasys[3] holds the patent (US9102099B1) for photopolymer jetting technology in 2015. Figure 1 represents the significant rise in research publications during a ten-year period, from 2011 to 2021, in polyjet 3D printing of polymers and multi-material

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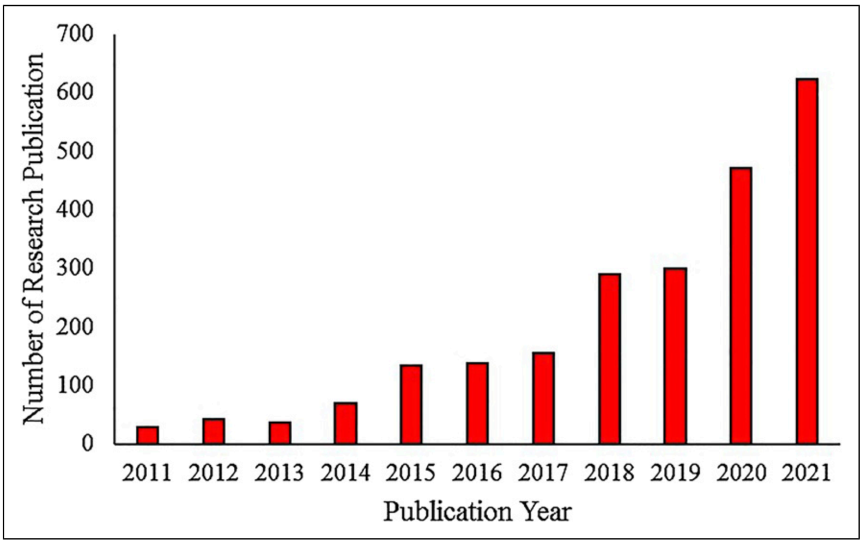


Figure 1. Annual evolution of research publications on polyjet 3D printing of polymers and multi-material structures from 2011 to 2021.[4].

Table 1. Parameters and control levels in photopolymer jetting technology.[2]

Parameter	Control levels
Model materials	Rigid and opaque material: Vero Transparent™, Vero Pure White™, Vero Magenta™, Vero Cyan™ Rubber-like material: Agilus 30™, Tango Plus™, Tango Black Plus™, Tango Gray™ Transparent material: Vero Clear™, RGD 720
Support material	Heavy–Lite
Surface finish	Glossy, ultra glossy, matte, dead matte
UV light wavelength	300 nm–400 nm
Physical material range	Opaque, transparent, translucent
Material grade	Rigid, flexible, brittle, temperature resistance, high strength
Print mode	High speed–high quality
Print heads	Single jet–multi jet (4 heads)
Hardness range	27–95(Shore hardness A)
Layer thickness	16 μm–30 μm

structures.[4] Polyjet printers are capable of generating complex components in a short period, which makes them ideal for creating realistic components and prototypes. A polyjet AM encompasses the widest range of colors and materials into a single end-use product. This method provides flexibility in selecting material exhibiting high tensile, fatigue, and torsional strength. Polyjet printing offers a good resolution and processing accuracy and can print layers as thin as 16 μm. The polyjet technique offers low polymerization shrinkage and permits the creation of items with a smooth surface finish. Table 1 enlists various printing modes such as part orientations, support materials, printing speed, and surface finish available in photopolymer jetting printers[2] that affect the mechanical properties of the fabricated specimen.This paper discusses the polyjet method's multi-material production capability, microscopic resolution, low surface roughness of polymeric structures, and the most recent industrial advancements in the field of photopolymer jetting technology. A detailed study of various industrial polyjet printers, process printing parameters, and the wide variety of thermoplastic resins has been done emphasizing their merits, drawbacks, and applications in a variety of fields, including fluidics and electronics, biomedical engineering, food packaging industries, automobile industries, toy industries, and fashion and textile industries. Several polyjet printing parameters have been reported to have a significant impact on the mechanical performance of polyjet-printed components, and best outputs to optimize strength and enhance the accuracy of the polyjet 3D printing process are highlighted. A particular emphasis is given to the manufacturing of complicated reinforced multi-material AM composites utilizing the multi-nozzle polyjet printing method. AM composites are categorized based on their characteristics, applications, and composition into particle reinforced fiber-reinforced and structural composites. Significant advancements in polyjet-printed functionally graded structures with continually variable material composition to achieve the desired functional qualities are discussed. The comprehensive discussion covers different reinforcement methods, mechanical characteristics, testing, and AM standards of fabricated structures. Furthermore, this article presents numerous FEA (finite element analysis) models and mathematical and numerical methods for simulating physical processes and predicting the mechanical performance of multi-material AM structures. While significant advances have been made in this field, there are still many critical fabrication challenges that are comprehensively addressed in terms of material range, product performance, and product characteristics. Benefits and drawbacks of various manufacturing techniques such as FDM, SLA, SLS, and polyjet are discussed. Furthermore, polyjet AM in 4D printing is another rapidly evolving technology that has been introduced. Thermo-responsive, moisture-responsive, and magneto and electro responsive smart materials are transforming the industrial sector.

Multi-material polyjet additively manufactured

Polyjet AM employing multi-material fabrication, in particular, seems to be a promising field since it improves mechanical characteristics including strength, stiffness, heat resistance, and durability.[5–10] 3D printed multi-material structures are combined with numerous particles, continuous, and discontinuous fibers as filler materials. These fabricated structures have been extensively researched as a viable alternative to conventional composite structures with sophisticated and expensive designs. Numerous developments have been made in the field of multi-material polyjet 3D printing.[11–16] Multi-material polyjet printers capable of fabricating a wide range of prototypes and industrial end-use products have emerged in recent years. Figure 2 illustrates a range of widely used typical polyjet 3D printers. The printer's maximal build size, manufacturing precision of the printed components, layer thickness during fabrication, and system weight is highlighted. The desktop design printers such as objet 30 pro and objet 30 prime 3D print precise components up to volumetric build volume of 0.02 m^3. The next category of polyjet printers makes use of the inkjet technique to deposit the resin, providing micro to macro-scale fabrication. The connex design series printers provide more flexibility in terms of materials and colors used during production. Numerous printers of this kind, including the objet 260 connex 1, objet 500 connex, objet 260 connex 3 TM, objet 500 connex 3 TM, and objet 350 connex 3 TM, fabricate a layer with a thickness of 10 microns. Stratasys J 735 TM, Stratasys 750^{TM}, and Objet 1000 plus^{TM} are widely used production series polyjet 3D printers. They offer the broadest variety of agility, aesthetics, size, and artistry at every step of production. These printers are focused more on industrial usage and print precise components up to a volumetric build volume of 0.04 m^3. Multi-material AM using polyjet technology is reported at various scales, resulting in improved dimensional conformity between proposed designs and fabricated structures.

Numerous advancements have been achieved in the field of bio-inspired polymer composites,[17–20] soft robotics,[21,22] and four-dimensional printing,[23–25] all of which have expanded the design space and overcome the constraints of conventional manufacturing techniques. Inspired by natural composites, the additively fabricated composite structure reported an enhancement in mechanical characteristics such as flexibility[26] and hardness[27] by integrating soft and hard elements into a single end-use product.[28] Specially designed and fabricated multi-material structures,[29–32] such as honeycomb structures,[29] photopolymer foams,[32] and architectural design based structures,[33,34] significantly increase the energy absorption capacity. Additively manufactured functionally graded structures (FGS) have tremendous possibilities owing to their improved mechanical performance and high flexibility in various fields, such as electronics, biomedical, and aerospace. The interface bond strength[35,36] of additively manufactured multi-material structures utilizing photopolymer jetting technology has been reported to be dependent on the print settings and materials.

Functionally graded materials and structures via polyjet additively manufactured

Functionally graded structures are the composite structures which includes sections with material gradient exhibiting a wide range of functional attributes.[16,20,69,102] As polyjet AM technology continues to advance, it is now possible to fabricate multi-material structures with progressively changing material compositions without using molds, conventional tool, and joining and assembly techniques. In a novel study employing polyjet 3D printing,[16] the FGM structures were designed and fabricated which allows for a desired strain rate by individually modifying the proportion of digital materials without impacting the overall structure. Figure 3(a) shows the tensile samples for three

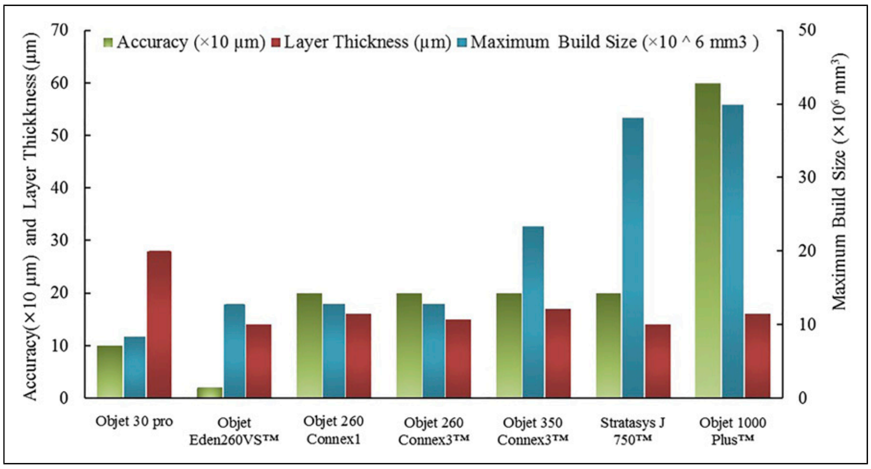


Figure 2. Comparison of the maximum build size, accuracy, and layer thickness of the Stratasys polyjet printers.

configuration of FGM structures with the (SEM) scanning electron microscopic images for Tango Black Plus, DM 60, DM 95, and Vero White Plus polymers in Figure 3(b). Figure 3(c) represents the Mooney–Rivlin meshing model in the interface region of functionally graded structures. A nonlinear model is used to discretize the structure's stiff and elastic components separately. Figure 3(d) represents the strain of the FGMs. A novel study on multi-material specimens compared the mechanical performance of step-wise gradients to that of continuous gradients and found that the latter performed better in terms of fracture performance.[20] Research has been reported on building a regression model to predict the mechanical behavior of functionally graded structures that experimentally and analytically combine soft and stiff polymers with variable material gradients.[102] Overall, the functionally graded structures are extensively manufactured employing polyjet AM, which has extremely customized capabilities due to accurate material composition control.

Reinforced additively manufactured composites

Reinforcement of AM structures significantly enhances the mechanical performance of the fabricated structure. The strengthening mechanism in the case of particle reinforced composite is carried out at the atomic level. Reinforced particles[37,38] are employed to enhance the characteristics of end-use products, depending on their intended purpose, for instance, tungsten carbide and titanium carbide are used as reinforcement to increase flexural modulus and tensile strength of cemented carbide,[38,39] carbon black spherical particles is added to increase wear resistance and toughness of vulcanized rubber-based automobile tires,[40,41] and alumina, ceramics, or tungsten particles are used to increase the dielectric permittivity of materials.[37,42–44] The mechanical properties of fiber-reinforced composite[45] are dependent on several parameters, including the stress-strain characteristics of the fiber and matrix materials, the volume fractions of the filler materials, and the direction of application of the load. Carbon fiber-reinforced composites, glass fiber-reinforced composites, and Aramid fiber-reinforced composites are the most commonly manufactured fiber-reinforced composites. Both short and continuous fiber-reinforced AM composites exhibit an increase in mechanical strength. Numerous short and continuous fiber-reinforced composites[46–48] using continuous filament Markforged printers have substantially improved the elastic modulus of the fabricated structure.

Several studies[49,50] show a significant improvement in thermal conductivity and energy absorption of the

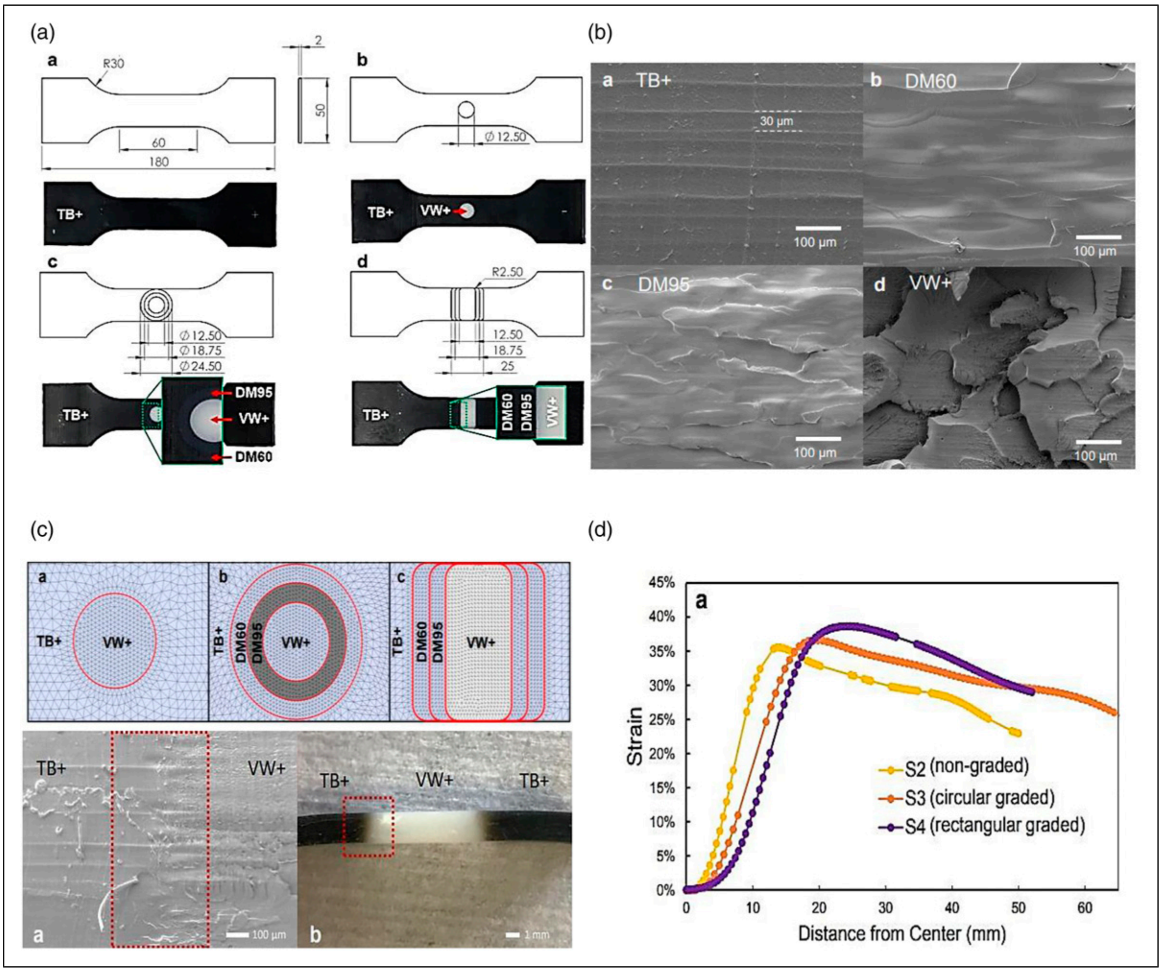


Figure 3. (a) Tensile samples for three configuration of FGM, (b) scanning electron microscopic images for Tanglo black plus, DM 60, DM 95, and Vero White Plus, (c) meshing performed at the interface of the two materials, and (d) stress-strain distribution for three functionally graded structures.[16]

continuous fiber composite specimen. Reinforcement length[51] is an essential factor required to effectively reinforce and stiffen the composite material. Laminar composites are fabricated by stacking two or more sheets or plates bonded together in a certain orientation. The enhancement in tensile and fatigue strength of un-notched and open-hole plywood laminates[52] manufactured using parallel wood sheets oriented at right angles was reported. The lightweight honeycomb sandwich composite panel[53] reported an exponential increase in flexural rigidity and bending strength. Table 2 summarizes the effect of particle reinforcement and fiber-reinforcement on the mechanical strength of AM composites fabricated using various AM techniques. Few studies[46,54] report the poor inferior

Table 2. Overview of reinforced composite using various AM methods.

	Ref	Fabrication technique	Matrix + reinforcement	Testing standard	Advantages	Disadvantages
Particle Reinforcement	66	FDM	ABS + TPE	Tensile testing, ASTM D-638	Enhancement of 5 % in ultimate tensile strength	Higher Extrusion temperature, over 300 0C
	67		ABS + TiO2	Tensile testing, ASTM D-638	An increment of 10 % in tensile strength	Decrease in fluroscence intensity by 10%
	68		PC + tungsten	Impact testing ASTM–256-10	An increment of 7.6 % in storage modulus	Decrease in flexural strength
	42	SLA	UV-cured resin + alumina	Light transmission testing	38% increased relative permitivity	No significant increase in mechanical str
	69		Acrylite resin + microdiamond	Specific gravity testing, ASTM D-1475	30% rise in heat transfer rate.	Reduction in mechanical strength due to poor diamond adhesion
	70		Epoxy resin + FeO	Tensile testing, ASTM D-638	Enhanced young's modulus	Weak particle chain-to-polymer interfacial bonding
	71	SLS	PA 11 + glass bead	Tensile testing, ASTM D-638, Compressive testing, ASTM D-695	Improved stiffness	Limited slection in powder particle sizes for optimum spreading
	72		Clear resin V4 + single-walled carbon nanotubes	Impact testing, ASTM E-23	Increased endurance limit upto 2919 cycles	Reduced impact resistance
	73		PA 11 + CN	Impact testing, ASTM E-23	54% enhanced impact strength	Formation of nano-sized micro-cracks
Fibre Reinforcement	47	FDM	Nylon + kelvar fiber	Stearing testing-14130 600	60% enhanced tensile strength and 500 % flexural strength	Increased air gaps owing to higher fibre content
	74		Nylon + carbon fiber	Flexural testing, ASTM D7079-10 213	213 % enhanced inter-laminar shear strength	Low transverse tensile strength of fibers
	75		Polypropylene + glass fiber	Impact testing, ASTM E-23-30	30 % improved impact I strength	Insufficient thermal characteristics
	76	SLA	Thermoplastic Polyamide + short and continuous carbon fiber	Tensile testing, ISO 527 -2: 1993 158	158 % enhanced tensile strength	High cost of photosensitive resin and equipments
	77		Polypropylene + short carbon fiber	Tensile testing, BS EN ISO 527-1: 1996	50% improved tensile and flexural strength	Decrease in overall isothermal crystallization rate
	78		Thermoplastic elastomer + ABS	Tensile testing, ASTM D-638-10	Enhanced tensile strength, notched impact strength, and bending modulus	Brittle cracking at low temperature
	79	SLS	nano-hydroxyapatite + /poly-ε-caprolactone	Compression testing, ASTM D-3410	78.54 % porosity and increased compressive strength	High porosity in femur specimens
	80		Silicon carbide + Polyamide 12	Tensile testing, ASTM D-638	Increased tensile strength	insufficient melting of polyamide and high structural porosity
	81		Wollastonite fiber + polyamide 12	Flexural creep testing, DIN EN ISO 899-2	76% enhanced ultimate tensile strength and 22 % flexural strengt	Large structural deformation due to high residual stresses

interfacial adhesion and void formation in AM composites as opposed to traditional molding composites. Inadequate inter-laminar adhesion, highly porous structure, and anisotropy limit the mechanical performance of the AM-fabricated composite.

Polyjet reinforced additively manufactured structures

The photopolymer jetting method has been extensively utilized to reinforce structures with particles, fibers, and laminates.[23,25,55–58] The various reinforcing materials are included in the matrix materials to improve strength and compensate for printing constraints associated with pure polymer printing, such as shrinkage, warping, and distortion. The photopolymer jetting technique enables the incorporation of a variety of photopolymer materials with a diverse range of mechanical properties such as stiffness, elasticity, opacity, and translucency. Reinforcing Vero Black[23] by altering the volume concentration in a Darus white polymer matrix fabricated using photopolymer jetting technology results in a 21.9% increase in elastic modulus when printed in the longitudinal direction. An exponential increase is achieved in tensile strengths of additively manufactured polymeric composites using photopolymer jetting[25] with a digital propylene reinforcement done in a homogeneous matrix by modulating the reinforcement volume percentage. Numerous multi-material surgical models and prototypes are manufactured utilizing polyjet technology employing Vero Clear, Vero White thermoplastic materials, as well as biocompatible materials such as MED 610.[56] A minor variance of 3% in dimensional deviation, and tensile strength is observed in the fabricated structures when compared to real biological tissues. The interfacial strength of a multi-material composite has a considerable effect on its strength and stiffness. The reduction in material thickness and the orientation of the printing at 90° enhance the mechanical strength of the AM-fabricated composite.[57] Figures 4(a)–(f) illustrate several reinforced polyjet-fabricated structures that are reported to improve a variety of mechanical attributes.[6,9,10,23,145] The particle-reinforced composite structure fabricated using the Stratasys J750 polyjet printer as shown in Figure 4(a) enhances the compressive strength of the structure by 20%. The polyjet-manufactured reinforced rectangular plate reinforced with randomly oriented Tango Plus thermoplastic material designed on CAD software as shown in Figure 4(c) increases the structure's stiffness by 15%.

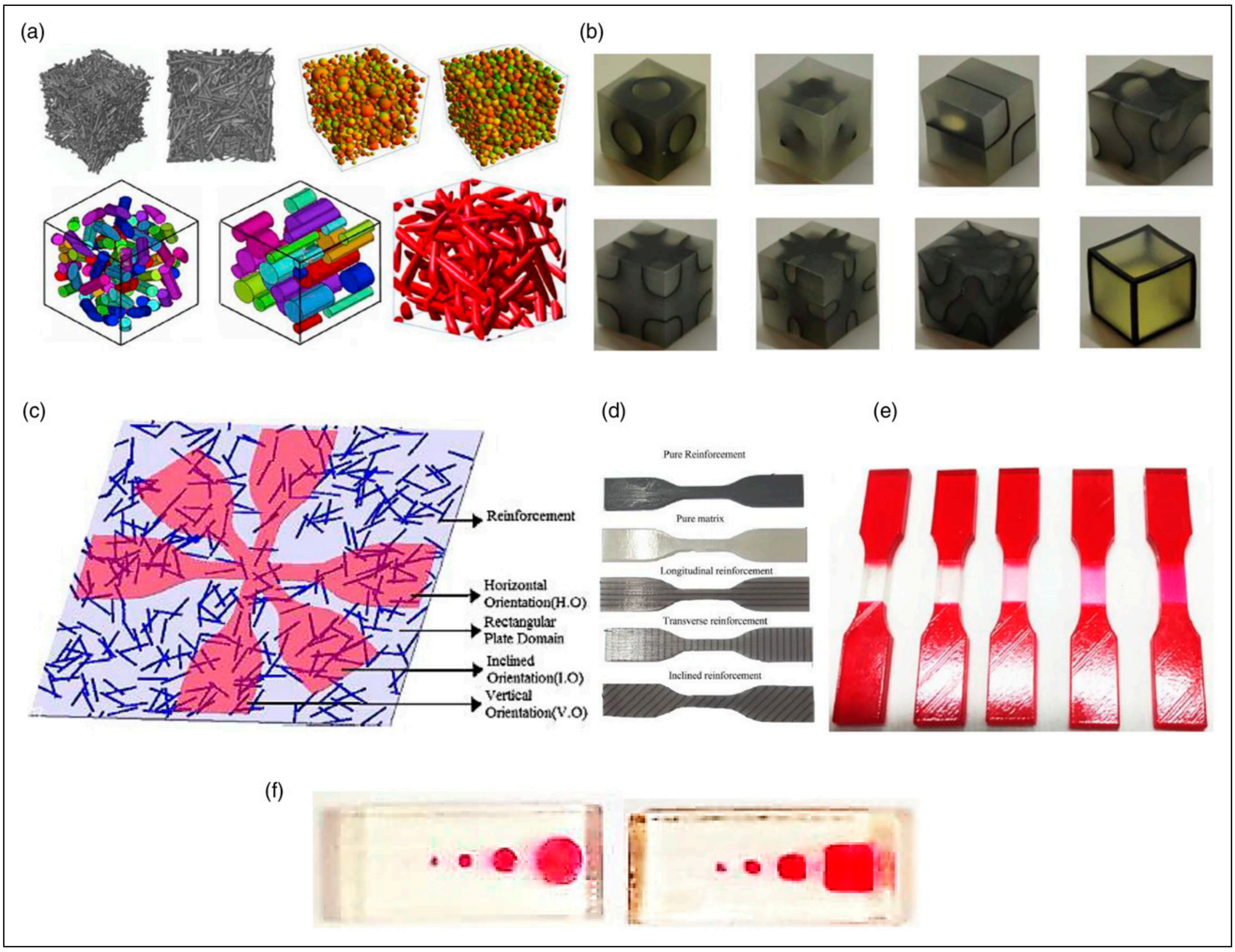


Figure 4. Polyjet AM-reinforced composite specimens, (a) microstructure of various multi-material shaped fillers,[10] (b) polyjet AM multi-phase structures,[9] (c) polyjet-manufactured reinforced rectangular plate,[6] (d) numerous reinforced tensile specimens,[23] (e) multi-material tensile specimens,[145] and (f) cuboid shaped composite samples.[145]

Tensile and compression samples comprised of a cubical composite of Vero Magenta VTM and Agilus 30 TM reinforced by photopolymer jetting as shown in Figures 4(e) and (f) significantly increases the ultimate tensile strength and elongation at break. Although polyjet reinforced AM structures have been significantly desirable to fabricate potential components from a variety of thermoplastic materials in electronics,[60] biomedical engineering,[61] food packaging industries,[62] automobile industries,[63] toy industry,[64] and fashion and textile industry[65] for creating complex-shaped, intricate-detailed, and delicate-featuring end-use industrial 3D printed components, still the overall strength of the fabricated structure is significantly less than that of the benchmarked carbon fiber composite[58,59] manufactured by traditional mold casting. The mechanical characteristics of a multi-material polyjet-AM composite structure are limited by the lack of interfacial strength between the matrix and the reinforcement owing to the existence of substantial voids.[9]

Process parameters for Polyjet printing

Photopolymer jetting[3] is a rapidly expanding AM process that allows for the incorporation of the broadest diversity of process parameters, materials, and designs into a single end-use product. The mechanical performance of polyjet printers are influenced by several process variables. Numerous printing parameters are investigated and varied at various levels to optimize and enhance the effectiveness of the 3D printing process. A variety of combination of materials is mixed at every level to explore the potential of the printer. Many such parameters that influence the printing process and efficiency are discussed in detail.

Material range

Photopolymers[2,82] are light-sensitive materials whose properties alter when exposed to ultraviolet light. They can transform from a water-like liquid material to a rigid plastic-like substance. The region is open to ultraviolet light solidifies, while the rest of the material remains liquid. These polymers find high importance in AM industries as polyjet technology encompasses a wide range of diverse materials.[2] The polyjet method[82,141,152] opens the platform for fabricating large-sized lattices based on the compressive peak strengths. Vero White Plus™ industrial thermoplastic resin was extensively employed to build the specimen's overhanging sections,[141] and SUP 705 was employed as a support material during photopolymer jetting 3D printing. Additionally, water jet machining is utilized to remove the SUP 705 support framework. The support removal problem is largely discussed as it has an impact on the surface roughness and solutions are identified to eliminate it. In the polyjet-printed specimens, directional anisotropy[13] is reported, affecting the component's strength and elastic modulus. Anisotropy in mechanical properties induces huge tolerances in 3D-printed specimens. It is found that an increase in material's anisotropy is observed during the printing of the PLA composite.Figures 5(a)–(b) illustrate the diverse materials interfaced and the mechanical characteristics of a composite manufactured by integrating Vero Magenta and Agilus 30 during polyjet 3D printing[83] of polymers with varying degrees of hardness. It is stated that material selection has a significant influence on the properties of mate surface and polished surface. Experiments[61,84] are performed for bone tissue engineering applications by varying the volume fraction of titanium particles from five to tenpercent, infill pattern, infill density,

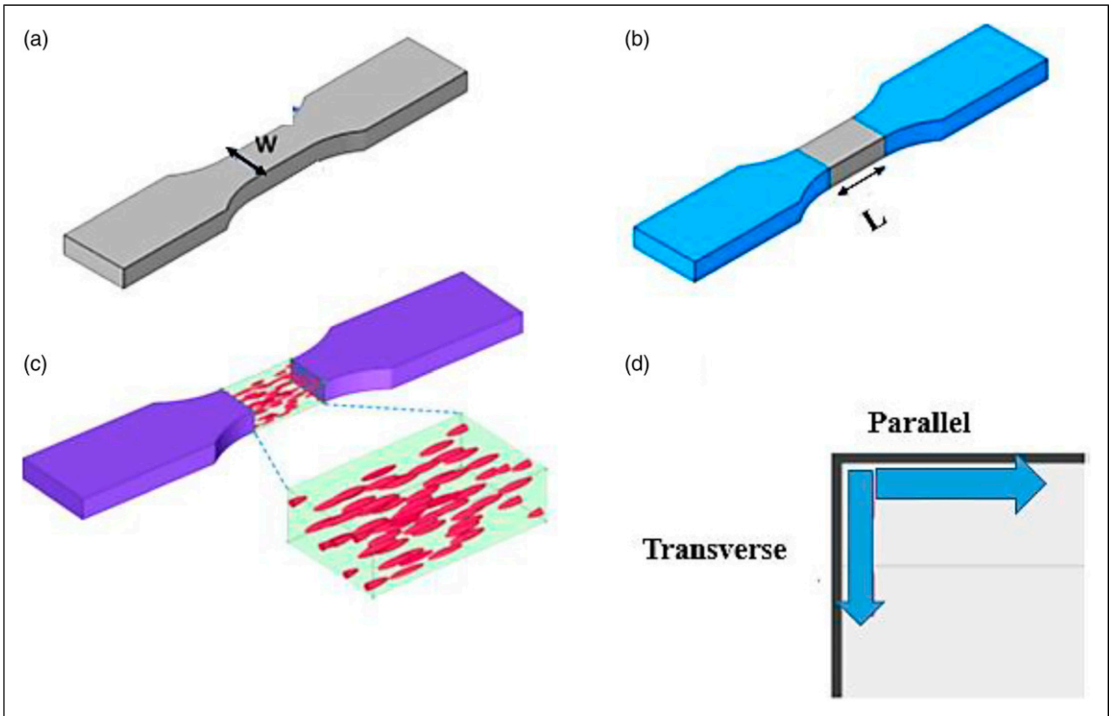


Figure 5. (a) Homogeneous 3D printed sample, (b) heterogeneous 3D printed sample, (c) hybrid 3D printed samples, and (d) print orientation of samples.[101]

Table 3. Polyjet materials, material type, property evaluation, and application of the fabricated polyjet parts.

Ref	Polyjet materials	Material types	Properties	Applications
Slesarenko et al.[148]	Digital ABS	RGD5160-DM	Impact-resistant, shock absorbent, temperature resistant	Engine parts, phone casings, electrical components, high-temperature parts
AbuElmagd et al.[150], ibrahim et al.[151]	Dental material	MED 610, MED 670, MED 690	High flexibility, fine resolution	Dental crowns, stone modules, bridges, dental wax, and cups
Königshofer et al.[56]	Biocompatible material	MED 610	Transparency, colorless, high dimensional stability	Surgical guides, surgical implants, medical equipment's
Tomar et al.[25]	Propylene material	Durus white - RGD-430, vero clear-RGD-810	Thermal resistance, flexibility	Medical lab equipment's, automotive parts, loudspeakers
Sugavaneswaran et al.[23]	Transparent materials	Vero Black Plus, RGD-875	Availability of transparent shades	Surgical applications, eyeglasses, color dyeing, artistic modeling
Salcedo et al.[16]	Rigid opaque material	RGD-850, RGD-835, RGD-840	Variety of colors, durable	Silicon molding, painting, movable parts, dyeing
Ituarte et al.[102]	Rubber material	Agilus 30, Tango Black FLX973, Tango Black Plus FLX980	High abrasion resistance, tear resistance, resilience	Gaskets, prototypes, seats, footwear's

infill speed, and print materials. Experiments with acrylonitrile butadiene styrene[84] revealed some very remarkable findings in terms of fracture strength. During the 3D printing of a PLA-Ti composite for bone tissue implant,[61] the existence of certain voids in the manufactured structure was observed. The fatigue strength of the printed specimen subjected to high creep load is determined by performing an optimum permutation with different parameters such as road width, air distance, several counters, and build orientation. Table 3 represents the polyjet printer's material range, material properties, and application of the fabricated polyjet parts.

Printing speed and precision

Printing speed[83,85,86–90,151] and precision[82,83,91–94] are the critical parameters that have to be taken into account for a 3D printing process. The influence of part placement, porosity, and part orientation[83] are observed on the dimensional accuracy in X, Y, and Z directions. Print orientation in polyjet printing has severe effects on the precision of mate surface and polished surface. The air bubbles and air gap present inside the fabricated specimen severely affects the accuracy and mechanical properties of the AM-fabricated specimen.[86] An algorithm[87] is proposed to reduce the dimensional deviation between the STL file and CAD model by modifying the facet density of the STL model. This algorithm is a minimization approach to modify the error based on chordal error, cusp height, and cylindricity error for cylindrical features. Additionally, the geometry is optimized using the surface modification method where selection criteria in the form of an algorithm are outlined for STL surfaces. Dimensional differences are compared in various studies[88,89,95,151] for various printing methods such as polyjet, fused deposition modeling, stereolithography, and powder bed fusion, and it was stated that polyjet technology resulted in a fine surface finish while fabricating the craniofacial skeleton.[150]. Polyjet printing reported a dimensional error of 2.14%, which was superior to stereolithography and powder bed fusion. A similar analysis[95] compares the dimensional variance of manufactured goods generated using various manufacturing techniques. Polyjet technology is generally associated with low printing speed as compared with other technologies[4,83,85,91,92]. Speed evaluation[85] for different additive manufactured machines is evaluated on ten prepared samples. Speed assessment is done on a 2k factorial model that presumes the linearity among individual points of the experiment. The major speed reduction and deviation challenges are encountered due to the high build tray ratio of the machine. The effect of photo-curing[90] on the accuracy of 3D printed samples is explored with a variety of variables including curing speed, large scale specimen, the thickness of the layer deposited, and high viscosity of resins used for 3D printing. Additionally, the light intensity has a significant effect on the printing speed. Figure 6 represents the spatial accuracy of additively manufactured M8 fasteners fabricated using photopolymer jetting technology.

Build orientation, number of counters, layer thickness, and print angles

Processing characteristics such as build orientation, number of contours, layer thickness, and print angle[84,92,96,97] have a significant impact on the finished part's design, quality, functionality, and structural characteristics. Several studies[91,93,98] have also focused on various multi-material extrusion-based 3D printing parameters such as (i) infill speed, (ii) infill density, and (iii) infill pattern along with various 3D printing materials, that is, ABS, PLA, CFR-PLA (carbon fiber-reinforced PLA), CFR-ABS (carbon fiber-reinforced ABS) and CNT-ABS (carbon nanotube reinforced ABS). CFR-PLA was found as a durable material in terms of compression, bending, and tension. Rather than focusing on the general features of 3D printing, a study was conducted to determine the compatibility of continuum models with FDM thermoplastics.[99,100] Three primary characteristics, layer height, number of layers, and raster orientations were used to determine the failure causes and distortions in polyjet-printed parts. Two kinds of failure were identified: (i) interlayer failure and (ii) inlayer failure. A similar study featured a special alignment style of the 3D

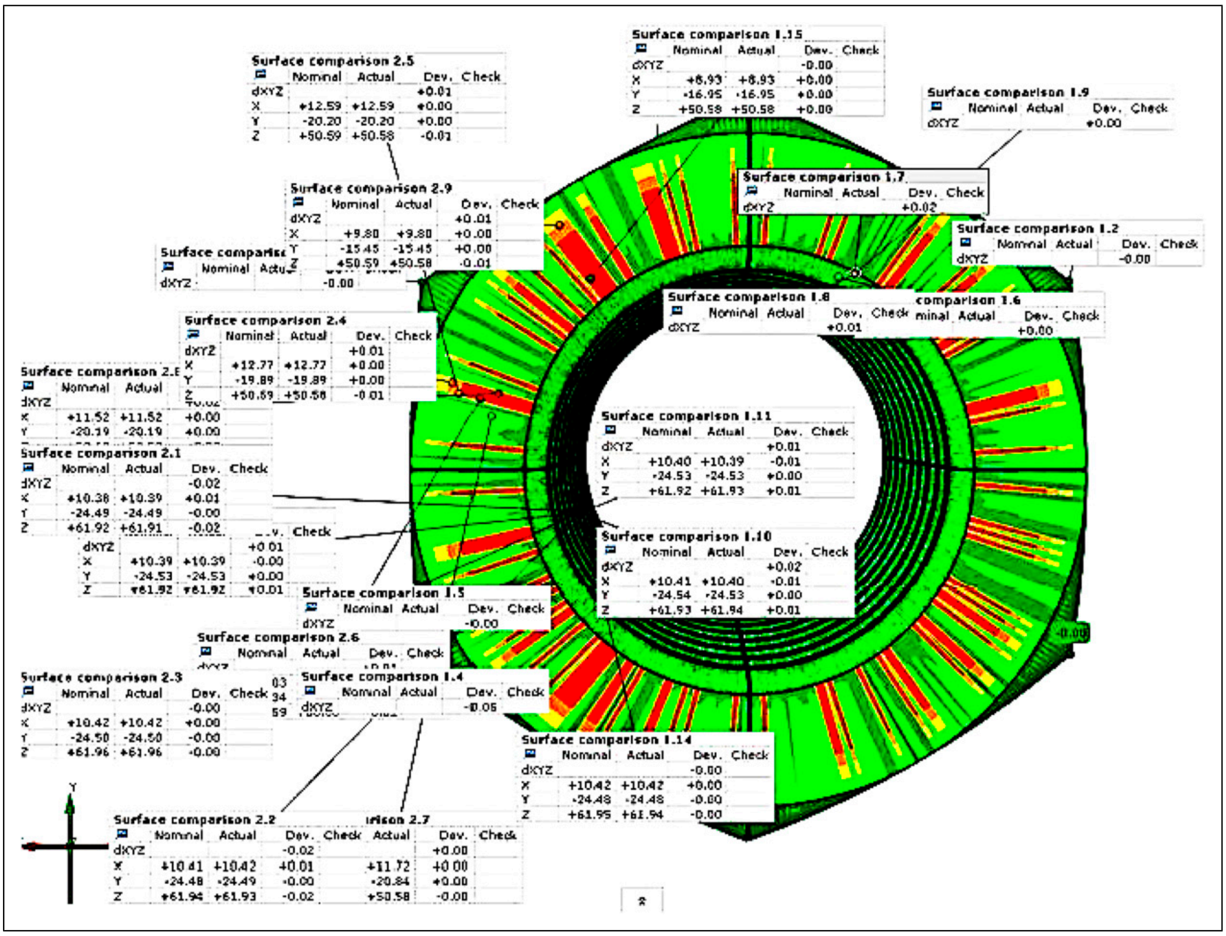


Figure 6. 3D tolerance chart of Vero Grey nut fabricated using the polyjet technique superimposed with an ISO Standard M8 nut, in mm.

printed specimen[142] to figure out aspects of fractured toughness. Numerous investigations[102–104] have been reported on the dimensional, geometric, and orientation effects of reinforced particles. The mechanical and fractographic behavior of the manufactured Vero magenta and Tango Black Plus composite[102] is examined under the influence of varying print orientation and volume proportion. A similar study[104] has been conducted on the influence of layer thickness and dimensional deviation on samples' bone tissues.

Figures 7(a)–(d) show the effect of raster angles,[142] the various print orientation, the print build directions,[13] and the print angles,[99] respectively, during the fabrication of the 3D printed composite. The mechanical accuracy and mechanical properties are investigated of the fabricated composite. FEA (finite element analysis)[103] was assessed to examine the mechanical behavior of AM functionally graded structures under uni-directional, bi-directional tensile, compressive, and cyclic loading. Additionally, stress and deformation patterns were explored, as well as the possibility of particle fracture.

Post-processing

Post-processing is a key parameter in optimizing the product manufacturing process and is critical for evaluating the component's surface roughness and hardness.[1,105,106,119,120,152] Various assumptions such as abrasive size, feed rate, chemical concentration, abrasive flow rate, and laser rate significantly influence the post-processing method needed for any fabricated object. A study presented in Ref. 106 indicates the various post-processing methods to improve surface finish value. Figure 8 displays the post-processing method to enhance the aesthetics of a printed part. Both 3D printed portraits are smoothed with acetone, and the result is a matte, seamless finish with no clear layer marks. It is reported that the continued exposure to UV light for a long time and a flat printing orientation increases the possibility of obtaining a glossy surface. The study in Ref. 107 serves as the foundation for fabricating large-sized polyjet lattices based on the compressive peak strengths. A drainage pathway is proposed as the additional post-processing for the unsolidified material void regions to escape. The presence of support material[152] not only increases the cost but also reduces the surface finish of the product. This analysis emphasizes the difficulties associated with removing support material and the measures required to remove them while fabricating the specimens using the photopolymer jetting technique. Moreover, self-supporting structures are designed utilizing two algorithms, namely projection-based design and overhang-constrained design. The strength-to-weight ratio performance[141] is a critical factor to consider when choosing a support material for bio-material fabrication. The location of support material is determined by the complex geometry, internal cavities in the standard

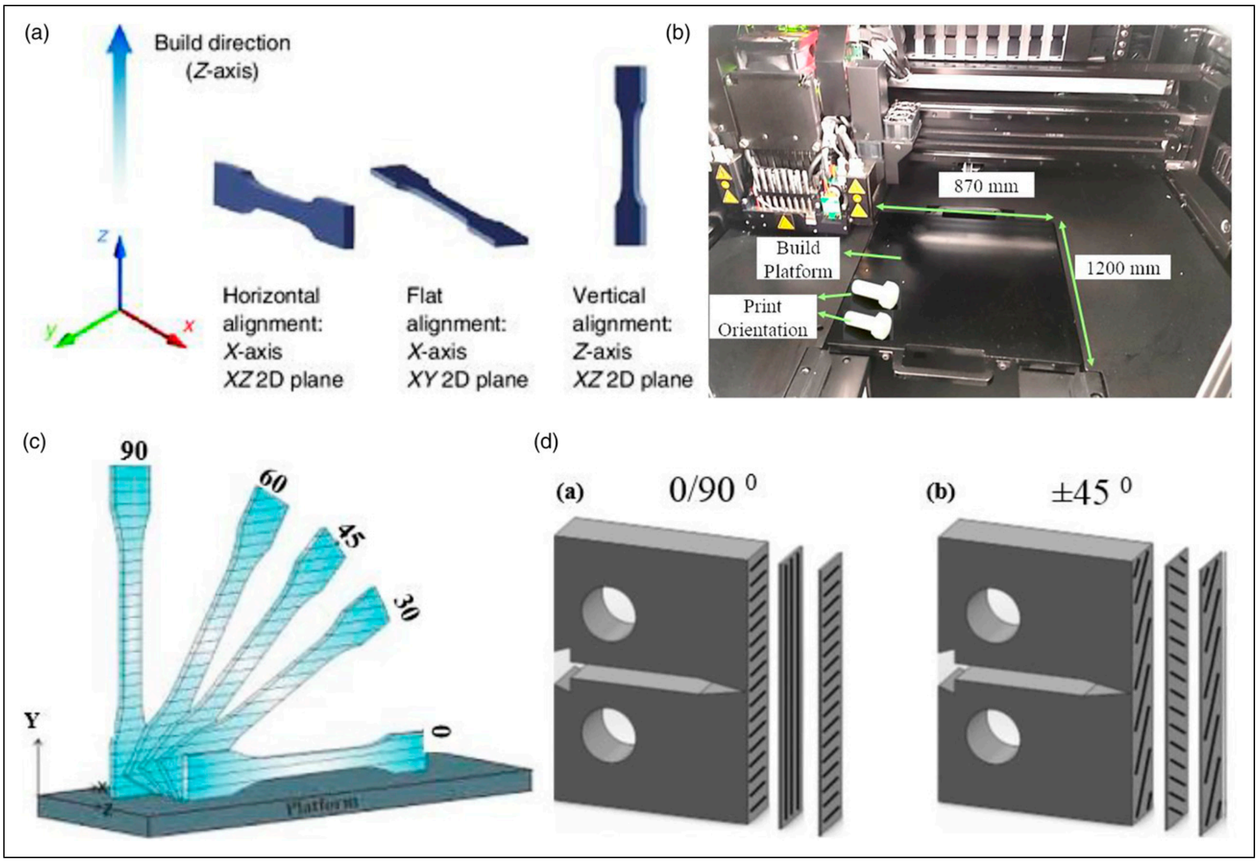


Figure 7. Polyjet printing parameters: (a) print build direction,[13] (b) print orientation, (c) print angles,[113] and (d) raster angles.[142]

Figure 8. Effect of post-processing on the surface finish.[106]

configuration, cell wall thickness, and volume fraction of materials.

Photo-curing

The photopolymer jetting technique uses ultraviolet (UV) lamps[90,108,109] to harden the liquid photopolymer by ejecting UV light from them. The ultraviolet light irradiance parameters play a significant impact in the photo-polymerization of resins. The wavelength and intensity of UV light[143] have a significant impact on resin curing. The impact of various laser strengths, halogen lights, and LEDs with a power range of 0.1–2 W on the curing efficiency of the photopolymer resin. Curing with a low conversion degree[110] provides several benefits such as easy crosslinking at ambient temperature to create a variety of coatings, reduced energy usage, and precise fabrication of components. Generally, wavelengths used for curing is ranged between 360–405 nm. However, few photo-curing-based challenges limit the efficiency of 3D printing. Photosensitive materials used in biomedical applications generally become brittle after the photo-curing effect.[82] Mostly photo cured materials are used for prototype designing and fabricating wax-type materials. The viscosity of the resin is a critical parameter in polyjet printing which requires a low viscosity to ensure easy deposition. A low-viscosity resin with a high degree of fluidity reaches the build tray quickly and is suitable for printing high-resolution designs.[143] It is essential to have a low-viscosity resin to be injected into the nozzle for a cost-effective solution.

Photosensitive resins with low viscosity are critical for good performance. Low viscosity is compatible with a wide range of substrates. The strength and hardness values are significantly dependent on the degree of curing of the polyjet-fabricated components. The excess curing of components[15,153] in the tray might potentially generate significant varying mechanical characteristics of the components with similar geometry. The changes in material characteristics are linked to how UV light is intended by the polyjet machine during processing. While printing several components that need numerous print pathways, the UV irradiation pattern affects various zones inside the production tray in various ways, and as a result, some components may get over-cured depending on their position. It is observed that the process parameters in photopolymer jetting affect a printed component's critical characteristics. Since a collection of material characteristics are available without any recommended printing parameters, the key challenge for designers is to configure the printer and optimize the parameters to achieve the best results for the design requirements. Optimization[82,111–113,146,150] entails minimizing material consumption and optimizing product output. A multi-objective optimization[15] must be conducted for the print parameters to produce durable and frivolous parts for various structural applications. The optimization of the polyjet printing process involves several parameters including a selection of material, part size, print resolution, turning speed, machine resolution, machine procurement cost, number of parts produced, positioning of the specimen, and post-processing. Manufacturing imperfections must be minimized using an optimization technique which takes dimensional deviation into account and evaluates the design. The most often utilized optimization approaches are Taguchi,[91] the response surface approach, and analysis of variance, or ANOVA[114] for experimental design for 3D printing processes. The finite element approaches[32] are popularly employed numerical methods for performing finite element analysis on any fabricated structure. 3D printed specimens are often simulated and verified using finite element analysis rather than physical testing since they eliminate the requirement for physically fabricated prototypes and allow for process parameter optimization as part of the design process.

Finite element analysis and mechanical characteristics of 3D printed specimens

Numerical and analytical approach has been employed in numerous investigations for estimating the strength of the 3D printed specimens.[16,83,105,115–118,141] The quasi-static boundary approach has been utilized to achieve accurate solutions for the mesoscale AM, and analytical solutions for a single droplet of thermoplastic rein are presented to demonstrate the manufacturing features of the mesoscale. An explicit solver[115,118] with an actual time scale model is utilized to analyze the 3D printing process that incorporates mass scaling under dynamic loading conditions. The meshing pattern during modeling was kept in a balanced way between feasibility of computational cost and accuracy of results. The computational efficiency[116] of simulated results is reported to be weak at rounded corners and sloped walls of the fabricated structure. A comparison using FEA is conducted at the interface of the two bonded materials. A nano-indentation test[61] is performed to measure the structural strength of multi-material additively produced composites. Before manufacturing end-use components, the strain analysis is performed to predict the strength. For instance, a composite[16] composed of ABS as the base material and Tango Black and Vero White as the parent material is simulated using ANSYS software to determine the interfacial bond interaction. Figure 9 shows FEA for estimating the strength of an AM fabricated composite sample solving numerous theorems. Analytical relations are also helpful in predicting and enhancing the strength of the composite structures fabricated using 3D printing. Numerous theories are proposed for determining the elastic modulus, bulk modulus, shear modulus, and tensile strength of 3D-printed composite structures.

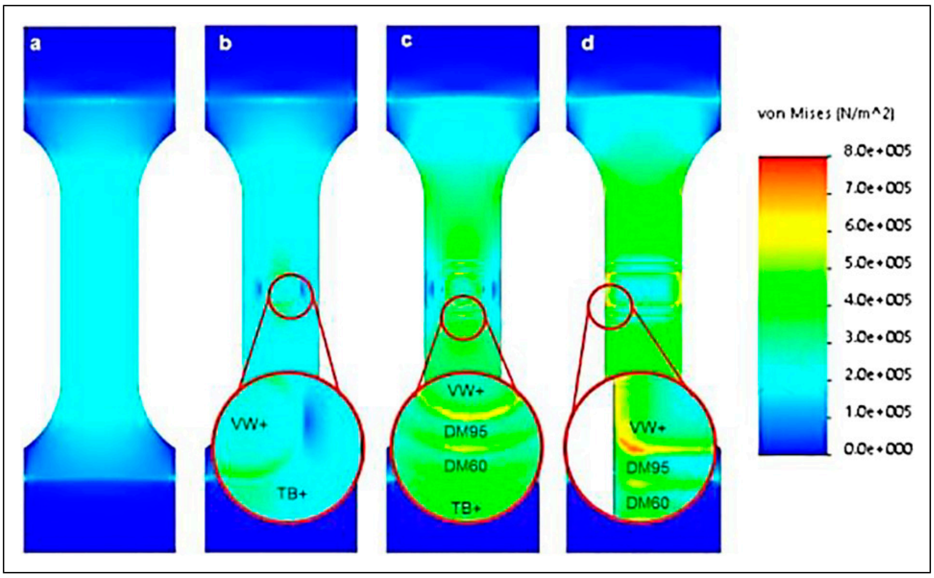


Figure 9. FEA for estimating the strength of the AM fabricated composite specimen.[16]

Rule of mixture and modified rule of mixture

Young's modulus of elasticity for 3D-printed composite structure is governed by the mechanical characteristics of its constituents, nature of loading, and the volumetric ratio of particulates. The (ROM) rule of mixture,[9,121] often referred to as the Voigt–Reuss (VR) theorem is widely used to determine the elastic modulus of 3D composite structures. The orientation of the reinforcement[129] greatly influences the mechanical properties. According to the ROM, the relationship between the longitudinal and transverse elastic moduli for laminates is expressed as

$$E_1 = E_r V_r + E_m V_m \tag{1}$$

$$1/E_2 = V_r/E_r + V_m/E_m \tag{2}$$

where E_2 and E_1 represent the transverse and longitudinal elastic modulus, E_m and E_r are elastic moduli of matrix and reinforcement structures, V_m and V_r are volume fractions of matrix and reinforcement structures. Further, the modified rule of mixture (MROM)[122–124] considers factors such as fiber orientation and fiber length while estimating the strength of the 3D-printed composite structures. The following equation is used to estimate the tensile characteristics of short fibre AM composites

$$\sigma_c = \gamma_1 \gamma_2 \sigma_f V_f + \sigma_m V_m \tag{3}$$

γ_1,γ_2 are the factors signifying fibre length and fibre orientation; σ_c, σ_m denotes the strength of the composite structure and matrix, respectively; and V_m and V_r are volume fractions of matrix and reinforcement structures. When the fibre length is constant and equal to L, and the fibre orientation variable becomes one and then the parameters γ_2 is defined as

$$\gamma_2 = L/2L_c \tag{4}$$

where L_c is the critical fibre length and $L < L_c$.

Modified Kelly and Tyson model

Modified Kelly and Tyson model[10,23] accurately predicts the mechanical characteristics such as elastic modulus, shear modulus, and Poisson's ratio of short fibre-reinforced AM composite structures where the size and alignment of the reinforced fibers must satisfy the assumptions that reinforced fibers must be longer and shorter than the length of critical fibre. For various orientations, the relationship of the reinforced AM structures is as follows

$$\sigma_c = \gamma_1 \left[\sum_{L_{\min}}^{L_c} \frac{v_i\, \sigma_f l_i}{2L_c} + \sum_{L_c}^{L_{\max}} v_i \sigma_f \left(1 - \frac{l_c}{2l_i}\right) \right] + \sigma_m V_m \tag{5}$$

where L_{min} and L_{max} depict the minimum and maximum critical fibre length, L_c, respectively; V_i represents the volume fraction of matrix and fibers in reinforced AM structure; and σ_c and σ_m denotes the strength of the composite structure and matrix, respectively. However, since polyjet AM objects often include a large amount of void space, modifications may be necessary when employing such techniques to AM products.

MESOTEX model

MESOTEX model[125,157] predicts the mechanical properties of the laminar AM composite which are fabricated by stacking two or more sheets or plates bonded together in a certain orientation. Although the AM reinforced structures provide superior mechanical performance, still the overall strength is dependent on the interfacial adhesion, stress distribution, and the orientation of the laminates. The strength of the composite structure is determined by the weakest interfacial adhesion point between the constituent materials. For various orientations, the relationship of the reinforced AM structures predicting stiffness *'S'* of the woven AM composite follows the matrix[125]

$$S = \begin{bmatrix} S'_{11} & S'_{12} & S'_{13} & 0 & 0 & 0 \\ S'_{21} & S'_{22} & S'_{23} & 0 & 0 & 0 \\ S'_{31} & S'_{32} & S'_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & S'_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & S'_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & S'_{66} \end{bmatrix} \tag{6}$$

where S_{ii} denotes the stiffness of the composite structure for the *'i'* element in the AM laminate composite structure. The elements of the S_{ii} matrix are expressed as

$$S'_{11} = \frac{1 - v'_{23}\, v'_{32}}{E'_2 E'_3 \theta'} \tag{7}$$

$$S'_{12} = S'_{21} = \frac{v'_{21} + v'_{23}\, v'_{31}}{E'_2 E'_3 \theta'} \tag{8}$$

$$S'_{22} = \frac{1 - v'_{13}\, v'_{31}}{E'_1 E'_3 \theta'} \tag{9}$$

$$S'_{23} = S'_{32} = \frac{v'_{32} + v'_{12}\, v'_{31}}{E'_1 E'_3 \theta'} \tag{10}$$

$$S'_{33} = \frac{1 - v'_{12}\, v'_{21}}{E'_1 E'_2 \theta'} \tag{11}$$

$$S'_{13} = S'_{31} = \frac{v'_{31} + v'_{21}\, v'_{32}}{E'_2 E'_3 \theta'} \tag{12}$$

$$\theta' = \frac{1 - v'_{12}v'_{21} - v'_{32}v'_{23} - v'_{13}v'_{31} - 2v'_{13}v'_{21}v'_{32}}{E'_2 E'_3 \theta'} \tag{13}$$

where v' indicates volume fraction of the laminate in the reinforced AM composite and E' denotes elastic property of the elements.

A good agreement has been found between practical and analytical results where the error is verified by computing the root mean square value.[16,61] Probabilistic models are utilized to minimize the degree of uncertainty associated with the results. The viscosity of the molten metal has a considerable influence on the backpressure created when analyzing the model during the printing process. The best-fitted regression model (for volume fraction <0.2) precisely predicts the value of young's modulus of the 3D printed specimen. However, when the engineering strain surpasses 0.25, the simulation results deviate somewhat from the

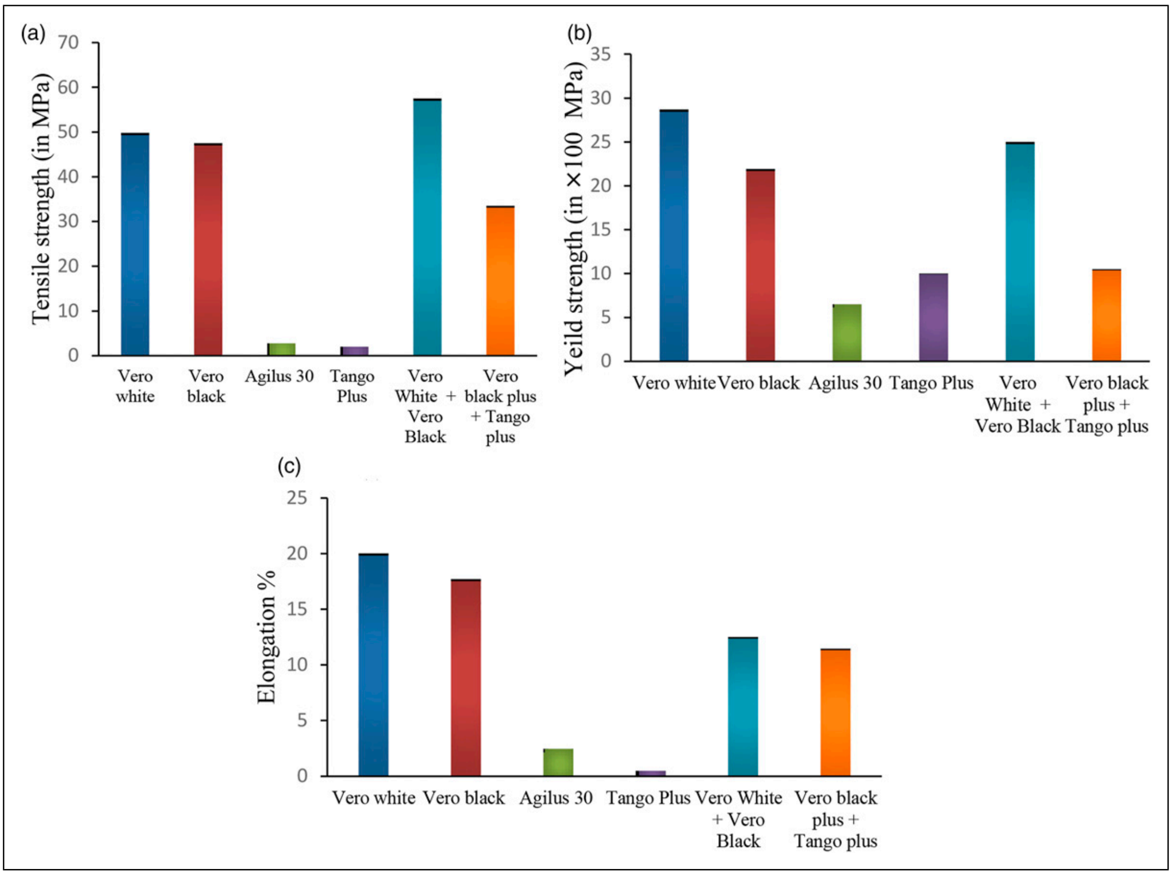


Figure 10. (a) Comparison of tensile strength for thermoplastic polymers, (b) comparison of yield strength for thermoplastic polymers, and (c) comparison of percentage elongation for thermoplastic polymers.

experimental data since the curvature of the geometry becomes a difficulty for mesh generation of experimental and validation data in terms of strain.

According to Wohlers Associates' report, photopolymer-generated prototypes account for almost half of the 3D printing market in industrial sectors.[126] Mechanical characteristics of the photopolymer play a crucial role in the fabrication of polyjet AM parts. The overall mechanical performance of a 3D printed component is governed by the printing accuracy and the strength of the thermoplastic resin employed. The polyjet technique is claimed to be one of the most accurate printing methods having a printing accuracy of ±0.16 mm. Furthermore, polyjet-printed thermoplastics offer a wide range of materials,[2] including stiff, opaque, translucent, rubber-like, and brittle. These thermos-plastics polymers possess high fatigue, tensile, and torsional strength that ensembles the requirement of most of the mechanical components. Multi-material composites provide improved mechanical characteristics in a variety of applications. A mechanical component is typically subjected to tensile, shear, and torsion loads [1100]. The tensile strength is the highest tension load that a fastener will withstand until failing whereas flexural strength is concerned about the material's susceptibility to deformation. Rigid polyjet thermoplastics are widely used in the additive manufacturing industry owing to their high tensile strength, which ranges between 50 and 65 MPa. Failure typically occurs due to a combination of forces that causes cracking. A polymer with a greater percentage of elongation is ductile, while a material with a reduced amount of elongation is brittle. Polyjet thermoplastics provide a wide range of materials with variable percentage elongation.Rubber-like thermoplastic polymers such as Agilus 30, Tango Plus, and Tango Grey have elongation percentages ranging from 5 to 25 percent. Digital materials are generated by mixing two or more polyjet photopolymers in precisely controlled concentrations and microstructures to form a composite material with hybrid properties. The mechanical properties of various polymers are illustrated in Figures 10(a)–(c) which compare the tensile strength, yield strength, and percentage elongation for rigid thermoplastics, rubber-like thermoplastics, and digital polymers. It can be noted that polyjet-printed thermoplastics fulfill a wide range of design criteria—resilience, stability, chemical, and corrosion-resistant, as well as being lightweight. Polyjet-printed thermoplastics are utilized in a wide variety of goods and industries due to their cheap cost, simplicity of production, flexibility, and water resistance. With the ever-increasing demand for 3D printing products, fabrication and testing standards offer a critical basis for the technology's broader implementation. Numerous fabrication standards have been established over time to enhance and ensure the safety and quality of 3D printed products and for calibration of additive manufacturing machines. ISO (International Organization for Standardization) and ASTM (American Society of Testing and Materials) are two independent international organizations that work to maintain the quality, safety, and efficiency of 3D printed products.

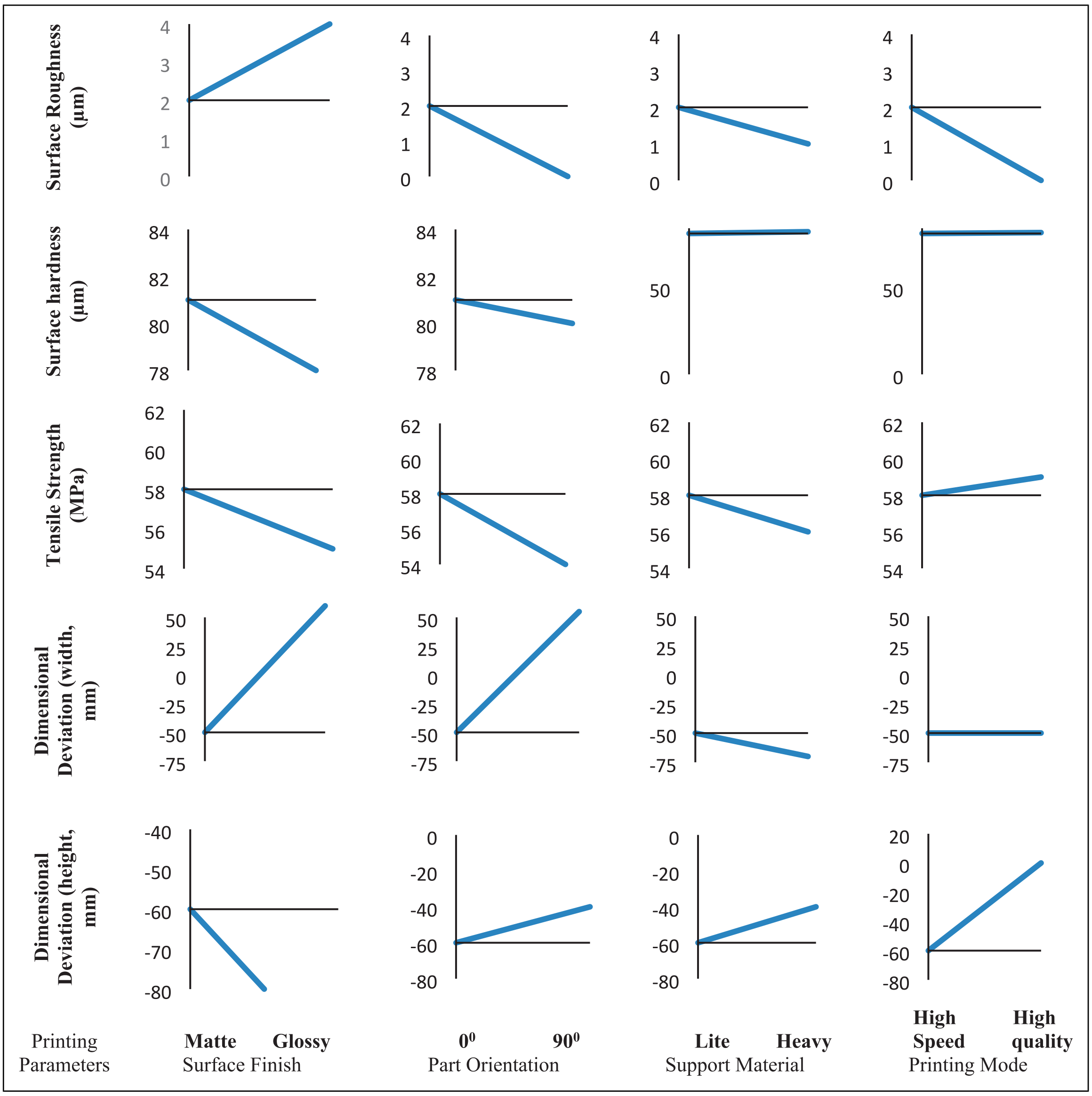


Figure 11. ANOVA results for surface roughness, surface hardness, tensile strength, dimensional deviation (width) dimensional deviation (height) for Vero Grey thermoplastic.

Polyjet printers have their own set of print settings such as component orientations, support materials, printing speed, and surface quality that determine the mechanical properties of the manufactured specimen. Experiments have been carried out to investigate the interdependence of numerous elements in the additive fabrication of molds. Figure 11 shows the ANOVA approach is used for experimental design in the polyjet 3D printing process to determine the best outcomes for mechanical parameters such as surface roughness, surface hardness, tensile strength, and dimensional deviation of fabricated products.[127] Changing the surface finish of the AM molds from glossy to matte reduces surface hardness, tensile strength, and dimensional deviation, but changing the part orientation from 0° to 90° increases dimensional deviation, tensile strength, and reduces surface roughness. The mechanical characteristics of the manufactured sample are also influenced by the support structure in polyjet AM. Surface roughness, tensile strength, and dimensional deviation all decrease when the support material is changed from heavy to lite. Moreover, the printing speed has a significant impact on dimensional variation and surface roughness. The ideal settings for obtaining the desired mechanical characteristics of the molds are shown in Table 4. The printer reports a reduced surface roughness when it is set to Matte-900-Heavy-High quality and increased surface hardness when it set to Matte-00-Heavy-High quality. To increase the tensile strength of the molds, the printer parameters are Matte-00-Lite-High quality and to minimize the dimensional deviation parameters are maintained at Glossy-900-Lite-High speed.

3D printing and testing standards

ASTM committee 42 published a report[63,128,129] on additive manufacturing which sums up the standard practices regarding the design aspect of the additive manufacturing standards for various technologies like FDM (fused deposition modelling), SLS (selective laser sintering), SLA (steriolithography), SLM (selective laser melting), LOM (laminated object manufacturing), EBM (digital beam

Table 4. Polyjet printing settings for the optimum mechanical characteristics.

Parameters	Surface roughness (μm)	Surface hardness (μm)	Tensile strength (MPa)	Dimensional deviation (height, mm)
Surface finish	Matte	Matte	Matte	Glossy
Part orientation	90°	0°	0°	90°
Support material	Heavy	Heavy	Lite	Lite
Printing mode	High quality	High quality	High quality	High speed

melting) and also illustrate fabricating standards such as ASTM D-638,[96,105,130] ASTM D-790,[62,131] ASTM D-2240,[63,105] ASTM D-412,[105,132] ASTM D-882,[133] ASTM D R178:1975,[105,134] ISO 527-1:2012,[135] ISO 527-2:2012,[136] and ISO 604:2002.[137] Numerous mechanical tests such as (a) bending, (b) compression, (c) tensile, (d) (DSC) differential scanning calorimetry, (e) (TGA) thermal gravimetric analysis, (e) thermal imaging, and (f) (SEM) scanning electron microscopy have been conducted to determine the mechanical and fractographic properties of various 3D printed materials. Tensile tests[86,87,91,138] are conducted on 3D printed specimens to explore their yield strength under the tensile load whereas compression tests[16,87,96,139] are performed to determine material's behavior under crushing loads necessary for the fabrication of equipment in biomedical, aerospace, military, automobile, and jewelry. Bending tests[6,13,14,140] are performed to measure a material's ductility or resistance to fracture which is necessary for the fabrication of structures such as beams, struts, and columns. TGA[88,141] is a thermal analysis technique where the mass of the samples is observed against temperature or time in a controlled environment. SEM[62,96,115] is intended for direct examination of hard object surfaces that use a light source for examining the large-sized polyjet lattices based on the compressive peak strengths. Mechanical performance of a variety of novel designs fabricated using ABS (acrylonitrile butadiene styrene)[142] indicated a 54% increase in fracture toughness. The ductile and flexural characteristics of FDM-3D printed composite specimens[5] such as PEEK, CF/PEEK, and GF/PEEK were examined, and the maximum mechanical performance was found at a nozzle temperature of 440°C. The numerical investigation[163] of the melting process in fused filament fabrication is complemented by experimental observations obtained using temperature-modulated differential scanning calorimetry (TMDSC) on spherocylindrical particles in Ref. 83. Figure 12 shows the 3D printed sample under compression, three-point bending, and tension test. It is noticed that no ASTM criteria for curing 3D printed specimens have yet been established. Also, there are no criteria for the quality control given on the raw polymeric material before printing. In addition, the absence of standardization for a variety of melt characteristics, such as melt viscosity or melt index, for extrusion processes such as polyjet AM results largely in anisotropic characteristics in printed specimens.

Industrial applications of polyjet additively manufactured

A variety of advancements in the fabrication of thermoplastic polymers using the photopolymer jetting technique is reported in the last 5 years [1541-162]. The polyjet AM methods and research fields are illustrated in Figure 13. This manufacturing technique has expanded the scope for three-dimensional printing of MFMS (multifunctional materials frameworks) and soft digital material.[148] Polyjet 3D printers have a wide range of use in the healthcare industry. The Jacobs Institute,[149] a leading medical innovation center, is utilizing polyjet AM to fabricate patient-specific vascular anatomy, allowing surgeons to perform surgery at patient reference points before complicated operations using Agilus 30 photopolymer resin. The dimensional precision of medical and dental implants manufactured using polyjet AM is claimed to have a dimensional error of 2.14%.[150,151] The mechanical properties of polyjet-fabricated lattices such as BCC and FCC are superior to those fabricated via traditional printing methods.[152,153] The three-dimensional mapping and printing of the human heart have been made possible with polyjet 3D printing. Medical training and preoperative preparation are facilitated by the AM-fabricated cardiac models. Polyjet-manufactured propeller[154] is manufactured as an end-use component that precisely aligns with the drone's motor shaft. Numerous features of polyjet 3D printing are inherently desirable in the context of fashion, clothes, and accessories.[155] It enables customers to customize the garment's size, color, material and even can provide the flexibility to fabricate 3D unique customized apparel. Numerous polyjet-fabricated safety equipments such as a biker's helmet are fabricated of thermoplastic resin that is capable of ensuring the driver's safety during accidents. Polyjet printing is widely utilized in the footwear industry[156] to expedite product development and to customize particular footwear features for a shorter product design cycle. The printing technique enables the fabrication of shoe soles with varying extents of density and stiffness allowing the designer to customize the product for improved mobility and fit using Stratasys J750 3D printer. This technique is extensively used in the motorsports industry to manufacture functioning components for automobiles including brake parts, suspension valves, and front and rear lights. The 3D printed light cover casing of the automobile rear light[157] is illustrated in Figure 1(f). The multi-material extrusion food 3D printing[158,159] is being widely used to manufacture complex-shaped eatables from semisolid, liquid, and foam materials such as chocolate, chips, processed meats, and meringues. With the surge in health trends and nutritional supplements, creating nutritionally focused edibles is a widely used approach that is being personalized to the individual. Creating protein-rich meals for individuals with dysphagia has been a significant use of 3D food printing utilizing liquid bioprinters with segmented ingredients. Polyjet technique is making it possible to create perfectly adapted medical devices[160] from casts to prosthetics. It is widely used to fabricate implants,

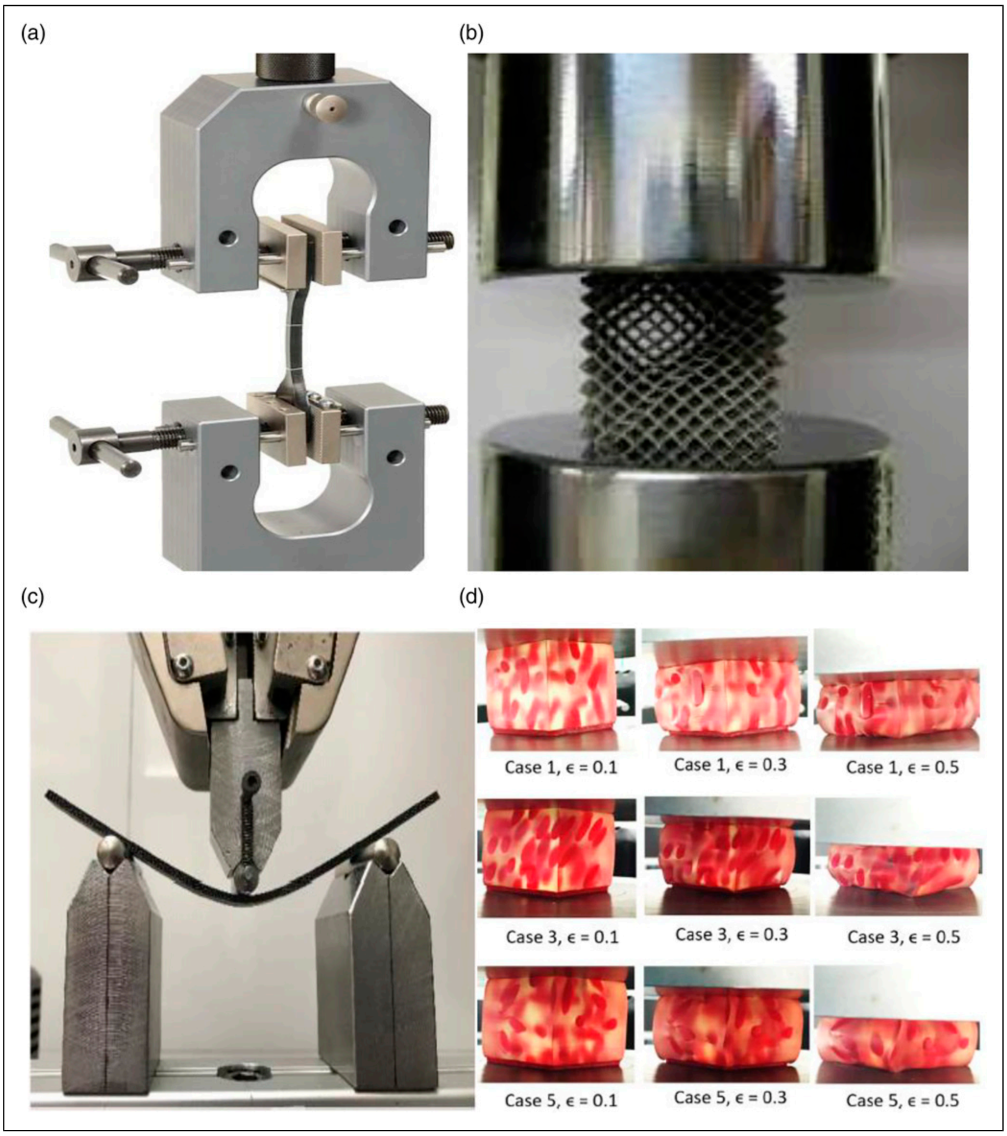


Figure 12. 3D printed sample under (a) tensile test, (b) compression test for polyjet AM lattice,[144] (c) three-point flexural test,[145] and (d) compression test for multi-material AM structure.[145]

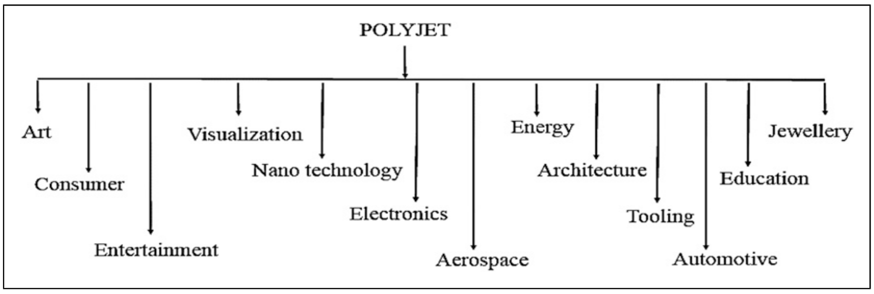


Figure 13. The polyjet method and various research field.

tools for surgeons, and to print 3D models of kidneys, heart, and foot to provide medical training and education. Among the most difficult aspects of anatomy is the structure of the skull. The precise skull models[161] for anatomy education have been widely constructed using polyjet technology. The aerospace sector[162] makes extensive use of polyjet 3D printers. High-performance thermoplastics are utilized to create jigs, clamps, check gauges, and finished aircraft components for precise prototyping that includes stiff, rubber-like, and transparent materials. Polyjet additive manufacturing has emerged as a cost-effective and flexible technique for fabricating multi-material functional composites. Designers and architects worldwide are increasingly using 3D printing to create almost every type of product and structure. As the complexity of the product geometry increases, AM is proven to be more reliable with fewer inventories, less tooling required, and minimal material wastage. With the fast advancement in 3D printing

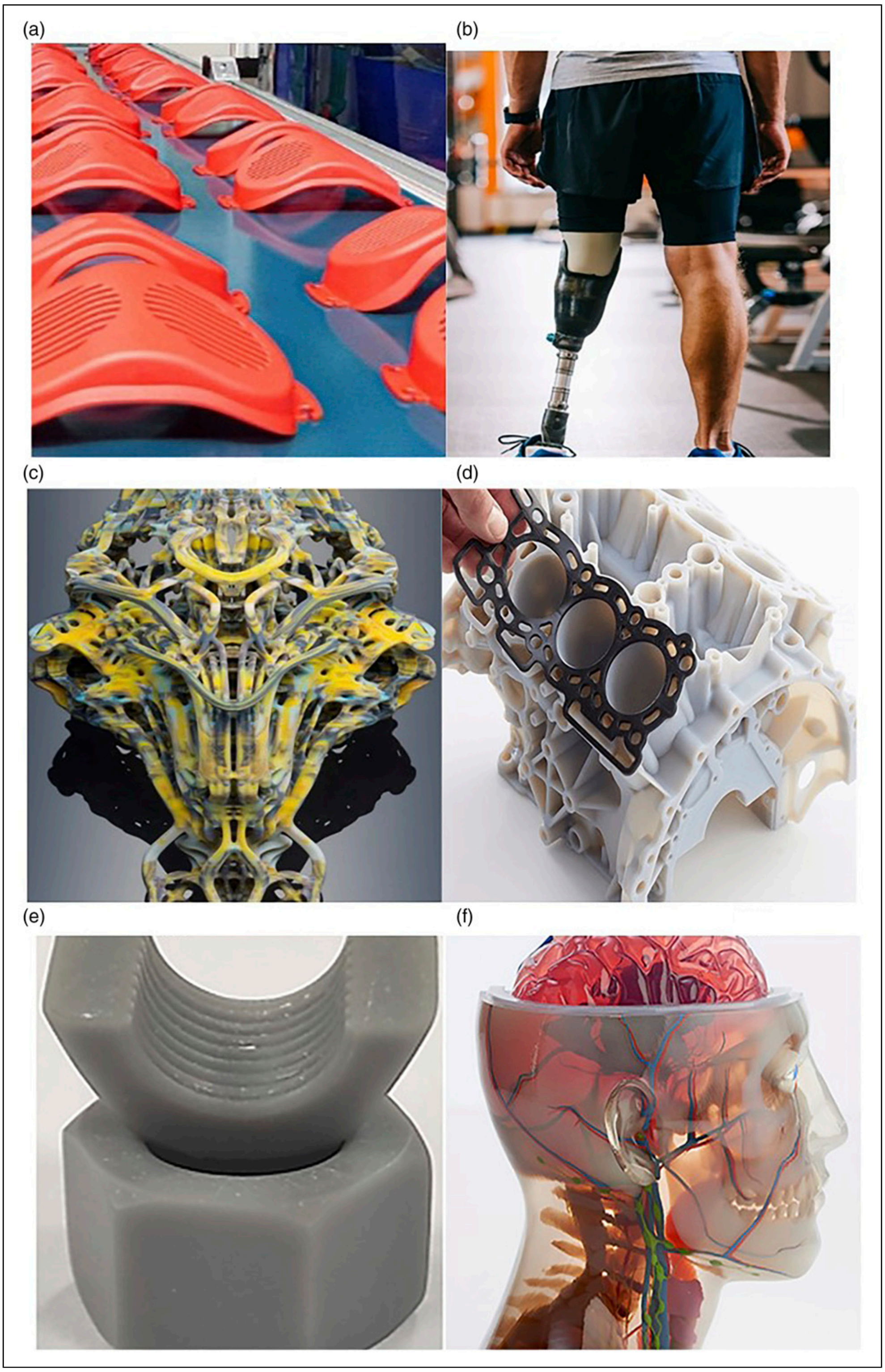


Figure 14. Multi-material 3D printed industrial products using polyjet technology: (a) 3D printed COVID-19 face masks,[163] (b) prosthetic leg implant,[164] (c) polyjet-printed wolfkiam,[165] (d) polyjet-fabricated engine block,[168] (e) polyjet-fabricated M8 nut, and (f) vascular anatomical AM model.[169]

reliability and mass production capabilities[64,156] and additive manufacture of conventional mechanical components such as fuel tanks, air ducts, horse sculptures, the water pump is emerging as a cost-effective manufacturing solution. Major construction equipment manufacturers, including volvo construction equipment (VCE),[11] use the polyjet AM method to fabricate 3D printed pump housing structures. The most recent 3D printing attempts against COVID-19 are reported where biocompatible face masks[163] are being rapidly manufactured to tackle the worldwide shortage of masks and other medical equipment. Face shields and PPE (personal protective equipment) kits are extensively manufactured for healthcare professionals for eliminating the COVID-19 infection. Figure 14(a) illustrates a face mask fabricated via photopolymer jetting. Polyjet technology[164] is rapidly being used to create high-tech, flexible, and versatile bespoke prosthetic 3D printed limbs for amputees. Patients can walk and participate in recreational and athletic activities. Figure 14(b) illustrates a prosthetic AM lower limb implant. Polyjet-printed components provide a substantial weight reduction, resulting in significant cost savings. Polyjet printing has become a significant tool in the fashion industry owing to its rapid production, versatile designs, and minimal wastage.[165,166] It is extensively utilized in the production of jewelry and art embellishments,[167] with the potential to replace conventional gems. Figure 14(c) depicts a 3D printed Wolfkiam design fabricated using various colored photopolymer resins on an Objet printer. The sculpture incorporates bright colors and complex details displaying a feeling of movement and fluidity, as well as symbolizing traditional cultural traditions. The use of materials with a high strength-to-weight ratio in internal combustion engines are becoming increasingly essential as fuel efficiency improves, thus reducing pollution. Figure 14(d) depicts a polyjet-fabricated lightweight engine block that can resist high temperatures. The proposed design is reported to give a 25% weight reduction.

Plastic and nylon fasteners are increasingly utilized in numerous fitting applications. There are currently no published standards for additive manufacture for plastics using photopolymer jetting technology. A study is conducted to evaluate the quality of additively manufactured specimens and to develop a fabrication standard for thermoplastic products manufactured using photopolymer jetting technology.

Figure 14(c) depicts a polyjet fabricated completely as well as a half M8 nut depicting internal threads for determining the fit of the components. These were subjected to two-dimensional as well as three-dimensional inspection under the Carl Zeiss COMET L3D2 3D scanner. It was realized that 3D printed fasteners using photopolymer jetting technology conformed to the IT 06 clearance fit grade. Polyjet technology is used in a variety of cardiovascular applications to create patient-specific multi-color and multi-material 3D models for medical education, research into valve and vessel performance, and surgery planning. Figure 14(f) illustrates a typical multi-material cardiovascular prototype. Lower limb prosthesis has increased globally, making it more difficult for patients to recover movement and independence. Table 5 summarizes the recent fabrications utilizing polyjet technology, and Table 6 enlists various multi-material additive manufacturing using the photopolymer jetting method[12,13,144,148] and the material extrusion method.[14–16]

Challenges of polyjet additively manufactured

Along with all the benefits, polyjet printing consists of its own set of constraints and limitations. First and foremost, identifying the optimal print parameters in photopolymer jetting that influence the essential characteristics of a printed component is crucial. Table 7 summarizes the different printing modes that influence the mechanical characteristics of the manufactured specimen, including component orientations, support materials, printing speed, and surface quality. As a consequence, an examination of the different printer settings is required to fine-tune the output in terms of both strength and accuracy. Limited research has been performed on the thermal and electrical properties of polyjet-printed products. More research into novel printable materials should be conducted to manufacture devices that meet both mechanical and electromagnetic criteria. More efforts are needed on the development of hybrid materials to satisfy the requirements of the industry. There is also a

Table 5. Overview of the printer manufacturer, printing materials, property evaluation, and application of photopolymer jetting additive manufacturing.

Ref	AM process	Material	Application	Remarks
Bandyopadhyay et al.[142]	Polyjet	Vero White Plus, Vero Clear-RGD-810, Black FLX973, Tango Black Plus FLX980	Triply periodic minimal surface, fiber-reinforced AM composite, 4D printed self-assembly of components	Polyjet-fabricated multi-material structures exhibit increased hardness, corrosion resistance, and chemical stability compared to traditionally manufactured structures
Vdovin et al.[147]	Polyjet	Fullcure 720™ and Vero white 830™	Acoustic meta-materials	Polyjet-fabricated meta-material samples enhances the sound absorbing capacity
AbuElmagd et al.[150]	Polyjet	Vero Magenta™, MED 610, MED 670	Surgical implant: Maxilla and mandible	Surgical implants manufactured using polyjet reports excellent flexibility, fine resolution, and high dimensional precision
Ibrahim et al.[151]	Polyjet	Acrylic resin, MED 690	Dental implants	2.14% dimensional error is reported in polyjet AM dental crowns, stone modules, bridges, dental wax, and cups
Liu et al.[152]	Polyjet	Vero White Plus RGD-835	Maximization of mechanical properties and solves support exclusion problem	Polyjet-fabricated snap-fitted lattices enhances the strength, energy absorption lattices
Gay et al.[153]	Polyjet	RGD240 acrylic photopolymer	AM automotive bumpers, helmets, foams	Enhanced mechanical performance of polyjet-fabricated flat parts under static and oscillating loads

Table 6. Summary of the printer manufacturer, typical materials, property evaluation, and application of multi-material additive manufacturing.

Ref	AM process	Material	Application	Remarks
Somireddy et al.[13]	Polyjet	Tango Black plus and Vero White plus	Stress reduction at the heterogeneous material junction	Enhanced fatigue strength of polyjet-fabricated polymeric composite
Archez et al.[14]	Fused fabrication filament	Alumina silicate composite (M1, M2, and A650)	Slump reduction during printing of geopolymer composite	Enhanced mechanical features, microstructural, and bond strength of the printing material's layers
Severseike et al.[15]	Fused fabrication filament	ABS and short carbon fiber	Classical laminate structures	Anisotropic behavior of laminated structures is highly influenced by the material composition and build orientation
Salcedo et al.[16]	MJT (material jetting)	Tango Black Plus^{TM}, DM95, and DM60	Functionally graded materials, silicon molding, painting, movable parts, dyeing	Accurate prediction of distortion behavior of multi-material structures to predict maximum strain
Haghighi et al.[144]	Polyjet	Tango Plus ^{TM} and Vero Clear RGD-810	Roller guides, plastic gears, bushes	Optimized polyjet printing settings to reduce dimensional clearance in assembled components
Slesarenko et al.[148]	Polyjet	DM 40, DM 50, DM 60, DM 70, DM 85, DM 95	Visco-elastic materials, soft rubber-like digital material	Enhanced mechanical performance of polyjet-fabricated digital materials

Table 7. Printing Parameters for photopolymer jetting.

Printer's parameters	Control levels	
Support material	Heavy	Lite
Print mode	High speed	High quality
Print orientation	0°	90°
Surface finish	Matte	Glossy

massive possibility of exploring lightweight and high-strength smart materials which could bear harsh environment zones such as extreme heat and cold storms, fire hazards, blasts, and high shocks.[170] Therefore, the availability of material restricts the application of certain print modes. It is noted that no ASTM standards for curing 3D printed specimens have been specified. Moreover, numerous fabricating and testing standards must be developed to ensure the universal adoption of polyjet additive manufacturing. Also, efforts are needed for completing finite element modeling of 3D printed multi-material polymeric structures for diverse loading conditions to precisely investigate the behavior of such materials. It is seen that the nonlinear behavior of the material is ineffectively predicted by finite element analysis. Hence, a novel approach is needed to be developed to demonstrate the capability of the model. Moreover, the formation of temperature gradients while the polyjet is printing the structures,[171,172] the development of large residual stresses in fabricated structures,[49,173] and poor interlayer adhesion among the 3D printed layers[174] limits the functionality of photopolymer jetting printing. The polyjet AM technique builds components layer by layer while curing the photopolymer resin, resulting in a temperature gradient. Hence, the presence of anisotropy in the microstructure of the polyjet-fabricated specimen affects its mechanical characteristics.[175]The microstructure and mechanical characteristics of polyjet-fabricated components vary significantly depending on the build direction. The development of voids[79] between successive layers of photopolymer resins arises as a result of insufficient layer bonding, resulting in the poor mechanical performance of fabricated parts. The development of a staircase effect[176] in additively manufactured components is a challenge in the polyjet-AM process. It has a major impact on the quality of internal manufactured surfaces.

Significance of polyjet additively manufactured in 4D printing

4D printing is viewed as a significant advancement over 3D printing since it employs the same types of additive processes like 3D printing but with the help of polymers which are designed to respond to sophisticated external stimuli. This method is based on the utilization of advanced materials with exceptional shape-changing capabilities. Polyjet AM is capable of controlling the structure's heterogeneity that may influence the starting sites of SME (shape memory effect), thereby improving the capacities of 4D printing. Commercial polyjet 3D printers are widely utilized in 4D printing of intelligent materials such as shape memory polymers and hydrogels for fabricating structures.[177,178,179] These materials are highly utilized in smart plumbing, fitting devices. Rapid innovations have extended the capabilities of polyjet AM to enable multi-material 4D printing. The medical, automobile, aviation, and retail sectors are anticipated to be the primary end-users of 4D printing technology. An auto-folding hydrogel shape memory composite[180] bounded by shape memory polymer and elastomeric films is fabricated using polyjet-AM. Figure 15 displays the shape change property when immersed in low-temperature followed by high-temperature water. National Aeronautics Space Administration has designed an adjustable fabric chain mail to be used as a covering in spaceship antennae.[181] Another significant advancement has been achieved by the University of Michigan which has designed a 4D AM airway splint to

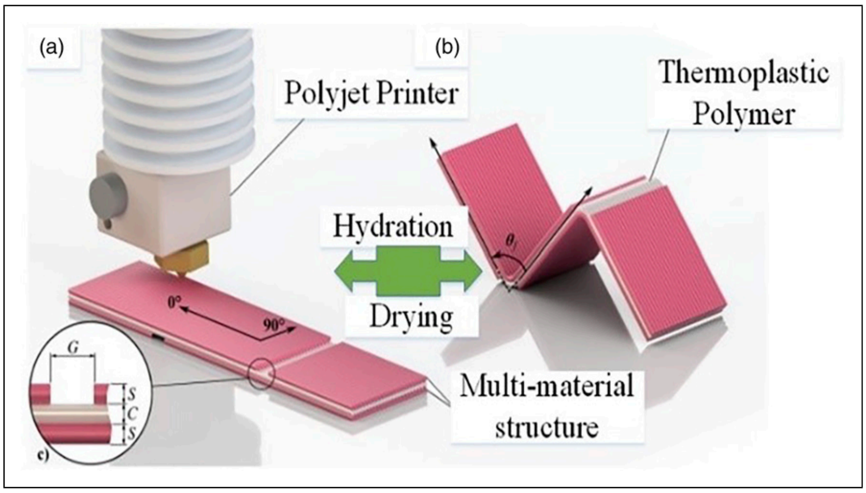
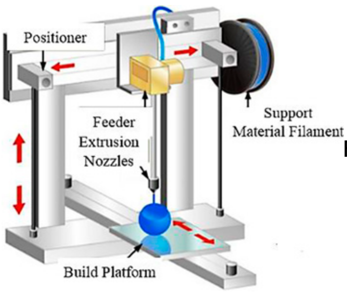
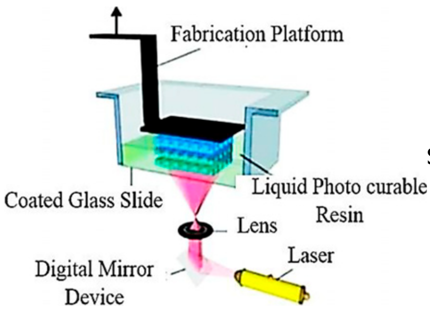
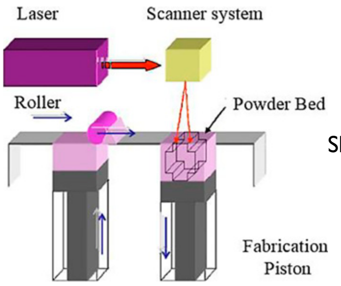
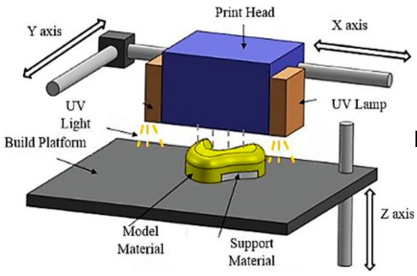


Figure 15. 4D printing of multi-material structures.

Table 8. Comparison table on the performance of numerous AM techniques reported for various industrial applications.

Ref	Fabrication Technique	Benefits	Limitations
66,68,181,183,184	 FDM	• Scalable • Less fabrication time • Cheapest fabrication technique • Rapid printing speed • Availability of broad range of thermoplastic materials • Suitable for mass production	• Poor 3D resolution • High surface roughness • Warping of fabricated products
69,70,185,186,187	 SLA	• High precision • Small features possible • Isotropic mechanical properties • Smooth surface finish of fabricated objects • Multi-material production • Used for rigid and flexible parts	• Smaller material range • Requires more post-processing • Curling of fabricated products • Extra wastage of resin during post-processing • Expensive manufacturing technique
71,72,187,188	 SLS	• Enhanced quality of the components • High strength of the product • Support-less fabrication possible • Fabrication of end-use products • Effective layer bonding • Multi-functionality of 3D printing	• high fragility of fabricated components • expensive printers • Not suited for mass production
87,95,189,190,191	 POLYJET	• High resolution • Accuracy of ± 0.12 mm • Low surface roughness • Multilayer and intricate fabrication possible • Multi-material and multi-color printing • Fabrication of end-use products • High fabrication speed • Easy post-processing • Suitable for cosmetic porotypes	• Not suitable for outdoor environment • High fabrication cost for large volume productions

closely track children's development.[182] Substantial advances have also been made in the sports and fashion industry. The University of Michigan and the Massachusetts Institute of Technology have developed self-assembling footwear and a self-inflammable silicone compound that changes form and size in response to air pulses.[183]With this approach, scientists and manufacturers will be inspired to develop innovative multi-responsive dampers and actuators. Next-generation soft robotics is expected to use polyjet-AM-derived more sensitive materials for a wide range of applications. Significant research efforts will be undertaken in the future years to initiate the development of smart materials, soft robotics, hydraulic, and pneumatic field. Self-healing roads and bridges may be implemented along the lines of 4D AM in the building sector. Although polyjet AM in 4D printing is in the initial stage of the research, but swift and significant advancements in this field have offered several promising possibilities. Finally, a comparison depicting the advantages and disadvantages of various fabrication techniques is shown in Table 8. All the benefits and drawbacks of the various manufacturing techniques are presented. Along with polyjet printing, FDM, SLA, and SLS are reported. Polyjet printing is proved to be beneficial in numerous ways including microscopic resolution, high fabrication accuracy, high fabrication speed, and low surface roughness. Polyjet printing has the capability of producing multi-color prints. Its ability to print several substrates at the same time enables the fabrication of complex and potential industry-based composite structures.

Conclusion and discussions

High-resolution polyjet 3D printing has revolutionized the rapid prototyping process. Multiple print heads in this method enable multi-material and multi-color printing of a wide variety of polymers, displaying the ability to change structural homogeneity by modifying material deposit ratios. Few remarkable key findings are summarized:

- High-precision polyjet printing technology is extensively fabricating medical functional components such as patient-specific neuro-vascular architecture with a dimensional deviation of less than 120 µm.
- Polyjet-manufactured durable leg implants and safe, nontoxic face masks are enormously being manufactured.
- Polyjet printing has lowered production costs and time by 60.86% and 14.72%, respectively, as depicted via development of a low-cost, high-quality drone propeller.
- Polyjet technology has fabricated innovative and multi-colored rear light designs in automobile sector having a variety of physical characteristics, including the transparency required for taillight prototype.
- The polyjet process enables the fabrication of robust, flexible, and chemically resistant thermoplastic washers, nuts, and bolts.

Reinforced polyjet AM structures display flexibility of design and enhanced mechanical, morphological, structural, and tribological properties of the manufactured end-use designs. Multi-material polyjet AM has also reported innovative fabrications at various scales including

- improved fatigue resistance of functionally graded voxel-based structures with various heterogeneous constituent properties;
- polyjet-printed photopolymer foams absorbing more than 90% of impact energy;
- polyjet-manufactured honeycomb structures displaying enhanced compressive strength during cyclic compression loading; and
- direction-specific characteristics of polyjet-manufactured structural laminates.

Support material, print mode, print orientation, and surface finish highly influence the durability, geometric variation, tensile strength, surface hardness, and surface roughness of fabricated thermoplastic polymers. The best-suited parameterization for the printer, as well as the best-suited material selection, is suggested to meet the specific needs of produced components. This article has further summarized numerous analytical relations for determining and predicting the mechanical properties of AM composite structures and a high degree of agreement with FEA results is seen. It is closely observed that the orientation, arrangement, and form of the filler particles have a significant effect on the AM structure's strength. Polyjet-AM provides remarkable 4D manufacturing in sports, fashion, and medical fields, but many smart materials, as well as thermos-responsive, moisture-responsive, magnet-responsive, and conductive thermoplastic, must arrive to meet a wide range of industrial applications which may result in lower manufacturing costs and high performance of 4D printed structures. Shape memory and shape-shifting technology using polyjet 4D printing have the potential to provide the lucrative option to fabricate complicated, intelligent, and long-term durable products for a range of applications such as airway Splint, hydraulic, and pneumatic grippers, soft robots, self-constructing, and shape-changing structures. The advancement of this technology may also be seen with rapid printing speeds and the development of sustainable and biodegradable printing resins.

Addressing the challenges of polyjet AM would substantially improve the fabrication quality. Insufficient interlayer adhesion is a common concern among polyjet-printed layers, limiting polyjet printing's functionality. Polyjet AM comprises of a few lightweight and high-strength smart materials that can withstand tough environmental zones. Therefore, more number of photopolymer materials should arrive that possess magnetic, thermal, and electrical characteristics. There are currently no ASTM standards for curing 3D printed specimens; hence, a lack of uniformity for a range of melt parameters, such as melt viscosity or melt index, in extrusion methods such as polyjet AM leads in a high degree of anisotropy in printed specimens. Studies can be carried out along the lines of polyjet-manufactured shape memory polymers in the coming years which can revolutionize the AM industry. Additionally, material waste may be significantly minimized via the recycling as well as post-processing of thermoplastic polymers.

Declaration of Conflicting Interests

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