Impact of Process Parameters on 3d Printed Composites and Polymeric Materials Fabricated Using Fdm Process: A Review

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Abstract:

Three dimensional printing is one of the rapidly evolved fabrication techniques, in which structures are printed by accumulating the materials layer by layer, based on 3D design data. Fused deposition modeling (i.e., FDM) is one of the frequently employed methodologies of 3D printing technology, in which filament of the material to be printed is fused and structure gets printed layer by layer. Even though, FDM is flexible enough to print wide category of polymer and composite based materials, these printed structures, in some scenarios, exhibit inferior mechanical relevant properties, due to the unsteady binding amidst the generated interior layers. Due to this inferiority w.r.t. toughness, stiffness and functional based attributes, FDM based 3D printed parts are mainly employed as prototypes, for research based investigations etc., and cannot expand its market towards several industrial scenarios, which demand for superior mechanical attributes. In this paper, recent experimental and research based investigations on FDM based 3D printing of PEEK (i.e., Polyether ether ketone) based composites, thermo-setting type polymers and continuous carbon fiber reinforced composites were reviewed. Innovations put forward w.r.t. various parts of FDM based printer like extruder by researchers to enhance the mechanical relevant properties of the printed structures were also addressed in this paper.

Keywords: *3D Printing, Fused deposition modeling, Polyether ether ketone, continuous carbon fiber reinforced composites, thermo-setting polymers*

Introduction

In this modern era, the technology of 3D printing have gained attraction in wide variety of industrial sectors including avionics, automotive, biomedical, electronics, ship building etc. Technology of 3D printing can be categorized as a rapid molding process in which the materials being melted are deposited on to a substrate layer by layer and eventually a 3D material structure is generated [1, 2]. When being compared with conventional machining processes, 3D printing can be described as an additive type of manufacturing process, which employs the principle of stacking and the melted materials are stacked one over the another (i.e., layer by layer), such that, direct printing of intricate and complex structures in three dimension is attained in a shorter duration with enhanced level of accuracy, thereby reducing the fabrication related costs [3–5].

Due to their attractive features and promising capabilities, including customization of printing attributes, the technology of 3D printing is widely preferred in several manufacturing sectors for fabricating convoluted components and parts [6, 7]. In the recent periods, much advancement have taken place w.r.t the technology of 3D printing such that, this 3D printing technology is not only employed for fabricating prototypes, but also employed to fabricate end use components and parts. As it is possible to fabricate parts and structures in three dimensions directly from a CAD based model and as the parts get printed in 3 dimensions by accumulating the melted material layers one

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over another, enhanced flexibility in printing of intricate geometrical shapes and structures is possible with this technology of 3D printing [8–10].

Fused deposition modeling

A wide variety of 3D printing technologies have evolved in the past few decades, which can be employed based on the demands of the end component and structures to be fabricated [11]. Various categories of 3D printing techniques includes direct metal deposition, selective laser melting, laser metal deposition, selective laser sintering, laminated object manufacturing, fused deposition modeling, stereolithography etc. These 3D printing techniques are differentiated based on their process potentialities, which include the methodology in which deposition of layers takes place and the nature of materials, which can be printed by them [12, 13].

For example, in the process of stereolithography, with the increase in the fiber based reinforcements, the viscosity of the fiber based resin escalates, thereby declining its process capability [14]. Some of the drawbacks of the laminated object manufacturing process are larger volume of wastage of materials and the impact of stair step. Even though, parts and structures can be fabricated with improved accuracy in selective laser sintering, the lengthier processing period and higher amount of cost act as barriers for employing this 3D printing technology to various sectors [15–17]. When being compared with all these 3D printing techniques, fused deposition modeling (FDM) seems to be more promising, owing to its reduced manufacturing cost, enhanced accuracy, simplicity of methodology, etc. [18, 19].

The process of FDM originated in the year 1990, in United States at Stratasys Limited, an American Israel based manufacturer of 3D printers. FDM is one of the extensively employed 3D printing technologies to fabricate functional based thermoplastic prototypes. In recent years, FDM has gained attraction, due to its capability to fabricate intricate parts in a safe, effective and perfect manner, within a short duration [20, 21]. In FDM technique, the parts and structures are printed in three dimensions by heating of the thermoplastic filaments, followed by extruding them through a micro sized nozzle and the path of deposition of these extruded material layers are controlled through a computer generated program. Usually in FDM, the layers of the extruded material are deposited onto the top of the previously deposited layer, so as to fabricate the required structure in three dimensions. Principle of working of FDM process is illustrated in the Fig.1. [22]

In FDM, parts and structures are usually fabricated with a three dimensional model which is then cleaved into specific number of layers as directed by a suitable slicing software and the thickness of each layer being sliced during this process is normally determined by the manufacturer. The employed slicing software then formulates a path in which the tool has to travel, so as to fill up the various boundaries of the layers. Usually, three dimensional printing of the parts in FDM begins with the generation of three dimensional models of the part or structure to be generated. This three dimensional model is then modified into STL file format and with the help of a suitable slicing type software, it is then cleaved into numerous layers. Subsequently, the intricate structures are printed in three dimensions, and then subjected to post cleaning process to attain the requirements [23–25].

Next to stereolithography, FDM is the 2nd most prominent 3D printing technology, owing to its adaptability in usage of materials, easiness in terms of portability, reduced consumption of power and equipment related cost. Another unique feature of the technology of FDM based 3D printing is that these printers can print intricate three dimensional structures using low cost thermoplastics possessing inferior melting points and these structures can be printed in shorter time, even at downgrade temperature [26]. Moreover, using the technology of FDM, parts and components can be printed at a faster rate, in a clean and economical manner and these FDM parts were found to possess superior stability w.r.t. dimension [27, 28].

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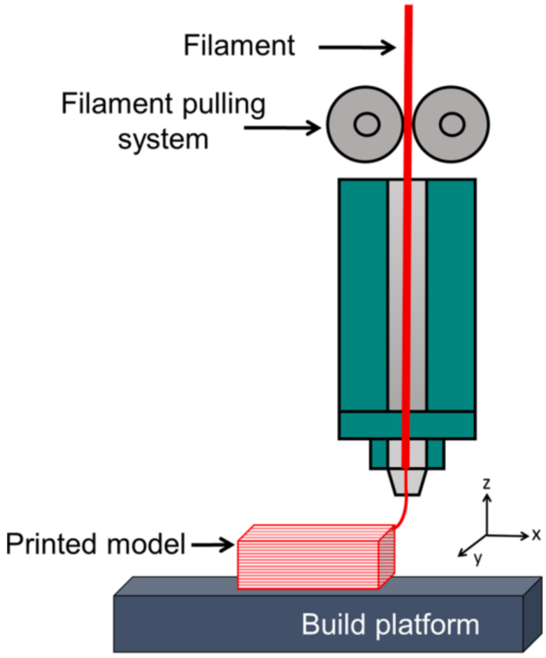

Figure 1. Principle of operation of the FDM Process as illustrated by Shanmugam et al. [22]

Parameters of FDM process

Efficiency of the 3D parts printed using the technique of FDM relies mainly on its several parameters including slice dimensions, thickness of the layer, Quality of the employed filament, nozzle specifications, percentage of infill, built temperature, distance amidst the plate and nozzle, temperature of the bed, speed of the nozzle, rate of extrusion of the filament, angle of raster, pattern of infill, levelling of the built plate, style of fill, settings relevant to height of the layer, speed of printing etc. [10, 19] Diagrammatic illustration of the various parameters of the FDM process can be seen in the Fig.2 [29]. It has been suggested by several researchers that, if these above mentioned parameters have been selected in a suitable combination, high quality three dimensional structures and parts can be printed using the technique of FDM, in a shorter duration, at a cheaper cost [3, 14].

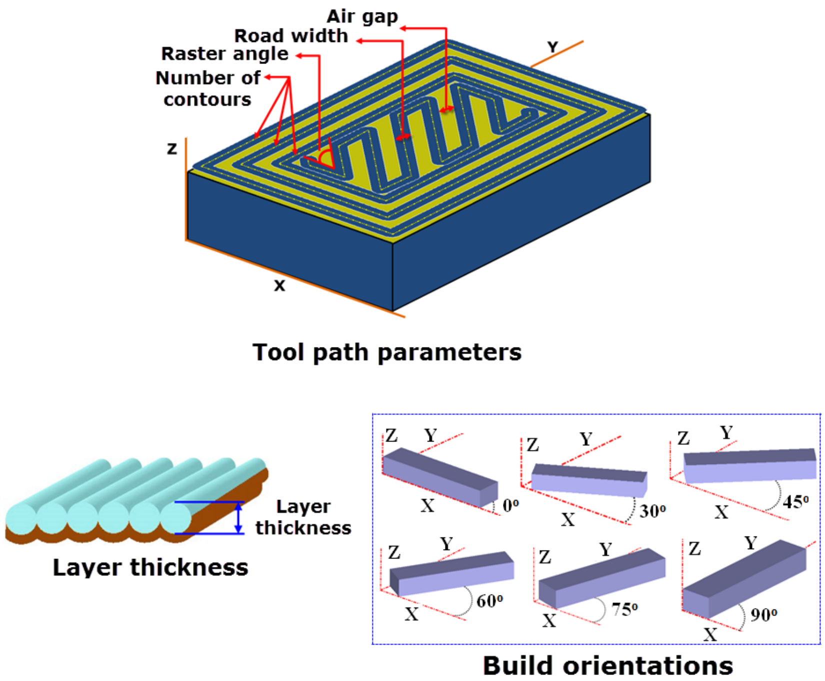

Figure 2. Various parameters of the FDM Process as portrayed by Mohamed et al. [29]

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At the same time, ambiguities prevailing in the FDM printed structures including flaws, voids, inadequate bonding of layers etc., escalate the circumstances of failure of these 3D printed parts and structures. The mechanism of failure relevant to dynamic as well as static conditions of loading during printing of polymer based three dimensional structures is also not clear. These issues severely hinder the implementation and development of this FDM technique in various sectors. For example, one of the most familiar print related failures is the occurrence of fragile binding amidst the built plate and print of 1st layer. Failures associated with print of 1st layer was recorded to happen because of improper levelling of the bed plate, improper spacing amidst the built plate and nozzle, very high speed of extrusion, inadequate filament heating, etc., and these 1st layer print failures cannot be monitored visually during large scale 3D printing of parts and structures. Thus, it can be understood that, the parameters of the FDM technique plays an inevitable part in determining the quality of the end product being printed [20, 30].

3D printing of Structures using FDM

Three dimensionally printed thermoplastics were proven to exhibit inferior mechanical properties and to overcome this scenario, some investigators have conducted experimental works, in which the reinforcing type fibers were added onto the filament of the polymer [15, 21]. Even though, the inclusion of these short nature fibers permitted the printing of three dimensional structures and parts, with improved mechanical features, the inclusion of these squat fibers inside the matrix of the polymer is restricted to only 50% of the fraction of the total fiber volume. Due to this restriction prevailing w.r.t inclusion, the structural based applications of these short fiber category reinforced filaments have been restricted. When compared with that of the short fibers, the tensile strength of the continuous fibers is 7 times higher and these continuous fibers retains about nearly 5 times the flexural strength of the short fibers [31, 32]. With the objective of overcoming these constraints w.r.t short fibers and to merge the gap prevailing amidst the traditionally fabricated composites and printed structures, several experimental attempts have been put forward to fabricate continuous carbon fiber type reinforcements in the three dimensional printed structures [8, 17].

FDM of continuous carbon fiber reinforced composites

Lower strength to cost ratio, inferiority w.r.t. stiffness and restrictions in including short fibers to plastic based matrixes have reduced the application domain of the short fiber based reinforcements. These, in turn, have motivated the researchers to fabricate continuous fiber based composites using the technology of FDM based 3D printing. Moreover, it was recorded by researchers that, these continuous fiber based composites possesses several merits including reduced fabrication related costs, enhanced mechanical features, easily recyclable etc. [6, 23].

Blok et al. [33] investigated the 3D printing of composite feedstocks, in which carbon type fibers were encapsulated into the matrix of the thermoplastics, with the intention of increasing their stiffness and strength. In this work, a typical open category fused filament fabrication type printer was employed to print short fiber (approximately 0.1mm) reinforced nylon type filaments and the continuous carbon based fiber composites were printed using a MarkOne 3D FDM printer. Fig. 3 (a) and (b) illustrate the microstructural images of the structures being printed out of short fiber carbon reinforced nylon materials.

Close observation of the printed part illustrated in Fig. 3(a) helps us to visualize the presence of triangular shaped voids amidst the printing grids during the fused filament fabrication process. Experimental tests revealed that, the 3D printing of continuous carbon based fibers employing the MarkOne 3D FDM printer have exhibited superior performance when compared with that of the short fiber reinforced filaments. It was also revealed that, the stiffness and tensile related strength of the continuous carbon fiber based 3D printed parts were 64 GPa and 986 MPa, which were higher

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when compared with that of the properties being exhibited by short fiber nylon 3D printed parts.

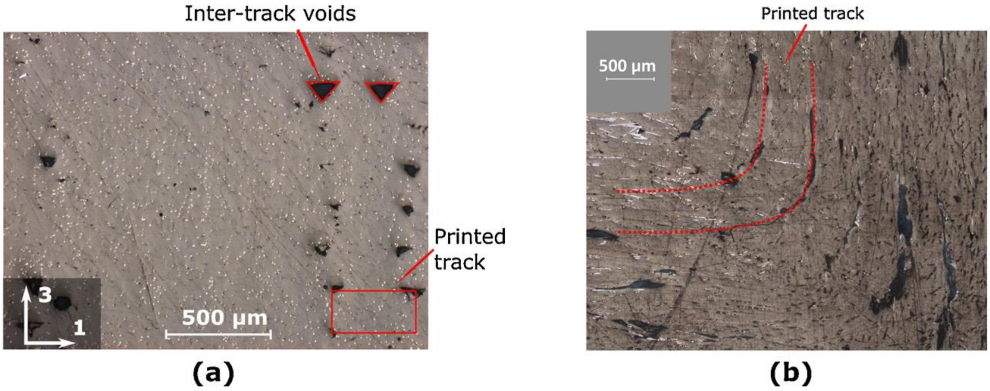

Figure 3. Microstructural images of the three dimensionally printed short fiber based nylon revealing its (a) cross section and (b) top view of its corner as described by Blok et al. [33]

With the objective of fabricating superior quality continuous fiber based reinforced thermoplastic type composites, Heidari-Rarani et al. [34] designed and developed a novel extruder. Graphical design drawing of this novel extruder and its actual photograph, taken after its fabrication are illustrated in Fig. 4 (a) and (b) respectively. Principle of operation of this extruder relied on the methodology of embedding based component and it was designed such that, this extruder can concurrently extrude the continuous fiber type reinforcements together with thermoplastic type matrixes. As a part of this attempt, numerous experimental assessments were performed with the objective of enhancing the fundamental parameters, so as to attain a superior quality 3D printed structure. These experimental assessments comprised of exhaustive assessment of numerous process based parameters including escalating the matrix and fiber binding through employment of PVA solution, injecting melted polymers and fibers concurrently, expeditious cooling of printed structures (immediately after deposition) through employment of cooling type fan and identifying the optimal diameter of carbon fiber. Examinations of the fabricated structures revealed us that, the bending and tensile related strengths of the continuous carbon fiber reinforced PLA composites have escalated to 108% and 35% when being compared with that of the original PLA (poly lactic acid). In addition to this, morphological based investigations were performed to understand the binding amidst the matrix of PLA and continuous carbon fibers and their modes of failure.

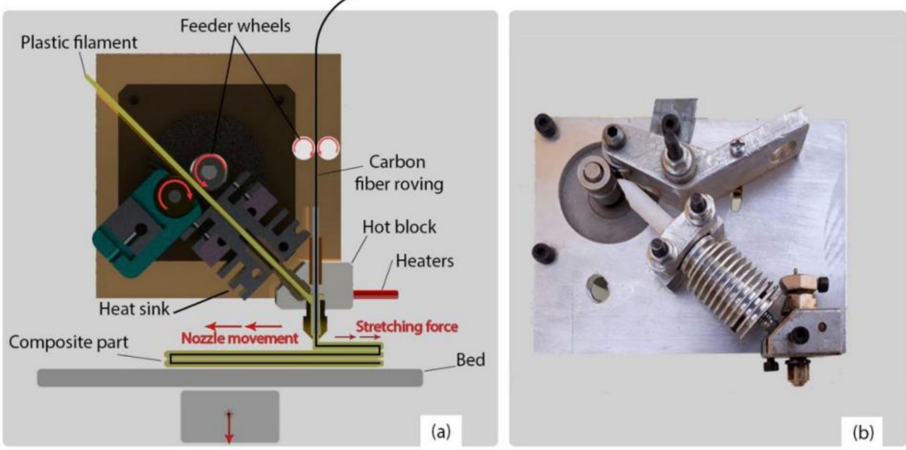

Figure 4. (a) Graphical illustration of designed innovative extruder and (b) actual photograph of successfully fabricated extruder as recorded by Heidari-Rarani et al. [34]

FDM of PEEK based composites

In the recent periods, PEEK (i.e., Polyether ether ketone), belonging to the category of superior performance three dimensionally printed polymers have received the attention of researchers, in various parts of the globe and this PEEK polymer possesses several desirable features

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including superior mechanical relevant properties, chemical based stability (against acids, organic based solvents and oils), superior heat deflection temperature, enhanced stabilization w.r.t resonance, low density etc. [35, 36]. Due to these excellent and attractive features, PEEK has the capability to meet the requirements in various domains including energy related storage, aerospace, bio medical implants (especially for repair of bones, control of infection etc.), electronics and in fabrication of several industrial components (including pumps, bearings, fluid chromatography columns etc.) [37].

At the same time, there prevail various constraints in printing PEEK based three dimensional structures using the technology of FDM. Larger viscosity and higher melting temperature are two major factors which act as barriers in employing PEEK as a material for FDM based 3D printing. The high viscosity of the PEEK prevents the fusion based melting during printing, thereby deteriorating the strength of the printed structures [38, 39]. Likewise, the higher melting point of the PEEK demands for a superior processing device and larger time to attain relevant amount of bonding, when compared with that of PLA. So, there exists a large research scope for overcoming these several constraints and to attain superior quality 3D PEEK based structures using the technology of FDM [40].

Li et al. [41] came up with an innovative method of fabricating PEEK based three dimensional structures possessing superior inter laminar binding strength and it was proposed to attain such superior quality FDM based PEEK by employing the pyrolysis based reaction of POSS (i.e., polyhedral oligomeric silsequioxane). The basic idea behind this innovative technique is to merge the chemical and physical based approaches to enhance the interfacial binding related strength of the three dimensional PEEK structures printed using the technology of FDM. Fig. 5 (a) – (c) portrays the graphical illustration of the three dimensionally printed PEEK/POSS nano composite structures. Through the addition of these POSS, the behavior and properties of the three dimensionally printed PEEK/POSS nanocomposites including their morphology, binding strength, rheology were proven to be dominated reasonably by the pyrolysis based products. Images obtained through SEM (scanning electron microscope) and TEM (transmission electron microscope) reported that morphological based changes have taken place during 3D printing of POSS and this have also contributed for the transition in the mode of failure of the PEEK/POSS based 3D printed structures.

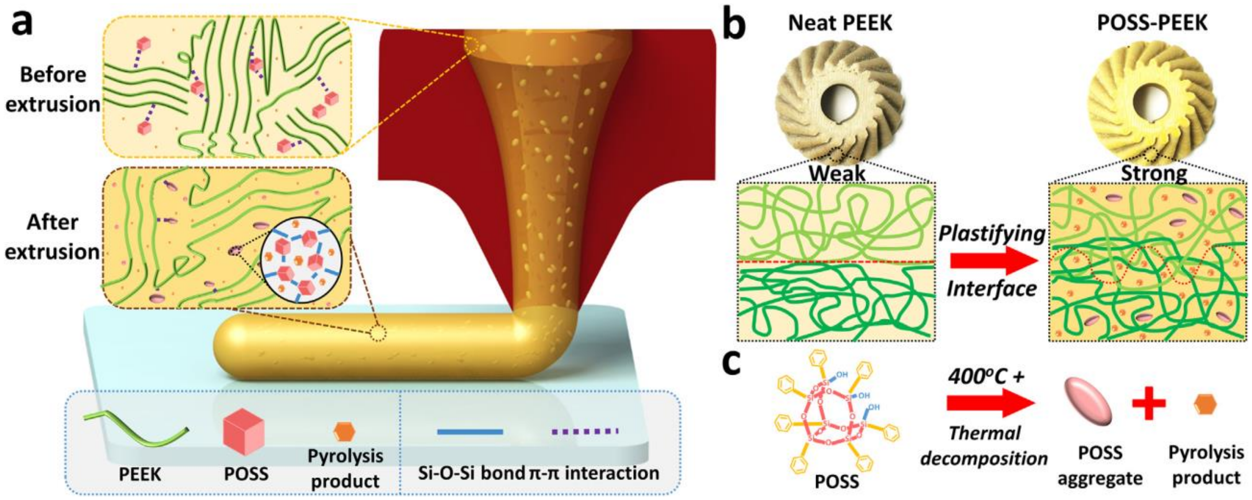

Figure 5. Graphical representation of the three dimensionally printed PEEK/POSS nano composite structures (a) morphology based modification induced through POSS during the three dimensional printing (b) POSS based pyrolysis products serves as plasticizers in enhancing the interface relevant binding strength and (c) process of pyrolysis & POSS related products as portrayed by Li et al. [41]

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In addition to this, during this experimental work, normal uniaxial tensile related experiments were carried out from macro level to micro level, with the objective of improving the impact of POSS on the interfacial related binding strength. Moreover, so as to enhance the interfacial related binding strength and its performance w.r.t. Z-axis, the temperature of the upper layer is modified suitably and a highest value of approximately 60 MPa was exhibited due to the modification of the temperature of the top layer. Based on these several experimental observations, it was recorded that the 3 weight % PEEK /POSS exhibited superior mechanical performance when compared with that of 1 weight % to 5 weight % PEEK/POSS

Incorporating fibers into the matrix of the thermoplastics was proven to be very much effective in enhancing the efficiency of the three dimensionally printed composite structures. It can be seen that, majority of the investigations on the FDM based 3D printing of fiber based composites were concentrated towards materials like PLA, ABS (i.e., Acrylonitrile Butadiene Styrene) and other polymer based matrixes [42]. Even though some researchers have made attempts in optimizing the fiber related contents and the parameters of FDM process during the 3D printing of composite structures, mechanical related performance of majority of the 3D printed reinforced fiber based composites seems to be inferior when compared with that of the original PEEK structures printed using FDM [43, 44]. As a result, there prevails an urgent need for identifying suitable combination of parameters (of FDM process) so as to attain 3D fiber reinforced PEEK composite structures, possessing enhanced mechanical relevant properties.

Wang et al. [45] made an experimental attempt to fabricate glass and carbon fiber reinforced PEEK filaments and to print them using the technology of FDM. In this work, the impacts of various FDM parameters namely temperature of the nozzle, thickness of the layer, speed of printing, temperature of the platform etc., on the mechanical relevant properties (including flexural, impact and tensile strength) on the three dimensionally printed glass fiber/PEEK and carbon fiber/PEEK structures were investigated. With the objective of understanding the logic behind the failure of 3D printed glass fiber/PEEK and carbon fiber/PEEK structures, the tensile surfaces of the fractured specimen were examined using SEM. The SEM micrographs of the interface amidst the PEEK and fiber in the three dimensionally printed composite structures at 4000c and 4400c nozzle temperature are portrayed in the Fig. 6 (a) and (b).

It was observed that, the flexural and tensile related strength of the glass fiber/PEEK and carbon fiber/PEEK structures escalated with the escalation in the temperature of platform and nozzle. At the same time, the impact related strength of these PEEK composite structures has not been affected by the changes in these temperatures. It was also recorded that the escalation in the thickness of the layer and speed of printing has contributed for the decline in the mechanical relevant properties (especially the impact related strength) of these PEEK composite structures. Optimal mechanical relevant properties were attained during the employment of 5mm/sec printing speed and 0.1mm thick layer.

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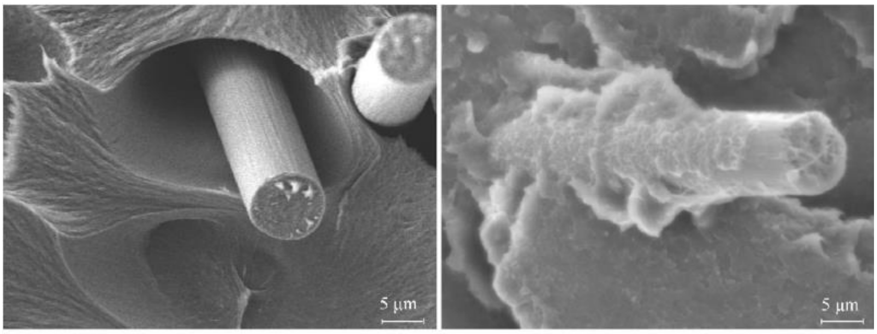

Figure 6. SEM micrographs of the interface amidst the PEEK and fiber in the three dimensionally printed composite structures at (a) 4000c and (b) 4400c nozzle temperature as observed by Wang et al. [45]

This experimental work by Wang et al. [45] compared the mechanical based properties of the three dimensionally printed original PEEK composite structures with PEEK structures possessing 5wt% carbon fibers and 5wt% glass fibers. It was revealed that, both the carbon and glass fiber based PEEK structures exhibited superior tensile and flexural based strength when compared with natural PEEK structures and this was mainly due to the intensified pinning impact of the fibers. Apart from this, it was also observed that, the three dimensionally printed glass fiber/PEEK structures exhibited better bending related performance than carbon fiber/PEEK structures and this was contributed by the discrepancies in the volume of the fiber content.

FDM of thermo-setting polymers

Fiber based thermosetting polymers, due to their attractive features, namely, superior chemical and thermal related stability, resistance against wear has gained attraction in various industrial sectors. In addition to this, these thermosetting polymers due to their cross linking based polymer matrix, exhibit superior performance in extreme temperatures [1, 33]. At the same time, traditional based manufacturing techniques employed for fabricating these thermosetting composites leads to large amount of material wastage, thereby raising their fabrication cost. So, there prevails a need for identifying a suitable low cost technique for fabricating these thermosetting polymers (as intricate structures), so that their scope of application will be improved. Recently, several researchers have shown interest in making attempts to fabricate continuous fiber type thermosetting polymer based composite structures, using the technology of FDM, owing to their superior inter–molecular based cross link structure [19, 29, 46].

For example, Ming et al. [47] made an experimental investigation to fabricate three dimensional continuous fiber reinforced thermosetting type polymer composite structures, in which continuous category 3K carbon fibers were employed as reinforcement and the thermosetting matrix used in the printing of this composite was EP-671 based epoxy. Dicyandiamide was employed as the agent of curing for this experimental work. A variety of process parameter combinations were employed and the three dimensionally attained composite structures were examined for identifying their flexural and tensile related strengths. Fig. 7 (a) and (b) portrays the photograph of the three dimensionally printed pentagram and honey comb based structures at optimized parameters of 500 mm/min speed of printing, together with a space of printing of 1.2 mm, thickness of the printed layers being 0.40 mm, at a curing temperature and pressure of 1700c and -90 kPa respectively.

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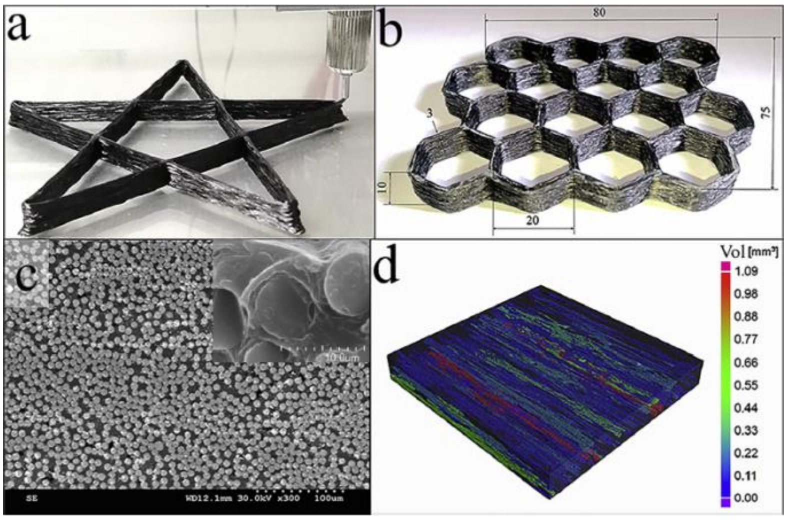

Figure 7. Photographs of three dimensionally printed (a) structure of pentagram (b) honey comb based structure (c) SEM micrograph of the cross section of the 3D structure and (d) analysis of interior structure using software as illustrated by Ming et al. [8]

As seen in the Fig. 7 (c) and (d), these three dimensionally printed composite structures were subjected to SEM based examinations and their interior structures obtained after curing were also analysed using suitable software and it was recorded that maximum flexural related strength was exhibited by the three dimensionally printed continuous fiber reinforced thermosetting type polymer composite structures possessing nearly 58 wt% of the fiber based content.

Conclusions

Three dimensional printing is a novel additive type of manufacturing technology in which the material gets printed layer by layer. Unique feature of this 3D printing technology is that, it does not require any molds, can print three dimensional complex structures very accurately at a faster rate, with minimized material wastage. Fused deposition modeling (FDM) is one of the extensively employed processes of 3D printing, owing to its reduced cost and simplicity of fabrication, thereby permitting to print wide range of materials (even in larger size) in several directions with perfect accuracy. At the same time, there prevails a continuous demand for improving mechanical relevant properties and dimensional stability of the three dimensionally printed parts, so as to meet their application based demands and this inferiority w.r.t mechanical properties of the three dimensionally printed structures (printed using the technique of FDM) arises due to the poor binding amidst the interior layers of the printed structures and the surface related roughness. This paper reviewed in detail, the recent research works and experimental investigations carried out in the field of three dimensional modeling using the technique of fused deposition modeling (FDM), with the major focus towards the 3D printing of continuous carbon fiber reinforced composites, PEEK (i.e., Polyether ether ketone) based composites and thermo-setting type polymers. This paper also reviewed the examinations performed with respect to three dimensionally printed structures (using the above mentioned materials), the changes in their morphology related characteristics, improvements in mechanical relevant properties etc. This paper also addressed the innovations carried out w.r.t the employed equipment (including extruder and other printer components) and methodology to fabricate 3D structures and parts.

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