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STRUCTURAL INTEGRITY OF THREE DIMENSIONAL PRINTED CARBON FIBER COMPOSITES/NANOCOMPOSITES FOR AERONAUTICAL COMPONENTS—CURRENT SCENARIOS AND OPPORTUNITIES

ABSTRACT

This state-of-the-art innovatory overview essentially debates practical worth of three-dimensional printed composites/nanocomposites (especially carbon fiber designs) for aerospace sector. Recently, three-dimensional printing (additive manufacturing) has competently transpired for designing high performance space structures. The manuscript systematically frameworks fundamentals of three-dimensional printing approach, ensuing high-tech aeronautical carbon fiber composites/nanocomposite systems, and space components/structural applications. Amongst carbonaceous fillers, short/continuous carbon fibers were inspected as outperforming reinforcements for aerospace. Additionally, surface modified/composited carbon fibers with nanocarbons (carbon nanotube, graphene) have been reported. Accordingly, polyamide, poly(lactic acid), poly(ether ether ketone), epoxies, etc. have been documented as substantial thermoplastic/thermosetting matrices. Ensuing radical polymer/carbon fiber or polymer/carbon fiber/nanocarbon hybrids have benefits regarding low-cost manufacturing, structural precision, complex geometries, high efficiency, least structural defects/voids, superior tensile and shear strength/modulus, compression strength, interlaminar strength, wear properties, thermo-dimensional constancy, and heat stability features, under extreme space environments. Consequently, cutting-edge three-dimensional printed carbon fiber hybrids offered myriad of promising opportunities for mechanically robust (nozzle wearing, strengthened wing spar/ribs, resilient rotating components, interlaminar strength/dimensional stability) and high temperature stable (cryogenic fuel storage, lower earth orbital stability, thermal-dimensional steadiness, thermal conductivity) for aerospace modules. Henceforth, three-dimensional printing owns enormous engineering potential to meet aeronautical manufacturing demands by overcoming challenges of traditional techniques.

Keywords: *three dimensional printing; carbon fiber; composites; aerospace; structures; mechanical; thermal*

INTRODUCTION

The polymer matrix aerospace composites with fibrous fillers (carbon fiber, Kevlar fibers, glass fibers) have gained an indispensable research stance owing to structure-property-performance vantages [1]. Conventionally, aerospace polymers or composites have been processed using communal techniques such as hand layup, prepreg, injection molding, vacuum bagging autoclave, and compression molding, to name a few [2]. However, there is a rapid shift towards advanced sophisticated processing techniques like three dimensional printing to meet the structural precision and harsh environment endurance demands of space industry [3, 4]. In this regard, numerous efficient three dimensional methodologies like fused deposition modeling, stereolithography, selective laser sintering, ink printing, Vat

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photopolymerization and extrusion printing have been examined for space intended printed objects [5]. These methods have overall benefits of inexpensiveness and facile operation. Progressions in three dimensional printing has led to the high-tech carbon fiber reinforced thermoplastics or thermosetting composites derived printed components [6]. Here, three dimensional printed carbon filer/nanocarbon hybrid structures have also been researched [7]. This technique has rendered the manufacturing of distinct structures having low density, well-defined microstructure/dimensions, superior mechanical (strength, stiffness, modulus, strain, toughness, compression/flexural strength, etc.), wear/corrosion, and thermal constancy at extreme temperatures, along with the suitable heat/electron conduction characters [8]. Correspondingly, carbon fiber composites/hybrids have been processed for the aeronautical wing parts, nozzle, engine blades, and other structural components of space related assemblies ranging from aircrafts to space/satellite structures [9-11].

Eventually, this review presents an all inclusive account covering the fundamentals of the opted advanced processing technique, leading design versatilities of three dimensional printed thermosets/carbon fibers and thermoplastic/carbon fibers, and heat/mechanical constancy performance of the finally constructed aerospace components. For the fabrication of three dimensional printed aerospace composites, both the continuous carbon fibers as well as short carbon fiber fillers have been used for the desired matrices. Few reports have also mentioned the state of using the carbon fibers in combination with nanocarbons (carbon nanotube, graphene) in these structures. Subsequently, plenteous exceptionally mechanically and thermally resilient three dimensional printed hybrids structures have been reviewed in this article for aerospace nozzle, wings, ribs, rotating parts, and allied engineering structural components. Besides, the essential prospects, challenges, and opportunities of this proficient technique as well as high-tech carbon fiber materials have been discussed for future aerospace industry. To the best of knowledge, no comprehensive, well-arranged, and well-interpreted recent review article reported so far depicting the actual state of three dimensional printed carbon fiber composites for engineering space architectures. However, individual research reports have been noticed on numerous related precisely printed carbon fiber designs. Therefore, it can be inferred that future advancements/challenges assessment in the arena of three dimensional printed space structure are not possible for the field scientists/engineers without getting prior knowledge of the topical literature in an aptly accumulated form. Hence, the present review will undoubtedly assist the forthcoming contributions/progress on next generation three dimensional printed carbon fiber hybrids derivative aeronautical units.

THREE DIMENSIONAL PRINTING

Three dimensional printing technologies have become a hot research topic, since past few eras [77]. This technique has been efficiently tested for processing the range of materials counting polymers, carbon, metals, ceramics, hybrids, and lots more [12]. For three dimensional printing number of valuable additive manufacturing techniques have been developed and scrutinized namely fused deposition modeling, selective laser sintering, stereolithography, direct ink writing, fused filament fabrication, Vat photopolymerization extrusion printing, and several others, for material manufacturing [13]. Among these, direct ink writing or direct ink printing employs the extrusion of desired material by means of a pressurized syringe (Fig. 1a) [14]. In this method, layer by layer material is deposited through three dimensional motion of the pressurized syringe head. Here, the final product features rely on the deposition rate as well as the sample viscosity. Fused deposition modeling is perhaps the most commonly used additive manufacturing approach using the thermoplastic filaments having well-regulated extrusion (Fig. 1 b) [15]. This technique also delivers a layer by layer material through filament melting to semi-liquid state. Here again, the product quality depends upon the printing parameters used. This technique has been applied to both the thermoplastic as well as thermoset precursors. Stereolithography, mostly used for thermosets (epoxies/acrylics), functions on the principle of photocuring (UV laser) and ultimate generation of patterned layers (Fig. 1 c) [16]. A powder based technique, selective laser sintering exploits a controlled laser beam approach for the formation of precise path scans (Fig. 1d) [17]. In this tactic, a liquid binder is used and laser irradiation causes the powder fusion. In this regard, particle size of powder sample, laser power, as well as scanning rate define the final product specifications. It can be interpreted that all the additive manufacturing procedures require parameter control and have relative recompences and drawbacks, which may guide towards the section an appropriate technique [18].

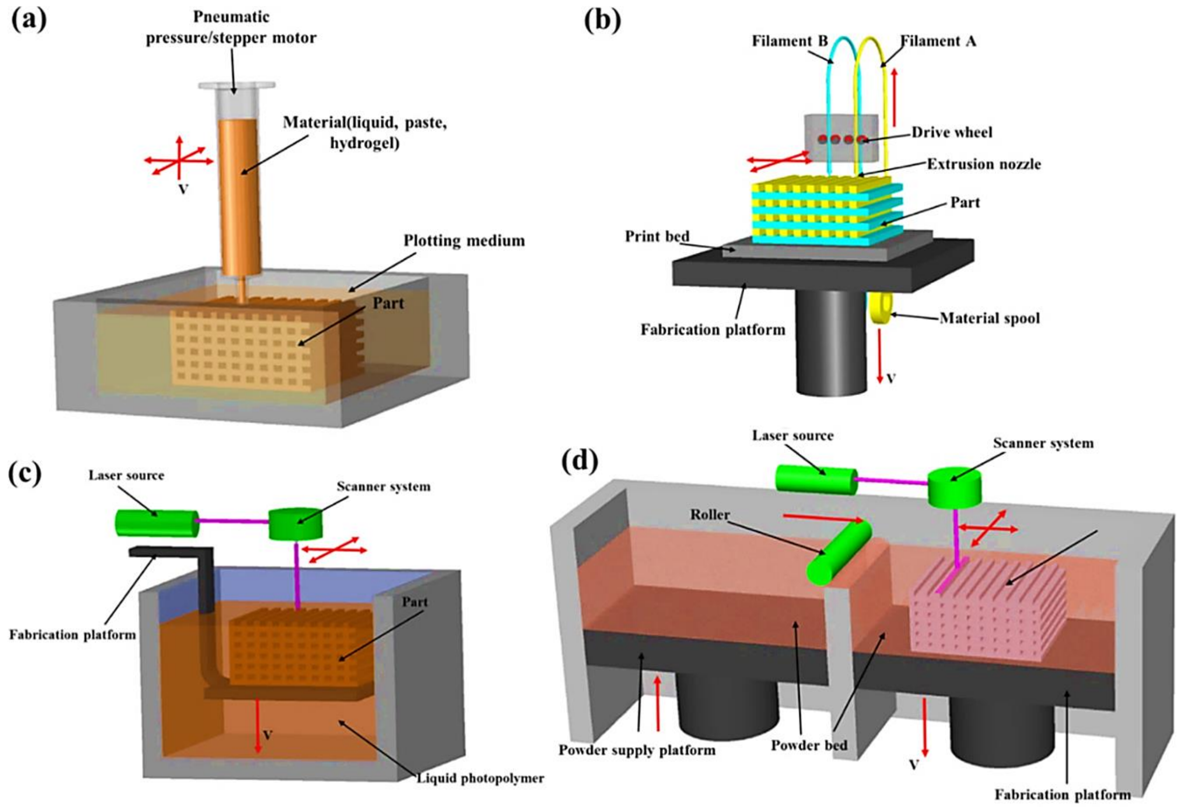

Fig. 1. Graphic representation of (a) direct ink writing (DIW); (b) fused deposition modeling (FDM); (c) stereolithography (SLA); and (d) selective laser sintering (SLS) techniques for three dimensional printing [19]. Reproduced with permission from Elsevier

Generally speaking, three dimensional printing has the greatest advantage of precise object formation without involving the molds or final machining/drilling steps, where conventional techniques seize up [20]. The tailoring of polymer or composite structures involves a sophisticated computer aided design (CAD) software for forming virtual objects and transformation into three dimensional printing [21]. Consequently, this technique has allowed the fabrication of complex three dimensional objects, which is not possible thru any traditional material processing tactic [22]. Additionally, there are advantages related to low price, rapid prototyping, and conversion to final product [23]. In this way, the usefulness of three dimensional printing has been realized in advanced engineering, defense, and space industries [24]. Table 1 outlines some important points controlling the beneficial aspects as well as shortcomings of three dimensional printing methods [25].

Table 1. *Technical benefits and encounters of three dimensional printing (additive manufacturing) approaches*

Technical benefits	Relevant encounters or challenges
Modified product development using small batches and later the large scale production, unlike conventional material fabrication approaches	Manufacturing speed is not up to the mark for large scale uses
Creation of three dimensional models devoid of molds/tools, contrary to traditional material synthesis	Need for further developments in additive manufacturing techniques, despite of beyond rapid prototyping
Performance efficiency in terms of conversion of digital files to further required data for customized objects	Requirements of advanced material standardization techniques
- No material wastage involved - ecological friendly	- Needs of post processing - Recycling of support structures required
Intricate structural geometries are possible	Processing of multi-materials
Negligible defects or porosities in final three dimensional printed objects	In multi-metallic materials, product finishing may be challenging due to layer by layer material deposition
High efficiency three dimensional printing options (fused deposition modeling, selective laser sintering, stereolithography, direct ink writing, fused filament fabrication) available according to the desired application	Need to develop advanced technique using the integration of different additive manufacturing methods

THREE DIMENSIONALLY PRINTED COMPOSITES/NANOCOMPOSITES FOR SPACE SECTOR

High performance three dimensional printed aeronautical carbon fiber composites

Carbon fiber reinforcement in polymeric matrices have opened new doors to high-end industrial solicitations in aeronautical arenas [26]. These carbon additives have been consumed in two important forms i.e., short carbon fibers or discontinuous fibers (50-400 μm length) [27] and long carbon fibers or continuous fibers (several mm length) [28]. In general, these carbon fibers own larger surface area to interact with the matrix phases and to enhance the composite properties like strength and heat resilience [29]. To eradicate the cost, formability, and processing berries of traditionally formed composite materials [30], research has turned towards the utilization of three dimensional printing technologies [31]. Additionally, the printing methods have advantages of processing without using molds or post cure requirements [32]. With the rapid evolution of three dimensional printing, carbon fibers and composites have also been constructed using this innovative approach [33]. In this concern, numerus thermosetting as well as thermoplastic polymers have been productively composited with the carbon fibers [34, 35]. Primarily, three dimensional printing based on stereolithography type additive manufacturing was applied for continuous fiber filled thermosetting composites (2012) [36]. Later developments directed to the structuring of three dimensional printed carbon fibers for space parts using fused deposition modeling [37] and direct ink writing [38]. Both for the short carbon fibers or continuous carbon fiber composites, research has spanned the fused deposition modeling due to the benefits of low price and high efficiency towards the formation of strengthened space structures, compared with the traditional fabrication routes [39]. Nevertheless, several other additive manufacturing techniques have also been used for the formation of aerospace related three dimensional printed carbon fiber composites, as discussed in the subsequent sections of this review.

Thermosetting matrices reinforced with carbon fibers have been widely explored in aerospace sector, particularly for elevated heat and mechanical robustness profiles [40]. Three dimensional printing has offered low cost and facile manufacturing route to form high performance thermoset/carbon fiber composites [41]. Lu et. al. [42] fabricated poly(ether ether ketone)/carbon fiber composites (variable fiber lengths) using screw extrusion based three dimensional printing approach. Significantly high tensile and flexural strength of 170 MPa and 223 MPa, respectively, were attained for the composite with average fiber length around 209 μm. Consequently, the results revealed 143% and 88% increments in the tensile and flexural strengths, respectively, of the material compared with the pristine poly(ether ether ketone) thermoset. Hence, the scope of three dimensional printed strengthened thermosetting composite was established for space structures. Yang et. al. [43] reported on the poly(ether ether ketone)/short carbon fiber composites obtained through fused deposition modelling based three dimensional printing. With the varying screw speed, porosities and tensile strength properties of the composites were studied (Fig. 2A). According to the results, 10 wt.% carbon fiber filled poly(ether ether ketone) composite revealed upsurge in the porosity of extruded filament in the range of 0.1-2.5%. Increasing the screw speed from 35-65 rpm also caused increment in tensile strength around 118-137 MPa. Therefore, the mechanical features were seemed to be reliant on the screw speed during processing. Consequently, the 10 wt.% poly(ether ether ketone)/carbon fiber composite was opted to design the three dimensional printed gear wheel, runner valve, bracket, and femoral stem parts (Fig. 2B a-d). Enhancing the heat treatment temperatures of poly(ether ether ketone)/carbon fiber composite around 175-300 °C significantly improved the crystallinity, tensile strength, and tensile modulus values in the range of 21-35%, 51-135 MPa, and 3.5-9.2 GPa, respectively. Moreover, the flexural strength and modulus were increased to 86-234 MPa and 3.7-9.5 GPa, respectively. Consequently, the relative densities of the three dimensional printed were found > 98 % i.e., well suited for aerospace structural units.

Islam et. al. [44] designed continuous carbon fiber reinforced thermosetting composite materials. Here, urethane acrylate based tough photocurable thermosetting resin was used in light assisted three dimensional ink printing method. The light assisted three dimensional printing assembly contains a print nozzle to feed the carbon fiber material and a syringe pump to feed the thermoset to the print head (Fig. 3A). For continual printing process, flexible needle tip was preferred. In scanning electron microscopy micrographs of fractured surface, the composite revealed fiber pull out phenomenon, failure marks, as well as cylindrical voids due to fiber pulling (Fig. 3B). The stress strain tests on the continuous carbon fiber reinforced thermosetting composite were also performed (Fig. 3C). The resulting scan revealed a linear increasing stress-strain behavior with maximum tensile strength close to 400 MPa. Moreover, the interlaminar strength was detected around 4 MPa (volume fraction 15.7%). Fig. 3D imaged the resulting failed sample. In this way, the exceptional increments in mechanical profile of the urethane acrylate resin/continuous carbon fiber composites matched the aerospace part deployment necessities.

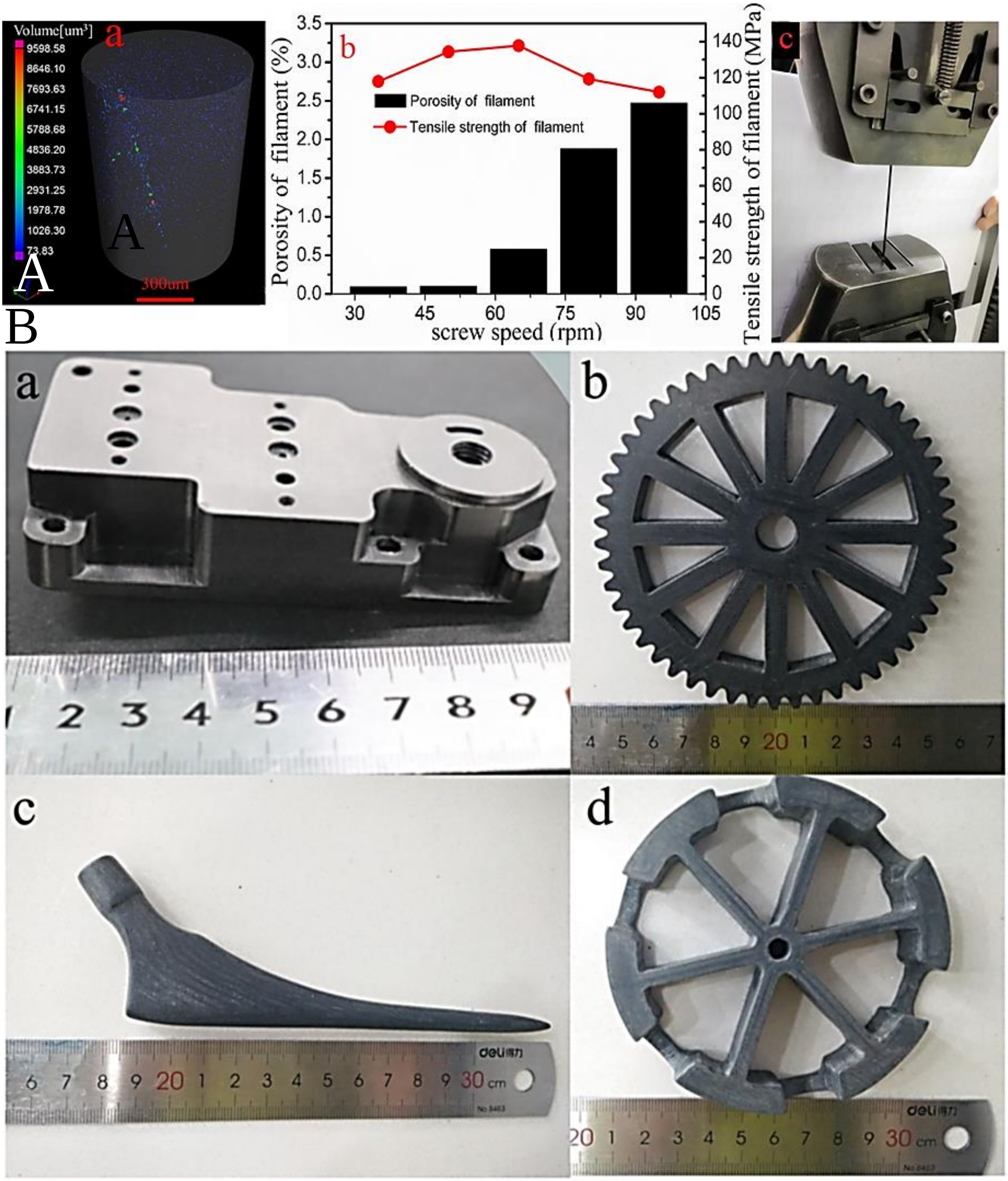

Fig. 2. (A) (a) prototype; (b) porosities and tensile strength of poly(ether ether ketone)/carbon fiber filaments formed at different screw speeds; (c) experimental setup used for testing tensile strength of filaments;
(B) CF/PEEK composite parts (with 10 wt.% carbon fiber) prepared by fused deposition modeling process at ambient temperature of 20 °C and subjected to subsequent heat treatment based recrystallization: (a) runner valve; (b) gear wheel; (c) femoral stem; and (d) bracket [43].
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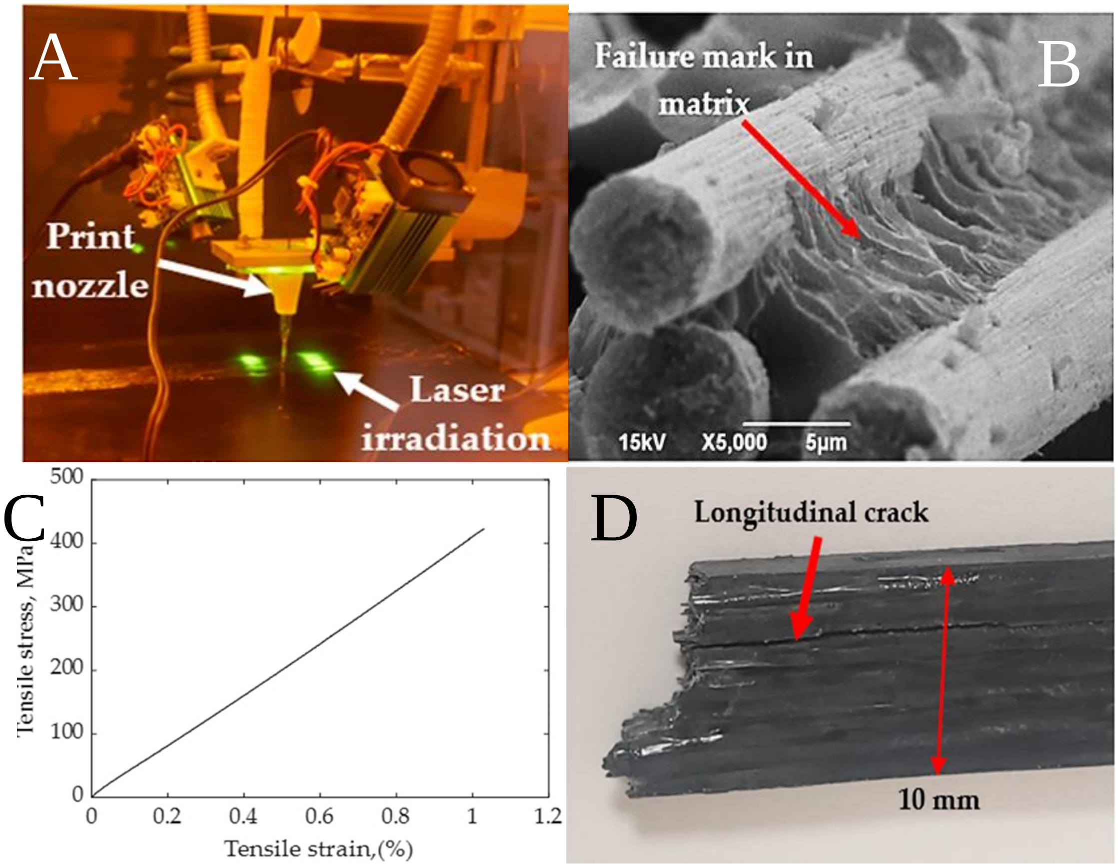

Fig. 3. (A) Light assisted three dimensional printing set up of carbon fiber reinforced thermoset composites, real-life picture; (B) scanning electron microscopy images of fracture surfaces tested under tensile load with fiber pull out and failure marks; (C) representative tensile test curve for continuous carbon fiber reinforced three dimensional printed thermoset composite; (D) fractured specimen [44].
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Furthermore, three dimensional printed carbon fiber composites have been investigated using theoretical and simulation techniques [45]. Here, computational fluid dynamics have been found operative to reveal the structure and features of three dimensional printed thermoset/carbon fiber composites [46]. Zach et. al. [47] opted finite element analyses related additive manufacturing technique to form precise designs of thermoset/carbon fiber materials. Accordingly, the fiber dispersion, alignment, and orientation in the matrix were investigated using the computational fluid dynamics.. The modeling technique proved useful to predict the structural features and their relation with three dimensional printing approach. Despite the successful attempts on three dimensional printed thermoset/carbon fiber composites so far, low shape durability has been found challenging owing to low viscosity of thermosetting resins [48].

In addition to thermosets, thermoplastic matrices have also been employed for three dimensional printed carbon fiber composites [49]. Al Rashid et. al. [50] applied fused filament fabrication mode to develop the polyamide 6/carbon fiber composites. Here, complex three dimensional triangular, hexagonal, or rectangular geometries having infill densities of 18-62 % were attained. The increase in the infill densities in turn upsurged the strength values in the range of 55-62%, relative to unfilled polyamide matrix. The rectangular geometry with superior in fill density had higher strength than the other two geometries studied. Chen et. al. [51] reinforced polyamide 6 or nylon 6 with carbon fibers using additive manufacturing based three dimensional printing technique. The variation in mechanical properties were explored vs. the printing parameters such as speed, temperature, and layer thickness. Under optimized conditions, 41% fiber content was found to upsurge the tensile strength and modulus up to 730 MPa and 29.23GPa, respectively. The results revealed 98 and 81 % rise in tensile strength and modulus, correspondingly, relative to the unoptimized printed samples. Thus, the parameter optimization of three dimensional printing was found indispensable in enhancing the mechanical profiles of these innovative materials. Mohammadizadeh et. al. [52] manufactured intricate geometries of nylon 6/continuous carbon fibers composites through fused filament fabrication based additive manufacturing process. Optical microscopy micrograph of composite depicted the interlayer adhesion among matrix-filler layered structure crucial to aid the load transfer properties (Fig. 4A).

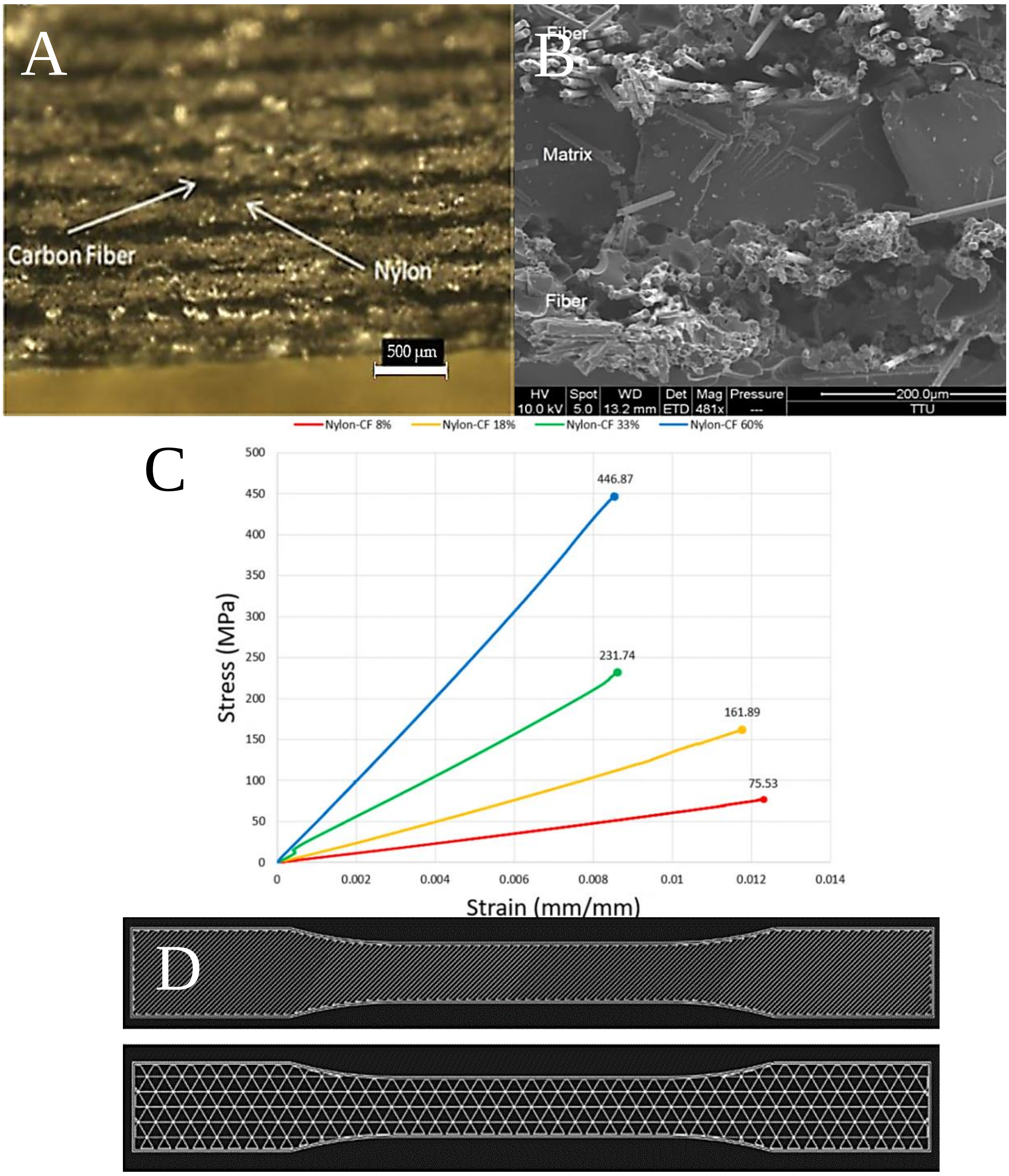

Fig. 4. (A) Optical microscopy of three dimensional printed (additive manufacturing) nylon/carbon fiber specimen; (B) scanning electron microscopy of printed fractured specimen; (C) effect of CF volume fraction on tensile strength of resulting nylon/carbon fiber; (D) infill patterns of rectilinear (up) and triangular (down) [52] Reproduced with permission from MDPI

SEM micrograph of fractured composite surface revealed fiber pull out and rupturing during composite failure (Fig. 4B). Furthermore, linear stress strain relationship was observed in the samples with fiber volume fraction up to 60% (Fig. 4C). Upon enhancing the fiber volume fraction to 60%, ultimate strength was remarkably increased to 446.9 MPa, relative to neat sample of 19.2 MPa (2231% increment). The microstructural adhesion at interfacial level was found responsible for such high mechanical features. The three dimensional printing was used to form rectilinear and triangular infill patterns of similar densities in pristine nylon 6 (Fig. 4D). Enhanced ultimate strength (12.62 MPa) was observed for triangular infill pattern, relative to rectilinear infill (8.93 MPa) showing the suitability of three dimensionally printed pattern according to orientation for high end uses. Kim and workers [53] used fused deposition modeling type additive manufacturing to form three dimensional printed poly(amide-imide) matrix composites for aerospace structures. These materials exhibited significantly high strength and glass transition values of 105 MPa and 295 °C, respectively, showing the effectiveness of the technique for the development of high performance three dimensional printed thermoplastic matrix composites.Tian et. al. [54] reported on the poly(lactic acid)/carbon fiber composites manufactured by fused deposition modeling. The three dimensional printed composites having 27% carbon fiber contents divulged exceptionally high flexural strength and modulus around 335 MPa and 30 GPa, respectively, appropriate for aerospace utilizations under extreme environments. Such elevated properties were credited to the compatible polymer-fiber interface formation using the advanced printing technique. Ferreira et. al. [55] also prepared three dimensional printed poly(lactic acid)/carbon fiber composites. They considered fused filament fabrication type additive manufacturing approach for the formation of strengthened printed objects. Resulting poly(lactic acid) matrix composites with 100 % carbon fiber volume fraction revealed considerably enhanced tensile strength and shear modulus of 3920 MPa and 1268 MPa, respectively, relative to the unfilled matrix (3125 MPa and 1092 MPa, correspondingly). Consequently, fused filament fabrication was found proficient to architect the three dimensional printed isogrid components for aerospace uses [56].

Design of three dimensional printed space nanomaterials with carbon nanoparticles (carbon nanotube, graphene)

Besides composites, nanocomposite materials have also been practically foreseen for high-tech space architectures [57]. For nanocomposites or hybrids, the final mechanical, thermal, and physical properties strongly rely on the nanofiller dispersion patterns in the polymeric matrices [58]. Owing to nano-scale sizes and high aspect ratio, the nano-additives own fine capability for interface formation and physical property enhancements [59]. For multifunctional aeronautical nanocomposites, carbonaceous nano-additives (carbon nanotube, graphene, carbon black) revealed enormous structural features and potential [60]. Carbon nanotube is one of the most popular one dimensional sp^2 hybridized carbon nanostructure [61]. It is a cylindrical tube shape nanocarbon having exceptional strength, modulus, electron mobilization, heat conduction, and countless other physical topographies [62]. Carbon nanotubes have been exploited for plenty of technological fields covering engineering/defense to energy/electronics zones [63]. With polymers, carbon nanotubes exhibited incomparable functional subsidies owing to high interacting surface area and interfacial effects [64]. Consequently, the carbon nanotube composites have been surveyed for high performance space structures [65]. For aeronautical applications, carbon nanotube and carbon fiber based hybrid fillers have been found valuable to enhance the composite properties [66]. Specifically, aerial craft body parts have been designed using the aeronautical-grade epoxy/carbon fiber/carbon nanotube nanocomposite panels [67]. Consequently, attempts have been reported on the processing of aerospace demanded polymer/carbon fiber/carbon nanotube nanocomposites through conventional processing techniques [68]. Wang and colleagues [69] produced epoxy/carbon fiber/carbon nanotube nanocomposites using traditional vacuum bagging technique. For space structural laminates, these composites exhibited high peak load recovery (96%) and fracture energy recovery (108%). Furthermore, Guadagno and group [70] predicted the thymine functional carbon nanotube filled epoxy/carbon fiber composites by traditional solution and infiltration methods. Addition of 0.5 wt.% carbon nanotube loading caused high self-healing efficiency up to 45%, desirable for space fuselage and autonomous damage repairing structures [71]. Notwithstanding the conventional methods, three dimensional printing via additive manufacturing revealed valuable space-age epoxy/carbon fiber/carbon nanotube structures [72]. Here, the printing technique has shown desirable worth to enhance the processing rate and fiber impregnation by minimizing the structural voids, and so the structural integrity was improved. Mansour et. al. [73] introduced acrylonitrile butadiene styrene/carbon fiber/carbon nanotube nanocomposites through fused filament fabrication of additive manufacturing. The ultimate strength and compression features of three dimensional printed hierarchical composite structures were investigated using finite element analysis. Accordingly, the ultimate strength of the three dimensional printed acrylonitrile butadiene styrene/carbon fiber/carbon nanotube nanocomposite (41-47 MPa) was found higher than the acrylonitrile butadiene styrene/carbon fiber (40-46 MPa) and neat matrix (32-38 MPa). Kasraie et. al. [74] opted the direct ink writing (additive manufacturing) tactic to develop the three dimensional printed multi-layered epoxy nanocomposite with carbon fiber/carbon nanotube (8.5/1.7 wt.%). The nanocomposite depicted the desirably low thermal conductivity (0.3 W/m.K), and high flexural modulus (6 GPa) and flexural strength (0.1 GPa), respectively, for structural applications.

In addition to carbon nanotube, graphene has been reported as a two dimensional sp^2 hybridized nanocarbon nanosheet [75]. Owing to inimitable nano-scale dimensions, high surface area, and characters, graphene has been fruitfully functional in for technological solicitations from aerospace to biomedical areas [76]. In this concern, Obad and workers [77] reported on the corrosion resisting polyurethane/graphene coatings for aluminum alloy 2024-T3 used in space structures. The nanocomposite coatings had fittingly high real impendence around 9068 % for corrosion defiance of aeronautical components. Like carbon nanotube, graphene has been amalgamated with carbon fibers to form the space grade architectures [78]. In due course, few reports were seen on the epoxy reinforced with graphene coated carbon fibers to enhance the fracture toughness [79]. Among three dimensional printed systems, Ghimire et. al. [80] reinforced carbon fibers and graphene in a commercial grade epoxy resin using fused filament fabrication. The multifunctional nanocomposites were found operative for aircraft systems due to superior ultimate compressive strength (136 MPa) and electrical resistance (61 G Ohms) features. Xiao et. al. [81] constructed thermosetting carbon fiber/graphene oxide nanocomposite system with oct-truss lattices through stereolithography. Inclusion of about 0.8 wt.% graphene oxide enhanced the compression strength up to 3 MPa, i.e., 10% higher than the unfilled matrix. Thomas et. al. [82] preferred the thermoplastic poly(ethylene terephthalate)/carbon fiber/graphene nanoplatelet nanocomposites through used filament fabrication. Here, varying the amounts of graphene nanoplatelets (0.01-5%) with 5% carbon fiber was monitored for suitability in high-tech cube microsatellite structure organizations. Conclusively, limited research attempts have been detected on three dimensional printed polymer/carbon fiber/carbon nanotube and polymer/carbon fiber/graphene nanocomposites up till now. Perceptibly, there is persuasive need of future investigations on three dimensional printed polymer/carbon fiber/nanocarbon nanomaterials for indispensable aeronautical applications.

APPLICATION OF 3D PRINTING TOWARDS STRUCTURAL INTEGRITY OF AERONAUTICAL COMPONENTS BASED ON CARBON FIBER COMPOSITES

MECHANICALLY ROBUST THREE DIMENSIONAL PRINTED SPACE COMPONENTS

Nozzle wear and structural strength

Relationship of the mechanical properties of space structures with nozzle wear has been investigated [83]. In aerospace industry, tool wear has emerged as a critical challenge hindering the processing of high performance strengthened structures [84]. Nozzle wear was found to directly affect the final surface finishing, so declining the mechanical characters of the end product [85]. Particularly, the three dimensional printed carbon fiber composites were found to be easily effected by nozzle wear owing to their intrinsic abrasion capacity [86]. Bianchi et. al. [87] developed polyamide and short carbon fiber reinforced composite by means of fused filament fabrication based additive manufacturing. Changes in the nozzle external geometry was studied by interrupting the three dimensional printing at different time periods (Fig. 5A). With the progressing time from 0-3560 min, enhancement in the nozzle wear was clearly visible through variations in orifice diameter and bore chamfered. Appropriately, the wear effects were credited to the abrasion produced by short carbon fiber filament on the nozzle surface. A clear difference between the non-wear nozzle (t = 0 min) and wear nozzle (5540 min) was studied by software ImageJ to further confirm the abrasion effects (Fig. 5B). According to stress strain investigations, tensile strength was declined by 37% after 5540 min (relative to t =0 min) (Fig. 5C). Hereafter, the connection between the wear and mechanical features of nozzle indicated the need of optimizing the additive manufacturing parameters to enhance the life span and durability of three dimensional printed objects towards space industry applications.

Strengthened wing spar and ribs

Advanced three dimensional printed carbon fiber reinforced composites have been frequently used to design the strengthened aerospace wing parts (wing spar and ribs) due to remarkable strength and durability characters in ariel conditions [88]. For flight vehicle structures, comparative studies have been performed using the traditional manufacturing as well as advanced three dimensional printing technologies [89]. Performance of ensuing composites was analyzed in terms of fiber orientation, material density, and ariel performance to unfold the design-performance advantages of three dimensional printed objects [90]. Huang and workers [91] proposed the fabrication of continuous carbon fiber composite based wing spar for aircraft through material extrusion and additive manufacturing processes. Consequently, three dimensional printed continuous fiber composite trajectory was inspected for the optimization of printing parameters to attain the long term wing spar performance under operational loads. The low density three dimensional printed wing spar depicted superior stiffness and peak load according to Messerschmitt-Bölkow-Blohm beam studies [92], i.e., appropriate for industrial scale aircraft wing structures.

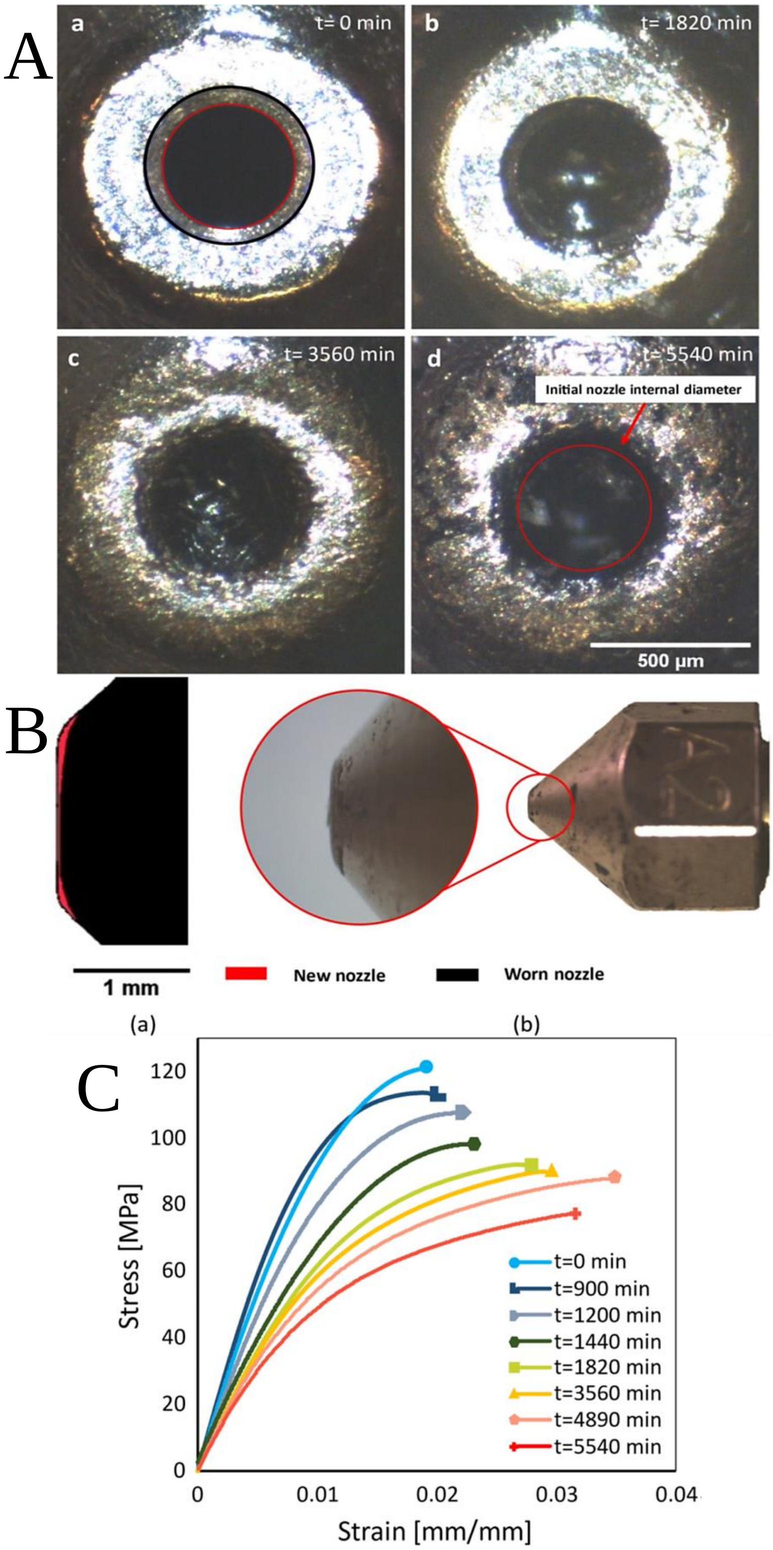

Fig. 5. (A) High magnification of the nozzle tip area (× 35) at varying printing time: (a) 0 min; (b) 1820 min; (c) 3560 min; (d) 5540 min; (B) (a) superimposition between worn nozzle (at t = 5540 min) and wear-free one (at t = 0 min); (b) longitudinal side of the worn nozzle; (C) effect of printing time on typical tensile stress vs. tensile strain curves of additively manufactured polyamide/carbon fiber specimens [87].
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Pappas et. al. [93] scrutinized poly(lactic acid)/continuous carbon fiber composites obtained through resin impregnation and fused filament fabrication based additive manufacturing. During the fiber impregnation, the resin infiltration through carbon fibers occurs under the pressure applied to wet the fibers (Fig. 6Ab-d).

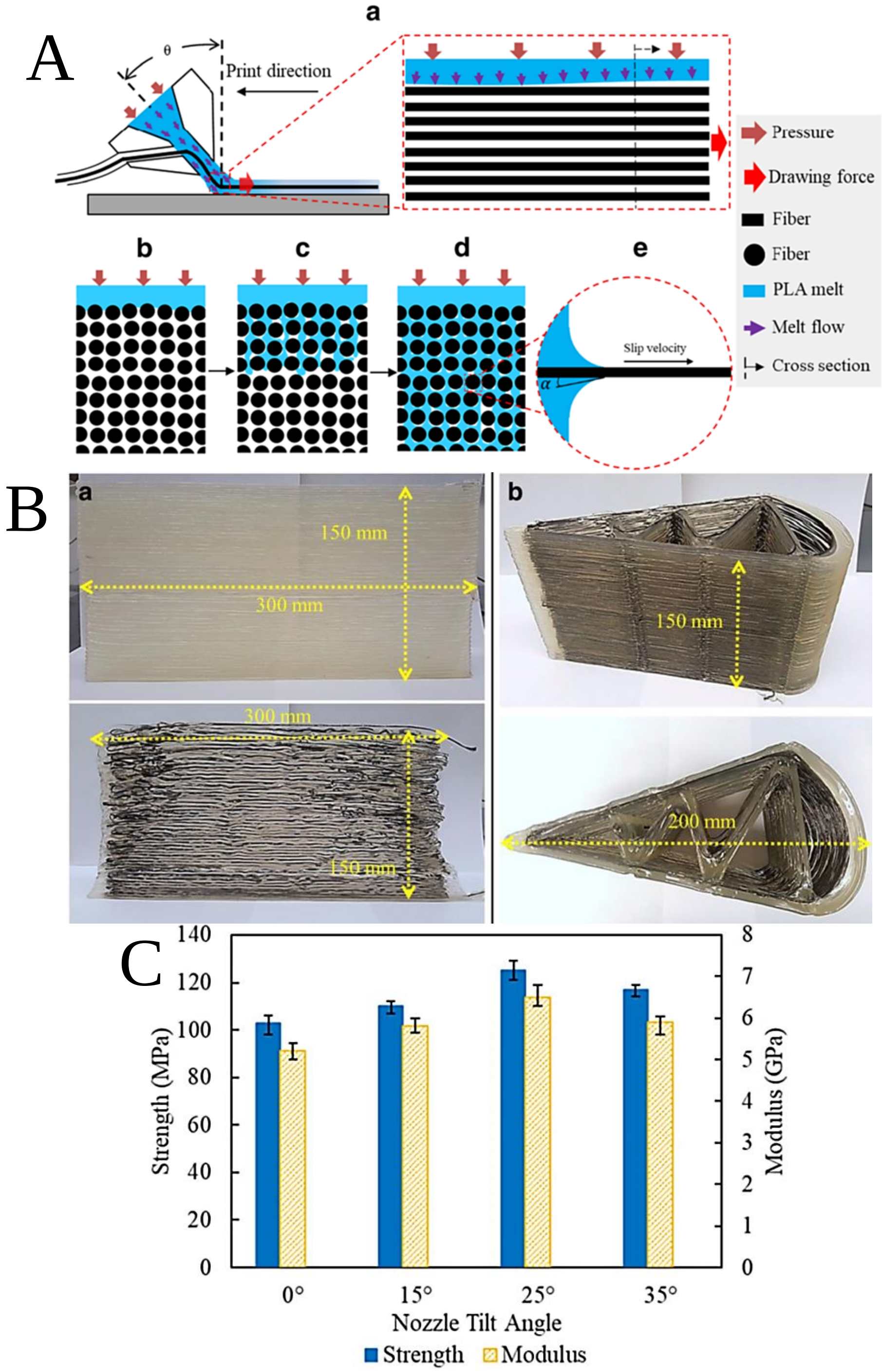

Fig. 6. (A) (a) schematics of fiber impregnation process; (b-d) transverse cross-sections of carbon fiber bundle and impregnation mechanisms as combined poly(lactic acid) (PLA) penetration of carbon fiber network at the mesoscale; (e) single fiber wetting process at micro-scale; (B) composite samples printed by the additive manufacturing set up with continuous carbon fibers (print speed 800 mm/min, deposition rate 13.3 g/min, nozzle tilt angle 0°): (a) thin wall structures printed without (top) and with (bottom) continuous carbon fiber reinforcement; (b) wing-rib structure printed with a single continuous carbon fiber bundle as reinforcement; (C) measured flexural strength and modulus through four point bending tests of continuous carbon fiber reinforced samples with varying nozzle tilt angles (print speed 800 mm/min; deposition rate of 5.7 g/min) [93].
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Adhesion or wetting of carbon fiber was explored and found to depend upon the resin slip velocity (Fig. 6Ae). The three dimensional printed poly(lactic acid)/continuous carbon fiber composite structures were designed using optimum additive manufacturing parameters like print speed and deposition rate around 800 mm/min and 13.3 g/min, respectively (Fig. 6B). Simple sample design was prepared using a single sheet of carbon fibers, however multi-sheets were also used for the generation of complex objects. The mechanical features (strength/modulus) of the three dimensional printed composites were investigated vs. varying nozzle tilt angle of 0-35° (Fig. 6C). It was observed that the tilt angle of 0° revealed lower strength (~ 100 MPa) and modulus (~ 5 GPa) values due to damage and wear effects on fiber surface. On the other hand, increasing the tilt angle to 35° was appropriate to print the samples without any rupturing effects on the fiber surface. Therefore, the strength and modulus properties were maximally enhanced to > 120 MPa and 7 GPa, respectively (tilt angle 25°). This research well predicted the potential of additive manufacturing for commercial scale aerospace applications through parameter optimization. Subsequently, the traditional wing spar and ribs designs have been successfully replaced with three dimensional printed carbon fiber hybrids in the internal aeronautical wing structures with the need of further process optimizations.

Generally speaking, for aerospace grade engineering structures, carbon fiber orientation seems to greatly affect the mechanical features of the related composites. Since, fiber orientations define the load transfer direction through the carbon fibers, so influence the resulting mechanical features of the materials. Herein, studies up till now revealed that generally carbon fiber laminates having 0° layer orientation had superior strength and modulus features, whereas, for instance, 45° fiber orientations in cross plies of carbon fiber based laminates showed higher strain properties [94].

Looking at the direction of mechanical force applied, applying longitudinal force on unidirectional carbon fiber laminates (0° fiber orientations) caused greater delamination/cracking, relative to that of the composites with cross plies (e.g., 45° fiber orientations). Consequently, it is notable that using different fiber orientations in the form of uni- plus cross-directionally layered plies may result in desired high strength space structures.

It is also important to correlate the mechanical robustness with the fiber orientation, which seemed to be affected by the printing conditions. It was observed that increasing printing speed at constant deposition rate may cause lack of the desired material contents, so exposing the fibers towards mechanical force applied, like stretching. Subsequently, enhancing the printing speed may cause carbon fiber knotting or clumping together, so hindering the smooth dispersion or flow of the polymeric material on fiber surfaces. This way, fiber orientation seemed to be evidently disturbed due to tangling of the fibers which can decrease the mechanical strength of the composite. Similarly, increasing deposition rate can also be problematic and may cause uneven print geometry throughout the material, therefore, decreasing the mechanical features of the composites.

Integrity of space components via interlaminar shear strength and dimensional stability

For the longstanding performance of aerospace structural components, interlaminar shear properties and interlaminar fracture behavior usually play a key role [95]. Therefore, studies have essentially focus the interlaminar shear strength of carbon fiber reinforced composites for aerospace [96]. Traditional large scale aerospace manufacturing techniques usually result in non-uniform fiber distribution, interlaminar voids, defects, and poor interlayer bonding. Consequently, the effect of three dimensional printing methods on enhancing the interlaminar shear strength and interlaminar fracture of the desired composites have been explored [97]. Iragi et. al. [98] fabricated the polyamide and continuous carbon fiber based printed laminates using fused filament fabrication type three dimensional printing. Outstanding composite performance was evaluated in terms of interlaminar shear strength (38 MPa) and fracture toughness (2 kJ/m^2). Superior interlaminar shear strength characters led to enhanced delamination resistance of the composite laminates. Similarly, related reports have been noticed on fused filament fabrication based three dimensional printed carbon fiber composites portraying superior interlaminar shear performance [99]. Hence, further utilization of advanced additive manufacturing techniques may reduce the of defects and limitations, by enhancing the interlaminar properties, in the future high-tech aerospace structure [100].

In due course, dimensional stability of aerospace components has been found indispensable for imperative structural applications like aero-engine blades [101]. Usually, the applied composites undergo creep deformation and volume shrinkage effects during the blade functioning, so decreasing the dimensional steadiness. For such high dimensional stability demanding applications, sophisticated three dimensional printing methods like Vat photopolymerization based additive manufacturing has been used [102]. This technique usually involves the light activated polymerization to cure the liquid resins. Niu et. al. [103] applied Vat photopolymerization to fabricate the polyurethane acrylate matrix composite for inner aero-engine blade structure. The three dimensional printed blade structure divulged orderly aligned fibers to minimize the shrinkage and interlayer defects to enhance the dimensional accuracy during the blade functioning. Other attempts have been observed on the fused deposition method derived poly(ether ether ketone)/continuous carbon fibers for effective utilization in rotating aerospace parts [104]. As a consequence, the optimization of three dimensional processing parameters have been studied and found critical for manufacturing the dimensionally stable rotating space components.

TEMPERATURE STABILITY OF 3D PRINTED SPACE MATERIALS AND PARTS

Cryogenic fuel storage

Advancements in the three dimensional printed materials led to their momentous utilization in cryogenic fuel storage tanks widely anticipated in aerospace sectors like small-scale spacecraft propulsion units [105]. In these systems, three dimensional printed thermoplastic/carbon fiber composites have acquired research attention, however, previously thermoset/glass fiber systems were also reported for cryogenic fuel containers [106, 107].

In this regard, Huang et. al. [108] applied fused filament fabrication based three dimensional printing on nylon 6/short carbon fiber composites and nylon 6/continuous carbon fiber composites. A schematic for the formation of three dimensional printed cylindrical vessel for cryogenic liquid storage is given in Fig. 7A. After post three bending tests in cryogenic conditions, the samples were studied for microcracking at varying strain rates (Fig. 7B). The sample depicted no cracks at 0.2 % strain, nevertheless, a prominent zig zag delamination crack was observed at higher strain of 0.40 %. The microcracking behavior of three dimensional printed composite after three bending tests at different strains was further studied using the computational micromechanical modeling approach. With the increasing strain value around 0.5-0.7 %, the microcracking was found to proceed through the crack initiation, matrix-filler debonding, and propagation mechanisms (Fig. 7Ca-d). Consequently, the nylon 6/short or continuous carbon fiber composites displayed resistant microcracking in cryogenic situations suitable for cryogenic fuel storage for aerospace applications.

Nevertheless, a substantial knowledge gap still exists regarding the thermos-mechanical resistance of printed structures and microcracking related defects to sustain the cryogenic environments.

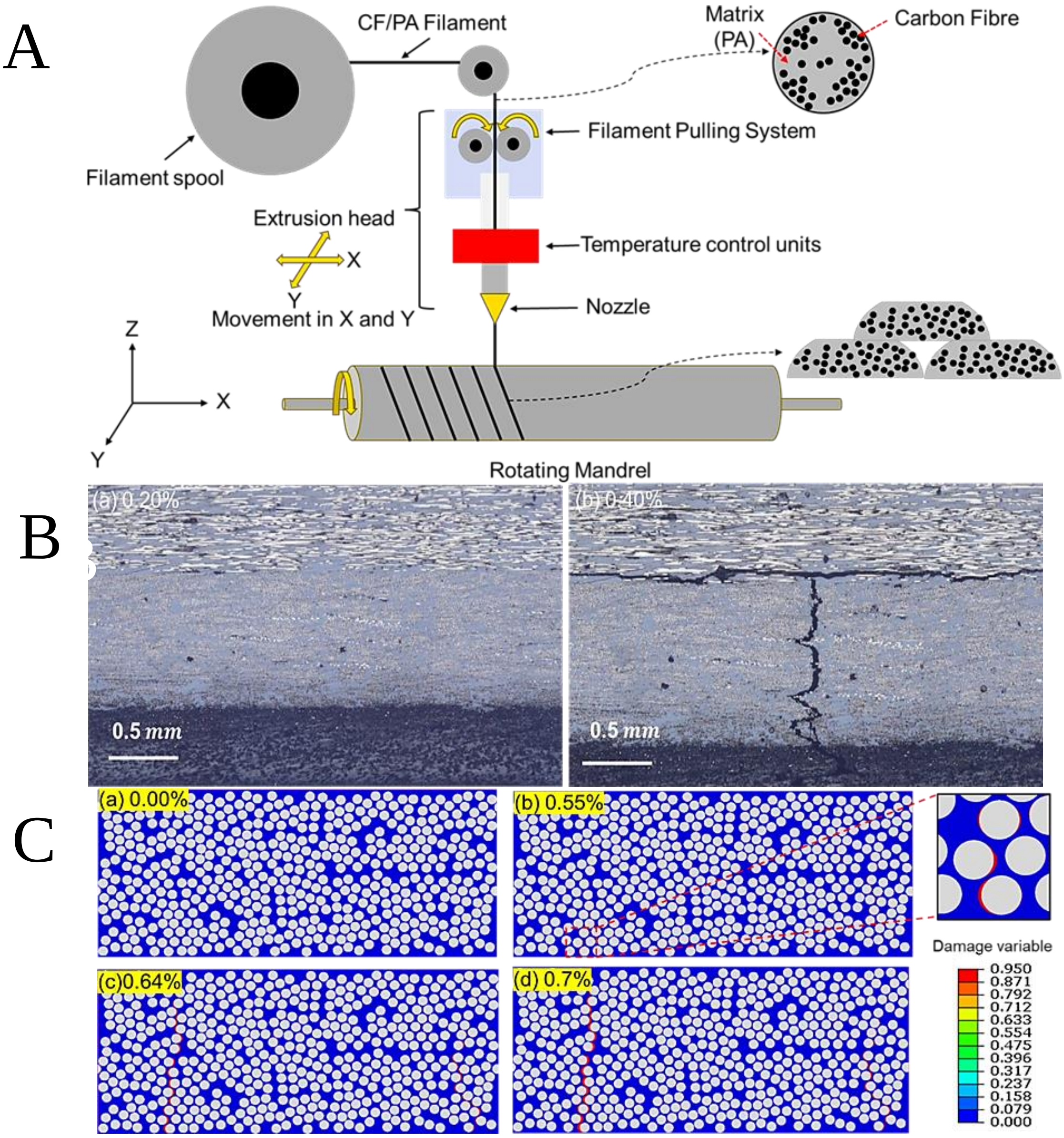

Fig. 7. (A) Three dimensional printing of a thermoplastic composite vessel for storing cryogenic liquids; (B) microcracking of heat treated three dimensional printed composite post three bending tests at cryogenic temperature under specific strains: (a) 0.20 %; (b) 0.40 %; (C) microcracking modelling of three dimensional printed composite after three bending tests at cryogenic temperature for different strains: (a) 0.00%; (b) 0.55%; (c) 0.64%; and (d) 0.70% [108]. Reproduced with permission from Elsevier.

Temperature stability in LEO

Another essential high temperature stability application of three dimensional printed carbon fiber composites was recognized in lower earth orbital environment [109]. In this concern, few literature reports have been seen so far regarding the outperforming thermoset/carbon fiber composites in LEO. Trani et. al. [110] adopted a fused filament fabrication derived carbon fiber composite design using high viscosity tetrafunctional epoxy resin matrix and 3,3′-sulfonyldianiline curing agent. The high performance composites were tested in LEO conditions for eight months by International Space Station via Japanese

Experimental Module (JEM) with Nanoracks External Platform (NREP). The sample location on ISS, JEM, and NREP, before and after exposure to lower earth orbital atmosphere was methodically analyzed (Fig. 8a-c). During the space mission, the composite samples were attached to the space flight test unit and integrated in NREP. The samples were allowed outside the international space station unit for exactly 8.63 months, i.e., 259 days. Accordingly, four thousand thermal cycles were applied with temperature variations of 121 °C in sun light and -157 °C in shaded conditions. Along with the extreme temperature variations applied, the samples were located 200-1000 km above the Earth's surface in LEO, so facing the harsh space environment having ultrahigh vacuum, cosmic, UV, plasma, and ionizing radiations and environmental contaminations. Scanning electron microscopy micrographs of the exposed and non-exposed composite surfaces were comparatively studied to see the morphological patterns (Fig. 8d). It was observed that the space exposure enhanced the surface brightness probably due to matrix decomposition and fiber surfacing along with the variations in surface conductivity and atomic number of the material in LEO.

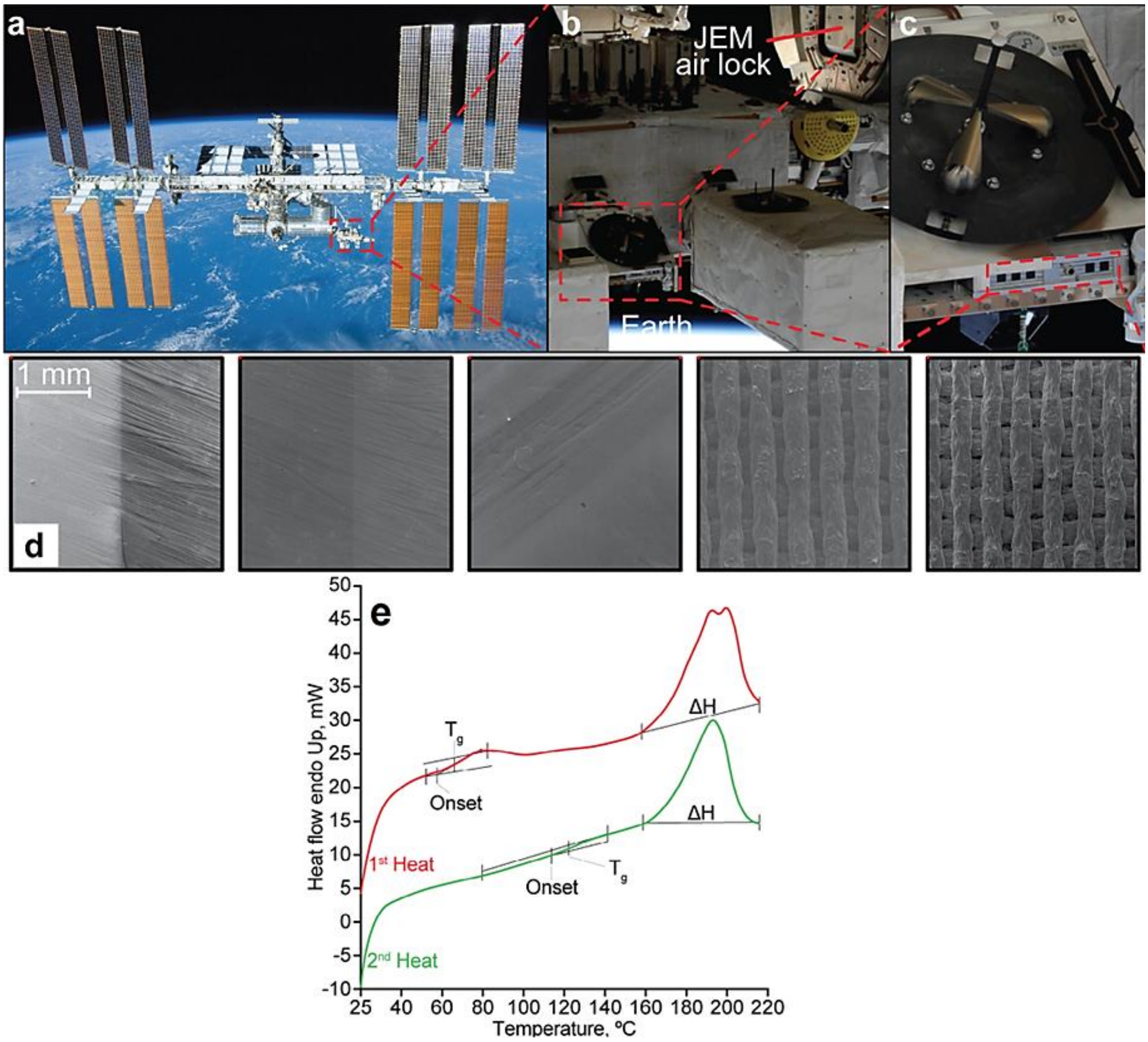

Fig. 8. Carbon fiber reinforced epoxy composites samples: (a) image of International Space Station (ISS) highlighting the sample location; (b) Japanese experiment module (JEM) with the location of the Nanoracks External Platform (NREP); (c) NREP with a highlight on samples exposed to lower earth orbital (LEO); (d) scanning electron microscopy images at interface between the exposed (left) and unexposed area (right); (e) representative differential scanning calorimetry curves for three dimensional printed sample [110]. Reproduced with permission from Wiley Open access

However, no microcracking was perceived in the morphology scans showing the stability of the composite material. Fig. 8e illustrates the differential scanning calorimetry thermograms of the tetrafunctional epoxy/carbon fiber composites in the range of 25-220 °C. The changes in the glass transition temperature and enthalpy were used to inspect the effect of LEO exposure on the thermal profiles of the composites. The thermograms were scanned for two heating cycles. No obvious changes in the glass transition or enthalpy of the materials before/after LEO exposure were observed revealing the exceptional heat stability of the tested composites. Here, most probable reason may be the formation of robust composite structure using crosslinked tetrafunctional polyepoxide chains and carbon fiber linked interfaces. Correspondingly, the worth of high-tech three dimensional printed carbon fiber composites has been established for an essential aerospace deployment like extreme temperature stability in LEO atmosphere, so demanding an intense need of further research in this field.

Low thermal conductivity of space structures

Low thermal conductivity materials have been continuously searched for structural designs needed in space shuttle application [111]. Both the conventionally processed as well as three dimensional printed composites have been examined for low heat conduction and better insulation requirements of aerospace vehicle parts [112]. Zhan et. al. [113] devised polypropylene/short carbon fiber composites by means of fused deposition modeling. The composite with 50 % carbon fiber contents had 40% increment in the bending strength, relative to unfilled polypropylene matrix. This system also exhibited the appropriately low thermal conductivity abound 0.266 W/mK. These results enhanced the importance of polyolefin matrix carbon fiber composites in space sector. Stepashkin and colleagues [114] devised poly(ether ether ketone)/continuous carbon fiber composites via fused deposition modeling based three dimensional printing. The finally obtained complex objects are displayed in Fig. 9a&b.The fractured surface study of as prepared 20 wt.% carbon fiber filled composite revealed unidirectional fiber orientation in the matrix (Fig. 9c). However, delamination caused visible cracks, surface breakage, and shear ladders due to the mechanical failure (Fig. 9d). As per thermal conductivity explorations (25-300 ºC.), the three dimensional printed composite had lower values around 0.21-0.25 W/m·K, relative to the as cast sample (0.27-0.30 W/m·K) (Fig. 9e). Thus, the validity of fused deposition modeling has been established for the space demanded low thermally conducting thermoset/carbon fiber composites. Hither, the traditional carbon fiber composites have been widely scrutinized for low thermal conductivity or insulation related applications in space sector, nonetheless there is restricted literature available regarding three dimensional printed composites for deployment in spacecraft parts with tailored heat conduction.

Thermo-dimensional stability demanding aeronautical parts

Further crucial heat stability aspect looked for aerospace solicitations (satellite antennas, engine components, thermal sensors, etc.) can be referred as thermal-dimensional stability [115]. In this concern, Chen and colleague [116] reinforced polyamide matrix with short carbon fibers as well as continuous carbon fibers using fused filament fabrication technique. The heat deformation and thermo-dimensional stability of ensuing three dimensional printed composites were deliberated through numerical finite-element analyses. The dual reinforced composite design with planar lattice structures supported the simultaneous constancy of materials under heat/dimensional changes [117].

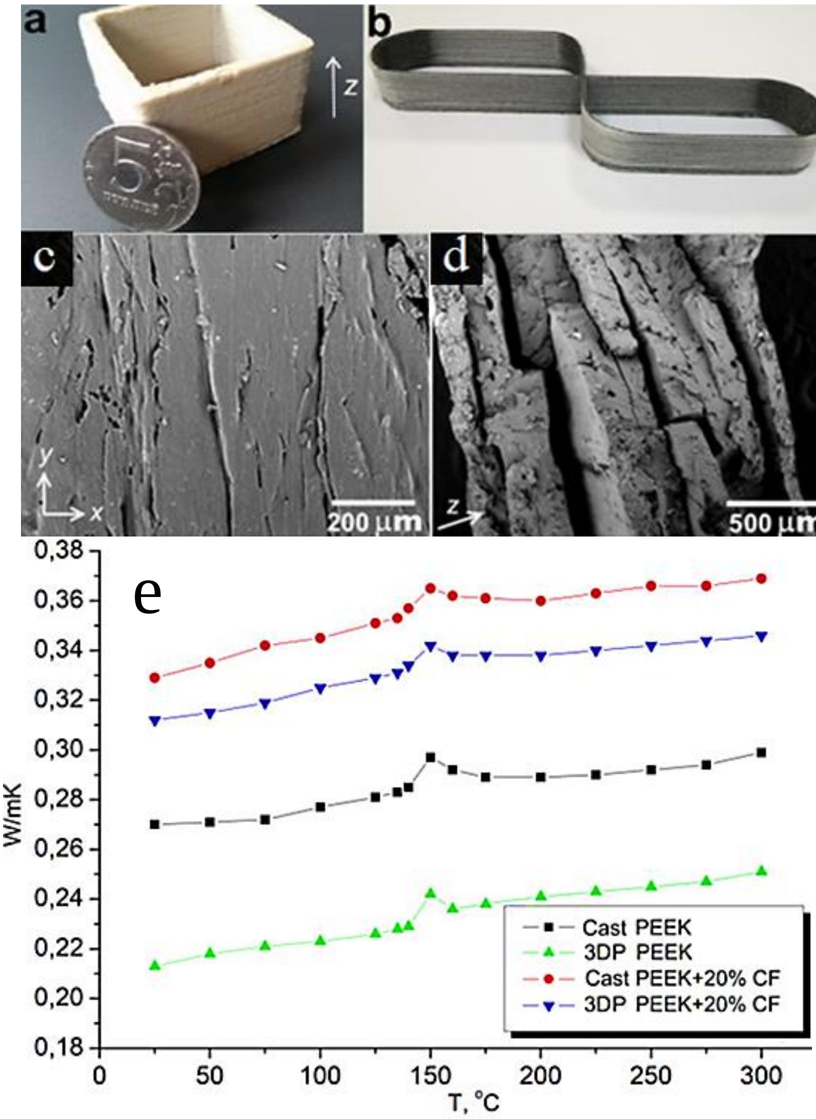

Fig. 9. (a&b) outlook of three dimensional printed poly(ether ether ketone)/carbon fiber articles; (c) the fracture surfaces of three dimensional printed poly(ether ether ketone) (PEEK)+20 % carbon fiber (CF); (d) obtained after mechanical delamination; (e) thermal conductivity of as cast and three dimensional printed (ether ether ketone)/carbon fiber composites [114]. Reproduced with permission from Elsevier

Hence, the fused filament fabrication based three dimensional printing was found successful to construct exceptionally stable aerospace structures sustaining the heat/delamination effects in exosphere. Here again, limited literature found specifically addressing the thermo-dimensional features of three dimensional printed carbon fiber materials for antennas, engines, or sensors in space sector.

ASPECTS, CHALLENGING AND FORTHCOMING OPPORTUNITIES

In recent eras, three dimensional printing has been frequently adopted in aeronautical sectors to attain precisely/accurately formed complex objects/structures [118]. Although, this technique has been used for metallic or ceramic materials, nevertheless it has shown great proficiency towards designing the polymer and related hybrid designs. Owing to trending research towards the deployment of carbon fiber reinforced composites in aerospace zones, likelihoods of three dimensional printed design precision and end performances have been sightseen. As surveyed in numerous forgoing sections/subsections of this review, variety of carbon fiber loaded composites have been designed through the wide ranging additive manufacturing tactics (Table 2).

Table 2. *Significant aspects of aerospace relevant three dimensional printed carbon fiber reinforced composites*

Matrix	Filler/nanofiller	Three dimensional printing technique	Features/Application	Ref.
Poly(ether ether ketone) thermoplastic	Carbon fiber	Screw extrusion based three dimensional printing	Average fiber length 209 μm; tensile and flexural strength 170 MPa and 223 MPa, respectively; 143% and 88% increment in tensile and flexural strength	[42]
Poly(ether ether ketone) Thermoplastic	Carbon fiber; 10 wt.%	Fused deposition modelling	Increasing screw speed 35-65 rpm enhanced tensile strength 118-137 MPa; within heat treatment temperatures 175-300 °C, crystallinity, tensile strength, and tensile modulus 21-35%, 51-135 MPa, and 3.5-9.2 GPa, respectively; flexural strength and modulus 86-234 MPa and 3.7-9.5 GPa, respectively	[43]
Urethane acrylate; tough photocurable thermosetting resin	Continuous carbon fiber; average fiber volume fraction 15.2-15.7%	Light assisted three dimensional ink printing	Scanning electron microscopy fractured surface with fiber pull out/cylindrical voids; maximum tensile strength 400 MPa; interlaminar strength 4 MPa	[44]
Polyamide 6	Carbon fiber; infill densities or volume fraction 18-62 %	Fused filament fabrication	Complex three dimensional triangular, hexagonal, or rectangular geometries; strength 55-62%; rectangular geometry superior in fill density	[50]
Polyamide 6	Carbon fiber; 41% fiber content	Additive manufacturing	mechanical properties vs. printing parameters; tensile strength and modulus 730 MPa and 29.23GPa, respectively; 98 and 81 % rise in tensile strength and modulus, correspondingly	[51]
Nylon 6	Continuous carbon fibers fiber volume fraction up to 60 %	Fused filament fabrication	Optical microscopy interlayer adhesion; scanning electron microscopy fractured surface fiber pull out/rupturing; fiber volume fraction up to 60%; composite ultimate strength 446.9 MPa; neat matrix ultimate strength 19.2 MPa; 2231% increment	[52]
Poly(amide-imide)	Carbon fiber	Fused deposition modeling	Strength and glass transition 105 MPa and 295 °C, respectively	[53]
Poly(lactic acid)	Carbon fiber; 27% carbon fiber contents considered as weight ratio	Fused deposition modeling	Flexural strength and modulus 335 MPa and 30 GPa, respectively	[54]

Poly(lactic acid)	Carbon fiber; Volume fraction 100 %	Additive manufacturing	Composite tensile strength and shear modulus 3920 MPa and 1268 MPa, respectively; unfilled matrix tensile strength and shear modulus 3125 MPa and 1092 MPa, correspondingly; dimensional printed isogrid components for aerospace	[55]
Acrylonitrile butadiene styrene	Carbon fiber; carbon nanotube; loading ratio 27 %	Fused deposition modeling	Ultimate strength of acrylonitrile butadiene styrene/carbon fiber/carbon nanotube 41-47 MPa; acrylonitrile butadiene styrene/carbon fiber 40-46 MPa; neat matrix 32-38 MPa	[73]
Epoxy	Carbon fiber; carbon nanotube; 10 phr	Direct ink writing	Thermal conductivity 0.3 W/m.K; flexural modulus 6 GPa; flexural strength 0.1 GPa	[74]
Epoxy	Carbon fiber; carbon nanotube	Fused filament fabrication	Ultimate compressive strength 136 MPa; electrical resistance 61 G Ohms	[80]
Epoxy	Carbon fiber; graphene oxide Carbon fiber:graphene oxide ratio 3:1	Stereolithography	0.8 wt.% graphene oxide compression strength 3 MPa; 10% rise	[81]
Polyamide	Short carbon fibers; 20 wt.%	Fused filament fabrication	Nozzle wear and mechanical properties; Wear time t = 0-5540 min; stress strain investigations, tensile strength declined by 37% after 5540 min, relative to t =0 min wear sample	[87]
Thermoset	Continuous carbon fiber filling 10-70 %	Additive manufacturing	Parameter optimization; Messerschmitt-Bölkow-Blohm beam studies; stiffness and peak load; wing spar for aircraft	[91]
Poly(lactic acid)	Continuous carbon fiber 10.5 vol. %	Fused filament fabrication	Print speed and deposition rate 800 mm/min and 13.3 g/min, respectively; varying nozzle tilt angle 0-35°; strength ~ 100 MPa and modulus ~ 5 GPa (tilt angle 0°); strength and modulus > 120 MPa and 7 GPa, respectively (tilt angle 25°); internal aeronautical wing structures	[93]
Polyamide	Continuous carbon fiber; 100% filling density	Fused filament fabrication	Interlaminar shear strength 38 MPa; fracture toughness 2 kJ/m^2; high-tech aerospace structure	[98]
Polyurethane	Carbon fibers 5-12.5 wt.%	Vat photopolymerizati on	Dimensional stability; minimum shrinkage/defects inner aero-engine blades	[103]

Poly(ether ether ketone)	Continuous carbon fibers	Fused deposition method	Dimensional stability; rotating space components	[104]
Nylon 6	Short carbon fibers	Fused filament fabrication	0.2 % strain no cracks; 0.40 % delamination zig zag crack; strain 0.5-0.7 % microcracking; cryogenic liquid storage	[108]
Tetrafunctional epoxy resin; 3,3′-sulfonyldianiline	Carbon fibers	Fused filament fabrication	Temperature stability in LEO; International Space Station; Japanese Experimental Module (JEM); of exposed/non-exposed composites; exposed composite surface brightness due to matrix decomposition/fiber surfacing/increase in atomic number; differential scanning calorimetry 25-220 °C	[110]
Polypropylene	Carbon fibers	Fused filament fabrication	Low thermal conductivity of space structures 0.266 W/mK; 50 % carbon fiber contents; 40% increment in bending strength	[113]
Poly(ether ether ketone)	Continuous carbon fiber 5-30 %	Fused deposition modelling	Printed composite thermal conductivity 0.21-0.25 W/m·K; non-printed sample thermal conductivity 0.27-0.30 W/m·K	[114]
Polyamide	Short carbon fibers; continuous carbon fibers	Numerical finite-element based additive manufacturing	Thermo-dimensionally stable aeronautical parts	[116]

Among these, fused deposition modelling and fused filament fabrication have been noticed as the predominantly employed three dimensional printing techniques for space linked carbon fiber composites. Certain attempts have also mentioned the composite processing through direct ink printing, light assisted ink printing, stereolithography, Vat photopolymerization, and few others. Consequently, three dimensional printed composite combinations of varying polymers with short or continuous carbon fiber fillers have been reported. According to the meagre research reports, carbonaceous nanofillers have also been loaded in the carbon fiber composites. It was noted that optimal short carbon fiber or continuous carbon fiber contents used for most of the three dimensionally printed composites were in the range of 10-30 wt.%. Nonetheless, few studies also explored the three dimensionally printed composites having higher carbon fiber ratio of 40-70 wt.%, according to the desired structural end performance. As per analysis, number of three dimensional additive manufacturing methodologies have been listed for carbon fiber composites focusing the space structures. For designing the aerospace structural components, fused filament fabrication, fused deposition modelling, Stereolithography, direct ink writing, light assisted ink printing, Vat photopolymerization, and others have been reported as additive manufacturing techniques. Each of the technique own vital inherent parameters and specific equipment influencing the fabrication and end functioning of the carbon fiber composites. Amidst these proficient tactics, literature mostly documents the manufacturing of three dimensional printing of aeronautical designs via fused filament fabrication and fused deposition modelling. For instance, as surveyed in this review article (outlined in Table 2), most of the studies on three dimensional printing of aeronautical structures, observed so far between 2021-2024 employed fused deposition modelling [43, 51, 53-55, 73, 91, 104, 114] and fused filament fabrication [50, 52, 80, 87, 93, 98, 108, 110, 113] techniques. Generally speaking, all the three dimensional printing tactics possess relative advantages and confines guiding towards the selection of an appropriate technique for the desired end product or application. Furthermore, optimization of process parameter seemed indispensable to attain the desired material precision and performance attributes. Accordingly, three dimensional printing techniques have been employed to construct complex objects having triangular, rectangular, hexagonal, gyroid, or other intricate geometries with varying infill densities. Consequently, infill densities have been found to influence the mechanical profiles of the printed articles. Among mechanical features, tensile strength and modulus, flexural strength and modulus, compression strength, shear strength and modulus, interlaminar strength, dimensional stability, and wear properties of the printed composites have been studied for performance examination. Furthermore, glass transition temperature, thermal conductivity, cryogenic stability, and thermo-mechanical or thermal-dimensional stability have been measured to assess the heat constancy of the three dimensional printed carbon fiber composites. Subsequently, the reported composite systems revealed mechanical or thermal performance depending upon the material selection as well as the opted printing method. Unlike traditional aerospace aimed solution/melt based processing techniques, three dimensional printing techniques do not require post treatments, specific molds, high costs, tedious functioning, low product purity, or finishing necessities. Furthermore, three dimensional printing possesses recompences related to low price fabrication, generation of precise structures, least structural voids, complex object formation, and rapid production rate. Subsequently, the ensuing multifunctional aerospace composites or hybrids own remarkable heat stability and mechanical robustness advantages under extreme space environments.

Despite the countless benefits of three dimensional printing in high end space structures, still challenges exist to define an appropriate method to meet the demands of high resolution intricate multifunctional objects. The combination of nanocarbon particle with carbon fibers can remarkably enhanced the aeronautical performance of the printed composites, however the research is restricted in this area due to the aggregation issues of the nanoparticles. Before introducing carbon fibers in the desired matrix, surface modification or sizing processes have been recommended in the literature via various techniques, including spraying/electrospraying, chemical vapor deposition, spin coating, electrophoretic, and chemical surface modification, to enhance the matrix/filler compatibility [119]. Among these carbon fiber coating techniques, sophisticated techniques, like chemical vapor deposition, seemed to be beneficial for fine carbon nanoparticle dispersion, adhesion, and deposition on the fiber surfaces. Spraying techniques have also been used for coating carbon nanofillers on the fiber surfaces. However, spraying techniques may cause nanocarbon aggregation and poor matrix-filler compatibility, therefore leading to processing complications as well as crack formation in the resultant polymer/carbon fiber composites [120]. Therefore, choice of an appropriate technique for coatings nanocarbons on the carbon fiber surfaces seems indispensable before processing with the polymeric matrices. In this way, graphene or carbon nanotube based uniformly coated carbon fibers can be produced for better interracially interlinked high performance space composites.

Although, success of carbon fiber composites has been attained in distinct aeronautical motifs like wings, engine parts, antennas, fuel storage systems, fuselage, and other exterior structural parts, more innovations in combining the functional fibers with efficient matrices have been found indispensable using an appropriate three dimensional printing technique. For aerospace structures, first main aspect is to analyze the validity of the manufacturing process through mechanical property characterizations of carbon fiber based composites including their tensile/bending strength, impact resistance, flexural strength/modulus, etc. Secondly, it is important to apply theoretical/simulation methods to analyze the structural/mechanical attributes of carbon fiber based composites, under applied forces. In this concern, theoretical studies on three dimensional printing of carbon fiber materials via finite element analysis and similar approaches have been found beneficial to gain insights into failure modes, deformation, and stress distribution in various space structures, such as wings, antennas, and outer body parts. After confirmation from theoretical analysis, large scale production and structural validation can be practiced for real world application of carbon fiber based composites. Herein, for practical commercial grade applications, only the carbon fiber composites having desired superior strength-to-weight ratio, stiffness-to-weight ratio, and corrosion/shock/radiation resistance can be considered for aerospace engineering.

Subsequently, the use of polymer/carbon fiber/nanocarbon hybrids has been scarily examined on industrial scale for these aeronautical units and systems. According to NASA, for example, using carbon nanotube modified carbon fibers offered an effective route for reducing the weight of space vehicles in computer modeling investigations [121]. Nevertheless, including carbon fillers/carbon nanotubes hybrid for cutting down the weight of space vehicles, while maintaining the desired structural performance, need further theoretical/experimental investigations, practical implementations, and testing for future industrial level aerospace applications. Hither, the process-structure-functioning relationships in the discussed printed materials need to be deeply scrutinized to achieve forthcoming success in the space linked zones. To sum up, there is an intense need to expand the research on three dimensional printed carbon fiber or carbon fiber/nanocarbon reinforced composited to step into a factual future aerospace industry. Last but not the least, future experimental/theoretical studies on three dimensional printing carbon fiber based composites or nanocomposites may open ways to allied high tech industrial applications [122]. For example, three dimensional printed carbon fiber reinforced geopolymers can be applied for sustainable construction structures having advantageous ecological, durability, and mechanical/thermal resistance characteristics for commercial scale utilizations in civil engineering sector [123].

CONCLUSIONS

Conclusively, this revolutionary overview underscores the scientific impression of three dimensional printing methods on manufacturing and structure-property-performance outcomes of polymer/carbon fiber composites, endeavoured for aerospace industry. The cutting-edge carbon nanofiber reinforced polymeric composites have been designed through advanced three dimensional printing technologies and exploited for high end aerospace applications. For three dimensional printed composite formation, various polymers from the categories of thermoplastics or thermosets have been utilized, as conversed in the preceding review sections. Additionally, carbon fibers have been filled in the space matrices along with the carbon nanoparticles to further upsurge the physical characters and performance of final nanocomposites. Subsequent advanced three dimensional printed carbon fiber reinforced composites/nanocomposites have been surveyed for performance in internal wing structure, nozzle resilience, engine blades, antennas, dimensionally stable structures, cryogenic fuel containers, LEO exposure, and other thermo-mechanical solicitations in aeronautical architectures. At this juncture, broad span research has been observed regarding the three dimensional printed carbon fiber composites, however few efforts were detected regarding the polymer/carbon fiber/nanocarbon nanocomposites. Although, three dimensional printing techniques offer the vantages of low cost, rapid modelling and fabrication, precise end designs, etc., as compared to the conventional aerospace composite processing, still challenges exist towards the innovation of further material combinations, selection of appropriate additive manufacturing, as well as the parameter optimization. Ultimately, three dimensional printed carbon fiber composites defines a scorching area of research for next generation outperforming aeronautical structures focusing the constructions/components of small aircrafts, space crafts, satellites, space shuttles, missiles, etc.

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