Polymer Based Composites via Fused Filament Fabrications (FFF) - A Review and Prospective

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***Abstract* -Additive Manufacturing has gained a wide popularity since its origination due to its versatility in terms of materials and easiness in manufacturing components with complex geometries. Additive Manufacturing has gained a wide importance in last few years owing to developments of advanced materials like composites the author has reviewed the work related to FFF with specific thrust on polymer composites and effects of various operating parameters on the efficacy of Additive Manufacturing.**

Keywords:* *Additive Manufacturing, Fused Filament Fabrication, Polymer Composites, operational parameter

I. INTRODUCTION

Additive manufacturing is a strong tool for effective fabrication of components reducing the time of manufacture and expenses involved. Additive Manufacturing process can be completely optimised in producing physical models from virtual ones. The Additive Manufacturing process is achieved by slicing the model into layers obtaining each layer at a time. Additive manufacturing is being used to fabricate components through a wide spectrum of fields which includes automobile and aerospace domains. The other important applications of additive manufacturing includes medical and dental implants, knee and hip replacements[1]. This additive manufacturing process has certain limitations with regards to the availability of materials. Although the general perception of AM technologies is easy-to-capture, the complicated dependencies of AM processes on several related technologies such as material modelling, design tools, computing, and process design represent a real challenge for both applied and basic research, as shown in Figure 1 [2]. It can be considered that the investigation of AM technology effects on polymer composite materials is still in the area of research and development, but the increase of academic and industrial studies on AM of composites via FFF can clearly be distinguished in the recent years [3].

Further the components produced by the additive manufacturing exhibit anisotropic properties and poor surface finish owing to material bonding. In recent times the additive manufacturing technology has crossed various barriers and improved by leaps and bounds in view of the advancement in the development of new materials. This has enabled the designers to fabricate complex components and assemblies using additive manufacturing, but the cost effectiveness of additive manufacturing has not been completely addressed.

The author here in has made an attempt to review the works carried out with regards additive manufacturing specifically on Fused Filament Fabrication (FFF). The thrust areas of FFF in which research is pursued vigorously pertain to new materials methods and problems.

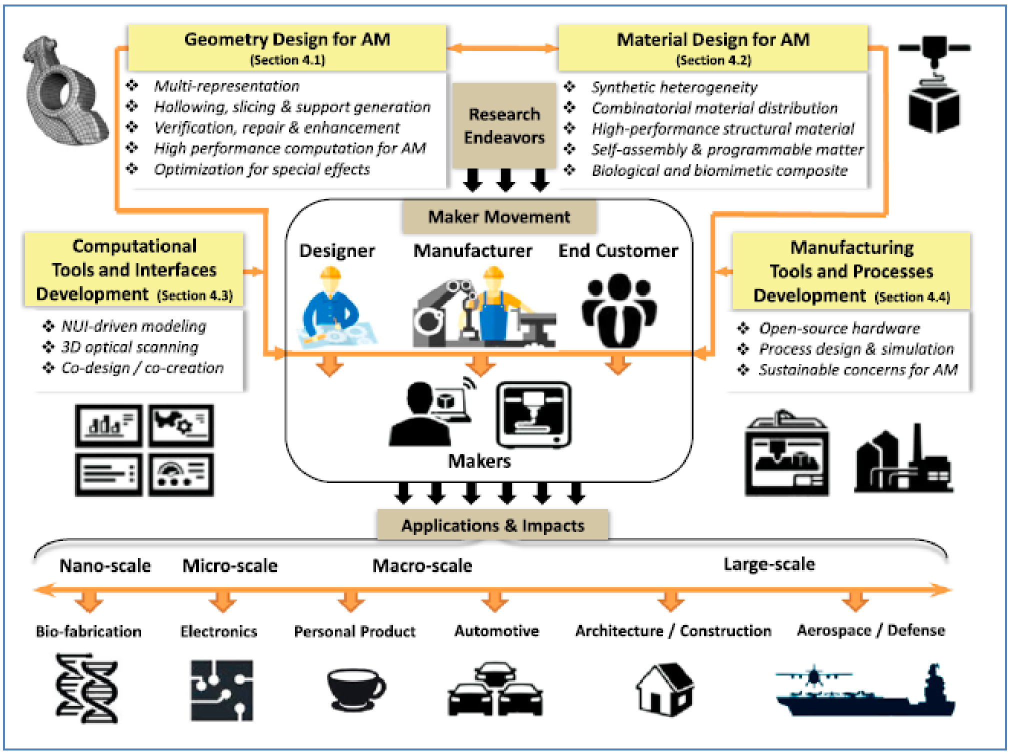

FIG 1. A GEOMETRY MATERIAL MACHINE PROCESS ROADMAP FOR AM [2]

II. FFF PROCESS PARAMETERS AND POLYMER COMPOSITE MATERIALS

Composites refer to the combination of two or more constituent materials, posessing significantly different properties, to create a single material offering increased performance as compared to the individual components.[4] The development of composite materials for AM processes is well established with both short fiber and continous fiber reinforcements.[5]–[13] Though still lagging behind conventionally manufactured fiber reinforced polymers, the addition of short fibers has proven to increase the tensile properties compared to the pure polymers, and the past decade of AM composite research and development has accommodated fruitful knowledge toward further exploration of their fracture properties. With unreinforced polymers the initiation of cracks and failure starts at the layer interfaces, where the amount of mixing between layers determines strength.[14] By contract, upon addition of the fibers, the layer bonding mechanisms change slightly and also the fibers introduce another mechanism of potential crack initiation.[11] Understanding the layer adhesion of fiber reinforced composites as a function of the fabrication process is crucial to the advancement of AM technology for end consumer use. The current market uptake is limited by the lack of established product standards and process certifications of AM parts, and robust mechanical testing of fracture mechanics must be performed in order to establish these standards.

Michael Hebda et al [15] presented a methodology in the form of equations for predicting height, width and cross section values for given process parameters in FFF process for initial lay down on to a glass surface.

The model presented is based on conservation of mass and simplifies to a large extent, the full CFD calculations required. The main objective of author is to model the first layer effects when the surface of the polymers is to be deposited on permanent solids namely glass. The model predicted the dimensions for a wide range of nozzle gaps size and velocity ratio with high precision. The author claims that the equation developed will allow the FFF user to design tool paths more effectively.

Sunpreet Singh et al [16] studied the mechanical characteristics of heat-treated fused filament fabricated parts. The main problem limiting the growth of FFF is the poor mechanical and surface properties of the components. Though FFF largely used for the manufacturing of different components, this barrier could not be overcome. These characters can be improved by using better materials, quality AM setups and maintaining the process variables. But pre and post treatment process are fond to expound the efficiency of the system. The author here in has devised a heat treatment process which improves the performance of components fabricated by FFF process. The components are fabricated with ABS with different infill densities(20%, 60% and 100%) and annealing process was carried out at three different temperatures ranging from 105^0C to 125^0C for three different time duration levels(20, 25 and 30 min). There exist various process variables that include infill density, raster angle, orientation, layer thickness, printing speed, printing environment, and extrusion temperature [17–23], which influence the quality characteristics (physical and mechanical) of the FFF products. The authors further optimized the Surface roughness, hardness, dimensional accuracy, temperature flexure and impact strengths using DOE through Taguchi. They concluded that the annealing process had a major influence the physical and mechanical properties due to reflow of the materials which will decrease the porosity by filling the inter layer gaps to significant extent.

Tianyun Yao et al [24] investigated a method to predict the ultimate tensile strength of 3D printing polylactic acid (PLA) materials with different printing orientations. They established a theoretical model firstly to predict the ultimate tensile strength of FDM PLA materials based on transverse isotropic hypothesis, classical lamination theory and Hill-Tsai anisotropic yield criterion, and then verified by tensile experiments. Compared with previous models, this model provided two kinds of in-plane shear modulus calculation methods, so the calculation results were more reliable. The specimens, designed according to the current plastic-multipurpose test specimens standard ISO 527-2-2012, were printed in seven different angles (0°, 15°, 30°, 45°, 60°, 75°, 90°) with three layer thicknesses (0.1 mm, 0.2 mm, 0.3 mm) for each angle. It was also found that the ultimate tensile strength decreased as the printing angle becomes smaller or the layer becomes thicker.

Yubo Tao et al [25] performed a case Study on Mechanical Modeling Optimization of Polymer Composites via FFF. In this research, the compression performance of FDM printed circle, square, and voronoi WPCs cellular structures were investigated using finite element simulations and compression experiments. The results showed that the circle cellular structure demonstrated great fluctuations between the simulations and experimental results. The cavity porosity was also found to increase with the increase of the print line width. Further, to improve the accuracy of simulations, the cavity porosity exists in the cellular structures was considered while revising the models. After modification, square cellular models compressed the least, followed by the circle and voronoi ones, which was consistent with the experimental results. Further noticed that the minimizing the print line width could reduce cavity porosity. Nonetheless, thinner print line width and smaller wood fiber size in filaments will likely increase manufacturing cost and difficulty.

Santiago Cano et al [26] on the works on Optimization of Material Properties for Highly-Filled Thermoplastic Polymers via FFF of Ceramic. They reported that the Filaments of polymer-based compounds highly-filled with ceramic powders (ca. 40-60 vol.%), known as feedstocks, can be processed by means of FFF to shape ceramic parts. Such parts are then debound in order to remove the polymer from the feedstock. A highly porous structure is obtained, which is sintered at high temperatures to produce dense ceramic components. The use of highly-filled polymers constitutes a processing challenge, due to their high viscosity that complicates the fabrication by FFF. The material properties of compounds filled with zirconia (ca. 47 vol%) were optimized by the incorporation of an additional low viscosity component. It was observed that by adding the low viscosity component, the mechanical properties (flexibility, strength and stiffness) and feedstock viscosity are suitable for the production of filaments and the FFF process. The mechanical properties of the filaments were evaluated with tensile tests to determine the processability by FFF [27,28]. Furthermore, the low viscosity component further promotes the defect-free removal of the major polymer fraction by leaching with a solvent.

William H. Ferrell and Stephanie TerMaath [29] have investigated on Print Parameter Effects of Fracture Properties of Composites via FFF. In the experimental investigations of this paper, carbon fiber reinforced plastic composites are manufactured using fused filament fabrication and the fracture properties are investigated as a function of printing parameters. End Notched Flexure tests are conducted to obtain the interlaminar energy release rate in shear. The effects of highly influential printing parameters on the fracture behavior of fused filament fabrication manufactured carbon fiber reinforced acrylonitrile butadiene styrene are investigated and reported .

Shahriar Bakrani Balani et al [30] studied the influence of printing parameters on the stability of deposited beads in fused filament fabrication of poly(lactic) acid

In this work, the FFF process applied to the PLA was investigated via experiments, analytical equations and numerical simulation. The effect of the printing parameters (i.e. nozzle diameter, feed rate and layer height) and the physical properties of the polymer (i.e. thermal transitions and rheological behaviour) on the inlet velocity, shear rate and viscosity in the liquefier was determined. Further, In parallel, a Multiphysics TPF model was developed to determine the viscosity of the polymer and shear rate according to various inlet velocities. Moreover, the numerical simulation was used to model the shape of the extrudate when it exits from the nozzle. The results obtained via numerical simulation were validated through experimental study. The numerical simulation focused on the shape of the deposited filament before deposition on the substrate for different flow regimes.

M.A. Caminero et al [31] carried out the works on impact damage resistance of 3D printed continuous fibre reinforced thermoplastic composites using FFF. The aim of this study is to evaluate the effect of build orientation, layer thickness and fibre volume content on the impact performance of 3D printed continuous carbon, glass, and Kevlar® fibre reinforced nylon composites, manufactured by FDM technique. Charpy impact tests are carried out to determine impact strength. SEM images of fractured surfaces are examined to assess failure mechanics of the different configurations. It is observed that the effect of layer thickness of nylon samples on the impact performance was different for flat and on- edge samples. Impact strength increases as layer thickness increases in flat samples but, conversely, it decreases in on-edge samples, depicting a more brittle fracture. In addition, the results show that impact strength increases as fibre volume content increases in most cases.

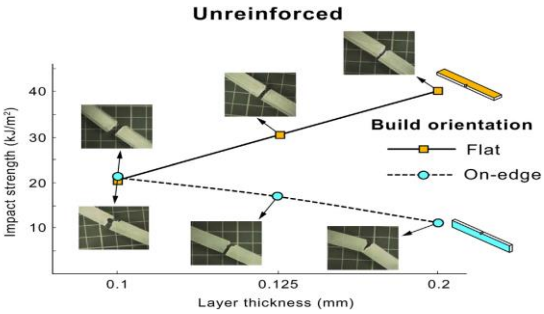

Fig. 2. Graphical comparison of average maximum impact strength of unreinforced nylon specimens. Effects of build orientation and layer thickness.[31].

TABLE I. AVERAGE IMPACT TEST RESULTS OF REINFORCED NYLON SAMPLES AND PROCESS PARAMETERS RANGES. STANDARD DEVIATION IS DEPICTED IN BRACKETS.[31]

Average impact strength of nylon samples ***EC*** (kJ/m2)			
Build orientation	Type A	Type B	Type C
Carbon fibre			
Flat	22.21(2.68)	33.21(0.94)	57.50(1.56)
On-edge	24.73(1.61)	59.76(3.98)	82.26(6.79)
Kevlar® fibre			
Flat	30.11(3.57)	83.69(6.10)	125.47(4.75)
On-edge	36.42(1.28)	95.11(7.05)	184.76(15.11)
Glass fibre			
Flat	74.16(7.96)	206.66(2.27)	271.19(9.67)
On-edge	86.30(8.02)	246.19(2.06)	280.95(3.77)

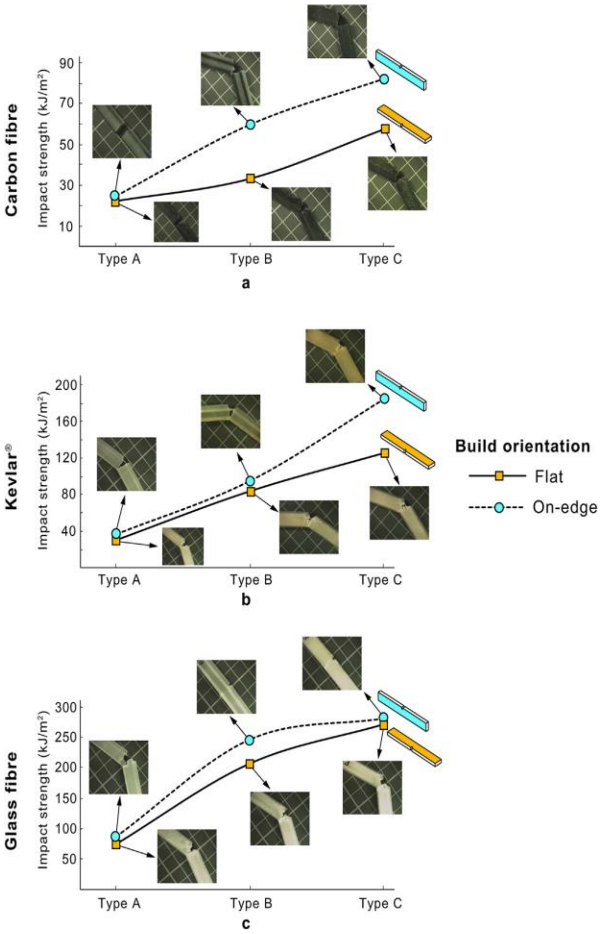

Fig. 3. Graphical comparison of average maximum impact strength of reinforced nylon specimens. Effects of build orientation and fibre volume content. A) carbon fibre, b) kevlar® fibre, c) glass fibre.[31]

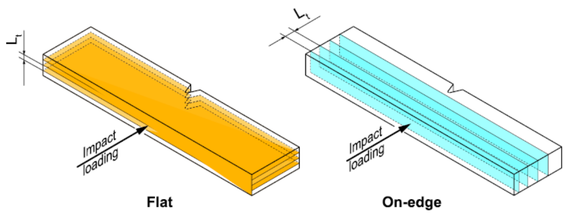

Fig. 4. Graphical description of the effect of layer thickness and build orientation on impact strength.[31]

Kazem et al [32] carried out the experimental works on Impact of Defects on Tensile Properties of 3D Printed Parts Manufactured by Fused Filament Fabrication. In this work, the directional properties of FFF 3D printed PLA specimens per ASTM 638-14. Tensile strength, modulus, and failure strain of specimens along and transverse to the printing direction are evaluated. It is observed that FFF 3D printing introduces anisotropic behavior to the manufactured part, e.g. tensile strength of 57.7 and 30.8 MPa for loading along and perpendicular to the printing direction, respectively. FFF 3D printers, like other automated manufacturing techniques, introduce defects into fabricated parts considering their tolerances, e.g. in the form of missing materials leading to gaps. This study investigates the impact of gaps on tensile strength, modulus, and failure strain of 3D printed parts. Compared with the baseline, 20.5% reduction in tensile strength, 9.6% in modulus, and 11.5% in failure strain are observed due to missing extrudates (gaps) transverse to the loading direction.

Shenglong Jiang et al [33] analysed the Mechanical properties of polyetherimide parts fabricated by fused deposition modelling In this work, PEI was applied in the fused deposition modeling (FDM)–based 3-D printing for the first time. The entire process from filament extrusion to printing was studied. It was observed that the filament orientation and nozzle temperature were closely related to the mechanical properties of printed samples. When the nozzle temperature is 370^0C, the mean tensile strength of FDM printing parts can reach to 104 MPa, which is only 7% lower than that of injection molded parts. It can be seen that the 0^0 orientation set of samples show the highest storage modulus (2492 MPa) followed by the 45^0 samples, and the 90^0 orientation set of samples show the minimum storage modulus (1420 MPa) at room temperature. The above results indicated that this technique allows the production of parts with adequate mechanical performance, which does not need to be restricted to the production of mock-ups and prototypes.

Chin-San Wu & Chi-Hui Tsou [34] worked on fabrication, characterization, and application of biocomposites from poly(lactic acid) with renewable rice husk as reinforcement. Filaments for three-dimensional printing were fabricated from composites based from biodegradable Poly(lactic Acid) (PLA) and renewable rice husk (RH). Acrylic acid (AA)-grafted PLA (PLA-g-AA) and coupling agent-treated rice husk (TRH) were incorporated to improve the properties of PLA/RH biocomposites. The biocomposite morphology, tensile properties, water absorption, and biodegradability were investigated. PLA-g-AA/TRH demonstrated superior tensile properties than PLA/RH because of the improved compatibility between the polymer and the TRH. TRH was evenly dispersed in the PLA-g-AA, brought about by ester reaction; consequently, branched and three-dimensional networks structures were generated. These PLA-g-AA/ TRH biocomposites can be used as biodegradable materials or filaments for 3D printing applications because of their low cost and excellent properties.

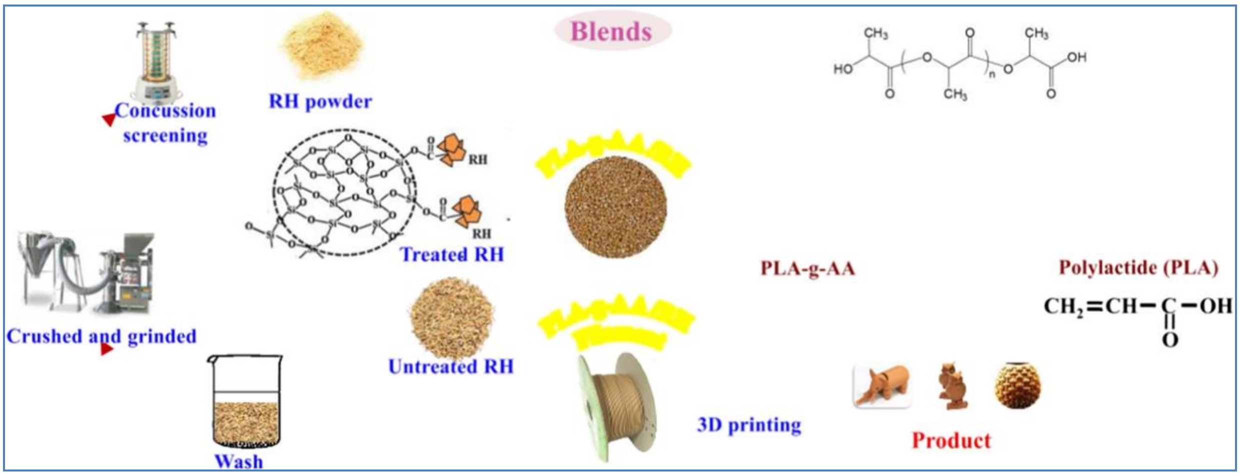

Fig. 5. Reaction scheme detailing processing of treated rice husk (trh) and grafted polylactic acid (pla-g-aa), producing filaments for 3d printing applications [34]

Juan Naranjo Lozada etal[35] studied on Tensile properties and failure behavior of chopped andcontinuous carbon fiber composites produced by Additive Manufacturing. In this work, 3D printed composites with continuous carbon fiber reinforcement and chopped carbon fiber (Onyx) composites were manufactured and tested. Onyx samples show small improvements with respect to Nylon. Results showed that factors such as infill density and infill patterns in 3D printed chopped composites affect part strength. As discussed, the Triangular shape has a better tensile performance and should be used whenever possible.

The influence of fiber volume fraction (VF) and fiber placement arrangement on continuous carbon fiber reinforcement composites were measured. As expected, the tensile properties for CFR composites have much better performance when the amount of fiber is increased. From the comparison of the two printing architectures (1R vs 3R) with the same volume fraction, it was shown that the arrangement of fibers has an effect on tensile properties with a slightly better performance for the wider arrangement. The effects of moving the initial point of reinforcement deposit on the fracture mechanisms, elastic moduli and tensile strength were also studied. A variation of the ROM method to predict elastic modulus for CFR composites with lower fiber content that considers different geometric characteristics was proposed. Good correspondence between predicted and experimental data was found for volume fractions smaller than 11%. Findings may help the designer to define the best parameters for the print part, and should also be helpful for the design of 3D printed composites.

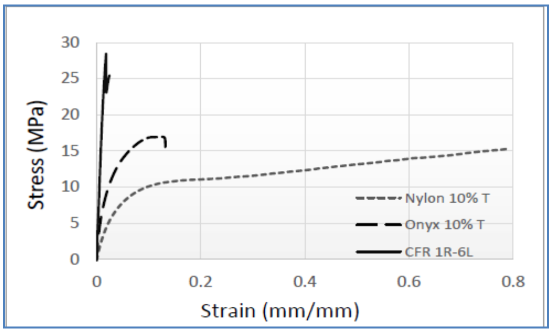

Fig 6. Mechanical behavior curves nylon, chopped composites (onyx), and cfr composites [35]

III. CONCLUSIONS

Additive manufacturing of polymer matrix composites has become a very interesting topic for researchers due to provided advantages such as weight reduction, part consolidation, design optimization and ability to produce very complex integrated geometries especially for aerospace and automotive applications. Most FDM studies of carbon reinforced polymer matrix composites which are conducted by the FDM process, conclude that the mechanical performance is significantly enhanced, especially in terms of tensile strength and flexural properties while the mechanical performance is severely dependent on the build direction and porosity. Moreover, it is also limited by the planar layer-by-layer nature of the AM processes. Thus, some extra enhancements in terms of material, performance and process are needed to further exploring of the full potential. Synthesis of different materials, reinforcement material range, fiber loading are the main barriers to be overcome on the material side whereas elimination of voids and enhancement of interfacial bonding and repeatability shall be considered on the performance aspect. The maximum part size, process resilience and productivity shall be improved in years of process.

REFERENCES

[1] R. J. Urbanic & S. M. Saqib "A manufacturing cost analysis framework to evaluate machining and fused filament fabrication additive manufacturing approaches" Int J Adv Manuf Technol (2019). https://doi.org/10.1007/s00170-019-03394-x

[2] W.Gao, Y. Zhang, D. Ramanujan. "The status, challenges, and future of additive manufacturing in engineering", Computer-Aided Design, 2015; 69: 65-89.

[3] J. Frketic, T. Dickens, S. Ramakrishnan. "Automated manufacturing and processing of fiberreinforced polymer composites", Additive Manufacturing: 2017; 14: 69-86.

[4] G. D. Goh, V. Dikshit, A. P. Nagalingam, G. L. Goh, S. Agarwala, S. L. Sing, J. Wei, and W. Y. Yeong, "Characterization of mechanical properties and fracture mode of additively manufactured carbon fiber and glass fiber reinforced thermoplastics," Mater. Des., vol. 137, pp. 79–89, 2018.

[5] L. J. Love, V. Kunc, O. Rios, C. E. Duty, A. M. Elliott, B. K. Post, R. J. Smith, and C. A. Blue, "The importance of carbon fiber to polymer additive manufacturing," J. Mater. Res., vol. 29, no. 17, pp. 1893–1898, 2014.

[6] H. L. Tekinalp, V. Kunc, G. M. Velez-Garcia, C. E. Duty, L. J. Love, A. K. Naskar, C. A. Blue, and S. Ozcan, "Highly oriented carbon fiber-polymer composites via additive manufacturing," Compos. Sci. Technol., vol. 105, pp. 144–150, 2014.

[7] W. Zhong, F. Li, Z. Zhang, L. Song, and Z. Li, "Short fiber reinforced composites for fused deposition modeling," Mater. Sci. Eng. A301, vol. 301, pp. 125–130, 2001.

[8] R. W. Gray, D. G. Baird, and J. Helge Bøhn, "Effects of processing conditions on short TLCP fiber reinforced FDM parts," Rapid Prototyp. J., vol. 4, no. 1, pp. 14–25, 1998.

[9] M. L. Shofner, K. Lozano, F. J. Rodríguez-Macías, and E. V. Barrera, "Nanofiber-reinforced polymers prepared by fused deposition modeling," J. Appl. Polym. Sci., vol. 89, no. 11, pp. 3081–3090, 2003.

[10] X. Wei, D. Li, W. Jiang, Z. Gu, X. Wang, Z. Zhang, and Z. Sun, "3D Printable Graphene Composite," Sci. Rep., vol. 5, pp. 1–7, 2015.

[11] S. Dul, L. Fambri, and A. Pegoretti, "Fused deposition modelling with ABS-graphene nanocomposites," Compos. Part A Appl. Sci. Manuf., vol. 85, pp. 181–191, 2016.

[12] S. H. Masood and W. Q. Song, "Development of new metal/polymer materials for rapid tooling using Fused deposition modelling," Mater. Des., vol. 25, no. 7, pp. 587–594, 2004.

[13] N. Li, Y. Li, and S. Liu, "Rapid prototyping of continuous carbon fiber reinforced polylactic acid composites by 3D printing," J. Mater. Process. Technol., vol. 238, pp. 218–225, 2016.

[14] X. Tian, T. Liu, C. Yang, Q. Wang, and D. Li, "Interface and performance of 3D printed continuous carbon fiber reinforced PLA composites," Compos. Part A Appl. Sci. Manuf., vol. 88, pp. 198–205, 2016.

[15] Michael Hebda, Claire McIlroy, Ben Whiteside, FinCaton-Rose, Phil Coates, "A method for predicting geometric characteristics of polymer deposition during fused-filament-fabrication", Additive Manufacturing, Volume 27, May 2019, Pages 99-108.

[16] Sunpreet Singh, Manjeet Singh, Chander Prakash, Munish Kumar Gupta, Mozammel Mia, Rupinder Singh, "Optimization and reliability analysis to improve surface quality and mechanical characteristics of heat-treated fused filament fabricated parts" Int J Adv Manuf Technol (2019). https://doi.org/10.1007/s00170-018-03276-8

[17] Anitha R, Arunachalam S, Radhakrishnan P, "Critical parameters influencing the quality of prototypes in fused deposition modelling" ,J Mater Process Technol,2001; 118:385–388

[18] Armillotta, "Assessment of surface quality on textured FDM prototypes. Rapid Prototype J A 2006; 12:35–41

[19] Panda SK, Padhee S, Sood AK, Mahapatra SS, "Optimization of fused deposition modelling (FDM) process parameters using bacterial foraging technique" Intell Inf Manag, 2009; 30:89

[20] Mohamed OA, Masood SH, Bhowmik JL, " Investigation on the flexural creep stiffness behavior of PC–ABS material processed by fused deposition modeling using response surface definitive screening design", JOM 2009;69:498–505

[21] Torres J, Cotelo J, Karl J, Gordon AP, Mechanical property optimization of FDM PLA in shear with multiple objectives", JOM 2015;67:1183–1193

[22] Basavaraj CK, Vishwas M, " Studies on effect of fused deposition modelling process parameters on ultimate tensile strength and dimensional accuracy of nylon". In IOP Conference Series: Materials Science and Engineering, 2016;149:012035

[23] Griffiths CA, Howarth J, De Almeida-Rowbotham G, Rees A, Kerton R "A design of experiments approach for the optimisation of energy and waste during the production of parts manufactured by 3D printing", J Clean Prod 2009; 139:74–85

[24] Tianyun Yao, Zichen Deng, Kai Zhang, Shiman Li, "A method to predict the ultimate tensile strength of 3D printing polylactic acid (PLA) materials with different printing orientations"

[25] Yubo Tao, Ling Pan, Dexi Liu, Peng Li "A Case Study: Mechanical Modeling Optimization of Cellular Structure Fabricated Using Wood Flour-Filled Polylactic Acid Composites with Fused Deposition Modeling" Additive Manufacturing, 2019; PII: S2214-8604(18)30809-1

[26] Santiago Canoa, Hrvoje Cajnerb, Joamin Gonzalez-Gutierrez a, Janak Sapkotaa, Christian Kuklac, Florian Arbeiterd, Stephan Schuschnigg a,Clemens Holzer a, "Optimization of Material Properties for Highly-Filled Thermoplastic Polymers used in Fused Filament Fabrication of Ceramics"

[27] N. Aliheidari, R. Tripuraneni, C. Hohimer, J. Christ, A. Ameli, and S. Nadimpalli, "The impact of nozzle and bed temperatures on the fracture resistance of FDM printed materials," in Proc. SPIE 10165,Behavior and Mechanics of Multifunctional Materials and Composites 2017, p. 1016512.

[28] M. Spoerk, Florian Arbeiter. "Polypropylene Filled With Glass Spheres in Extrusion-Based Additive Manufacturing: Effect of Filler Size and Printing Chamber Temperature" Macromol. Mater. Eng. 2018, 303, 1800179

[29] William H. Ferrell and Stephanie TerMaath, "Print Parameter Effects on Fracture Properties of Composites Fabricated Through Fused Filament Fabrication" AIAA SciTech Forum, 7-11 January 2019, San Diego, California

[30] Shahriar Bakrani Balania,, France Chabert,, Valérie Nassieta, Arthur Cantarel, "Influence of printing parameters on the stability of deposited beads in fused filament fabrication of poly(lactic) acid" , Additive Manufacturing 25 (2019) 112–121

[31] M.A. Camineroa, J.M. Chacónb, I. García-Morenoa, G.P. Rodrígueza, "Impact damage resistance of 3D printed continuous fibre reinforced thermoplastic composites using fused deposition modelling" Composites Part B 148 (2018) 93–103

[32] Kazem Fayazbakhsh, Mobina Movahedi, Jordan Kalman, "The Impact of Defects on Tensile Properties of 3D Printed Parts Manufactured by Fused Filament Fabrication" Materials Today Communications Volume 18, March 2019, Pages 140-148

[33] Shenglong Jiang, Guangxin Liao, Dingding Xu, Fenghua Liu , Wen Li1, Yuchuan Cheng, Zhixiang Li and Gaojie Xu, "Mechanical properties analysis of polyetherimide parts fabricated by fused deposition modelling" High Performance Polymers Vol 31, Issue 1, 2019;1–10

[34] Chin-San Wu & Chi-Hui Tsou, " Fabrication, characterization, and application of biocomposites from poly(lactic acid) with renewable rice husk as reinforcement", Journal of Polymer ResearchFebruary 2019, 26:44

[35] Juan Naranjo Lozada, Horacio Ahuett-Garza, Pedro, Orta Casta˜n´on, Wilco M.H. Verbeeten, Daniel S´aiz Gonz´alez, "Tensile properties and failure behavior of chopped and continuous carbon fiber composites produced by Additive Manufacturing", Additive Manufacturing, Volume 26, March 2019, Pages 227-241