ESKİŞEHİR TECHNICAL UNIVERSITY JOURNAL OF SCIENCE AND TECHNOLOGY
A- APPLIED SCIENCES AND ENGINEERING

2019, 20(2), pp. 195 - 203, DOI:10.18038/aubtda.498606

ANISOTROPIC IMPACT TOUGHNNESS OF CHOPPED CARBON FIBER REINFORCED NYLON FABRICATED BY MATERIAL-EXTRUSION-BASED ADDITIVE MANUFACTURING

Evren YASA*

Mechanical Engineering, Eskişehir Osmangazi University, Eskişehir, Turkey

ABSTRACT

3D printed polymer composites are gaining more interest due to weight reduction and high geometrical complexity freedom especially for highly demanding applications such as aerospace and defense. Using the material-extrusion based processes, polymer matrix composite parts with complex geometries can be designed and realized to improve the mechanical properties of pure thermoplastic parts. However, in addition to porosity found at the fracture interfaces, the layered nature additive manufacturing processes may become a limitation for the direct replacement for functional applications. In this study, the results of Charpy impact testing of chopped carbon fiber reinforced nylon fabricated by fused filament fabrication (FFF) are reported. The effects of the build direction and customized density by different infill strategies on the obtained toughness are presented in comparison to the one of nylon without any reinforcement. The toughness results show a severe anisotropy in toughness and high dependence on the infill strategy.

Keywords: 3-D Printing, Mechanical testing, Polymer-matrix composites (PMCs)

1. INTRODUCTION

Additive manufacturing (AM) of various materials including mainly metals and polymers, has gained importance especially in the last decade due to its advantages. Although AM has found place in a diverse range of applications from jewellery, electronics, dies/molds and homeware, the main leading industrial sectors are mainly aerospace and biomedical due to the provided opportunities. These include ability to build very complex geometries even lattices or hollow parts, weight reduction, customization, reduced time from design to part validation, etc [1, 2]. As defined in ASTM F2792-12a presenting standard terminology for additive manufacturing technologies, AM is a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies [3]. While some polymer and metal materials are considered as commercially available for a wide range of applications from prototyping to functional part production for small series and single parts, ceramics and composites are rather new and still under research [4]. Yet, the engineering applications are becoming more demanding and these requirements can sometimes not be fulfilled by using metals, ceramics or polymers only. On the other hand, a composite material is made of a mixture of various types of material by certain processes. These composite materials can still keep the advantages of the original materials while overcoming some shortcomings. Some composites may even show some new desired properties [5]. Although the share of composite materials in the aerospace is only 1-2%, the most advanced technologies especially for polymer matrix composites (PMCs) are first developed and adopted in the aircraft industry mainly to reduce weight. For example, the weight of PMCs in some rotorcrafts, i.e. Boeing/Sikorsky RAH-66 Comanche, can go up to 50% of the total weight showing the importance of composite materials for aviation [5]. For challenging applications with the requirements of high mechanical properties and weight reduction, the strong opportunities provided by the use of composites can be joined together with AM technologies which are opening a new manufacturing age changing the rules of design. The most commonly used AM process for PMCs is the material extrusion processes, of which Fused Filament Fabrication (FFF) is the most common method. In this process, a

*Corresponding Author: eyasa@ogu.edu.tr
Receiving: 17.12.2018 Accepted: 18.06.2019

feedstock filament of the raw material on a spool is fed into the extrusion head by a tractor wheel arrangement and a heating chamber liquefies the solid material. As schematically shown in Figure 1, the liquefied material is fed through a nozzle on the print bed or the already printed layers to generate the 3D geometry in a layerwise manner [6]. Considerable research has been conducted in the field of FFF process to enable the use of produced parts as prototypes and functional parts especially for polymeric materials. There are various factors affecting the part quality in this process such as material properties, slicing and deposition strategy, machine parameters including nozzle characteristics and positioning accuracy, the cooling strategy, process stability, etc. [7]. Many studies have been focussed on the mechanical behaviour of polymers in terms of tensile and flexural properties but the number of studies with PMCs produced by FFF is limited [8, 9]. One of the most commonly used matrix material for chopped fiber reinforcement is ABS (acrylonitrile–butadiene–styrene) whereas the most common material used as the fiber is carbon. Tekinalp et al. [10] has studied carbon fiber reinforced ABS polymers at different fiber loadings in order to evaluate the potential for load-bearing components. The tensile testing results show that FFF composites showed significant porosity problem as compared to compression-molding specimens whereas a high fiber orientation in the printing direction was encountered with FFF. They have concluded that FFF composites with highly dispersed and highly oriented carbon fibers have a great potential for load-bearing parts provided that the pore formation during printing and fiber breakage during compounding could be minimized [10]. The tensile properties of ABS reinforced with glass fibers were also studied by Zhong et al. [11]. The study results showed that the glass reinforcement could improve the tensile strength and surface rigidity at the expense of flexibility and handlability [11]. In addition to tensile properties, the flexural properties of PMCs by FFF were investigated by Ning et al. [12] by varying the carbon fiber content between 0 and 15% reinforcing ABS plastics. Compared to pure ABS, the carbon reinforcement increased the tensile strength, Young's modulus but the toughness, yield strength and ductility were reduced. Moreover, the porosity was encountered as a severe problem [12].

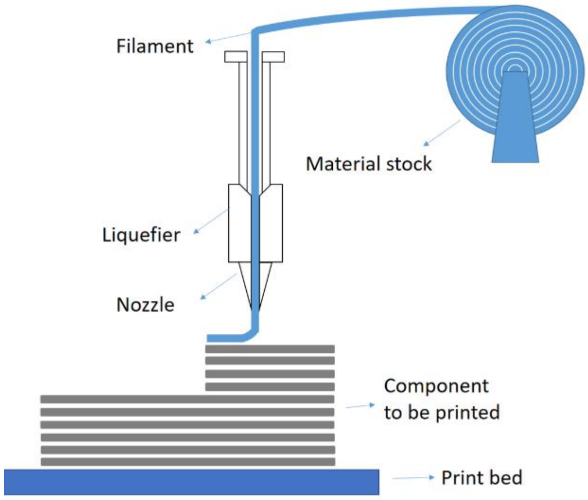

Figure 1. Schematic demonstration of the FFF process

More recently, studies on embedding continuous fiber in the plastic materials are realized mainly using FFF for different applications [13-18]. Various matrix materials such as Polyamide (PA), nylon, ULTEM®, Poly Lactic Acid (PLA) and Polypropylene (PP) are used whereas the most commonly used reinforcement materials is carbon [13-18]. Some studies also focus on using glass fibers or graphene as the reinforcement material [19,20]. In the study conducted by Yao et al. [13], it is shown that carbon fibers significantly improve the tensile strength by over 70% and bending strength by 18.7%. In the study by Dickson et al. [18] continuous glass, carbon and Kevlar fibers into nylon material were reinforced. The tensile and flexural strengths were significantly enhanced while the most improvement was obtained with the carbon fiber. The research by Matsuzaki et al [17] is in good agreement with these results. Their results show that the tensile modulus and strength of continuous carbon fiber reinforced

PLA composites were improved almost to a 6-fold and 4.3-fold of the tensile modulus and strength, respectively, of the pure PLA specimens. The main advantages of using fiber reinforced polymer matrix composites are mainly reported as the enhanced tensile strength, flexural properties and dimensional stability [18]. Thus, the other mechanical properties of PMCs produced by FFF rather these are not well addressed in the literature. Toughness, defined as the ability of a material to absorb energy and plastically deform without fracturing, and the key to toughness is a good combination of strength and ductility [21]. Unfortunately, very limited information can be found in the open literature regarding the toughness properties of FFF PMCs. Ning et al. [12] has studied the effect of carbon fiber loading in the ABS matrix on the obtained toughness but no testing was carried out for specimens built in different orientations. Young et al. have very recently studied the interlayer fracture toughness of additively manufactured unreinforced and carbon-fiber-reinforced ABS [22]. However, this study does not consider the impact toughness but rather aims to develop a test methodology for characterization of interlayer fracture toughness of FFF components using a modified version of ASTM D5528 standard. Thus, this study aims to investigate the impact toughness of carbon fiber reinforced nylon material produced by FFF in order to investigate the potential of PMCs to be utilized as functional load-bearing parts for various applications.

2. MATERIALS AND METHODS

In order to study the build-axis dependance of the impact toughness of carbon fiber reinforced tough nylon, commercially known as MarkForged Onyx, the specimens compatible to ISO 179 PlasticsDetermination of Charpy Impact Properties were produced on a Markforged Mark Two® equipment with standard parameters [23]. The maximum size of the print volume of this printer is 320x132x154 mm. The Onyx material is nylon pre-impregnated with chopped microcarbon fibers in filament form, combining the toughness of nylon and thermal properties of carbon [24, 25]. The tested geometry with the dimensions and tolerances is shown in Figure 2a. Five specimens were produced in each of three different build directions and the specimens are called as A, B and C specimens as demonstrated in Figure 2b.

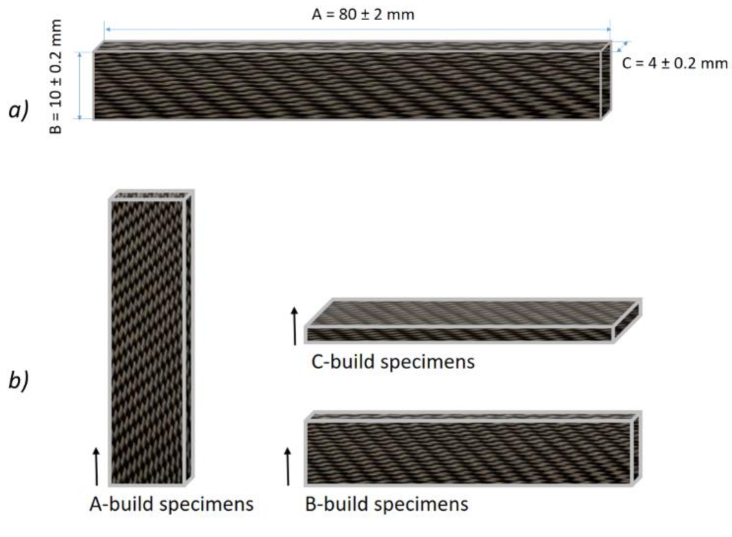

Figure 2. a) Specimen Geometry per ISO 179 [23], b) Naming of specimens built along different axes

In addition to specimens to test the influence of the build direction, five specimens were produced only from tough nylon with no reinforcement in order to evaluate the effect of the reinforcement on the toughness. These pure nylon specimens together with Onyx specimens were produced with an infill ratio of 100%. In addition, two more sets of specimens were produced to test the effect the density where the infill parameters are set to generate 75% and 50% density by using triangular infill strategy (see Figure 3). The full list of tested specimens are given in Table 1 in detail.

The specimens were produced in the form of unnotched geometry because the notches could not directly be produced by FFF per required specifications. Moreover, opening the notches afterwards by machining would add some uncontrolled variance among different specimens. Especially, for specimens which are not fully dense, this was considered to potentially cause some limitations. The unnotched specimens were tested on a Ceast Impactor equipment located in TUBİTAK MAM at room temperature.

After all the specimens were produced, a dimensional inspection was carried out and none of the specimens presented a non-conformance.

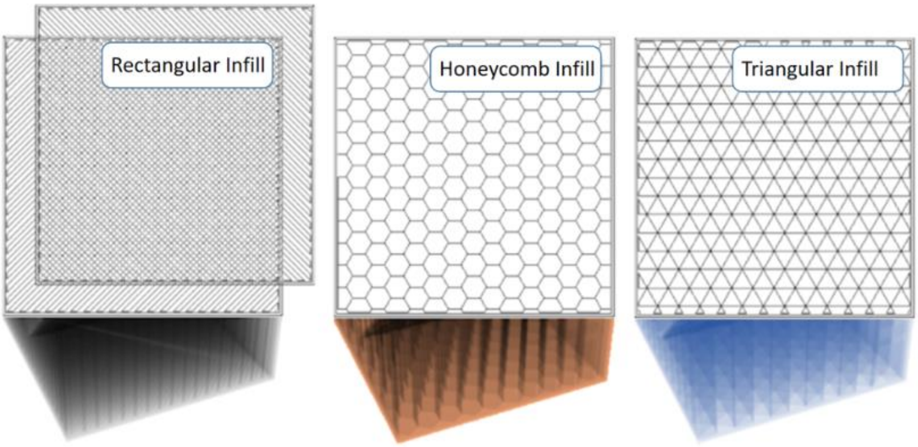

Figure 3. Various infill strategies from left to right: rectangular infill preferred for 100% density where the deposition orientation is varied from layer to layer; honeycomb and triangular infill strategies which are more preferable for weight reduction [26]

Table 1. The list of tested specimens

No.	Part	Material	Infill Strategy	% Infill Density	Layer thickness	# of specimens
1	C-Build Onyx 100%	ONYX	Rectangular	100%	0.1 mm	5
2	B-Build Onyx 100%	ONYX	Rectangular	100%	0.1 mm	5
3	A-Build Onyx 100%	ONYX	Rectangular	100%	0.1 mm	5
4	C-Build Nylon 100%	NYLON	Rectangular	100%	0.1 mm	5
5	C-Build Onyx 75%	ONYX	Triangular	75%	0.1 mm	5
6	C-Build Onyx 50%	ONYX	Triangular	50%	0.1 mm	5

3. RESULTS AND DISCUSSION

The toughness results of specimens built in different orientations are shown in Figure 4 along with the results of nylon specimens built only in one direction given for comparison. The error bars shows the 95% confidence intervals. As evident from this figure, specimens made of only nylon (#4: C-Build Nylon 100%) exhibit a much higher toughness value compared to carbon fiber reinforced specimens made of Onyx material (#1: C-Build Onyx 100%). As expected, the nylon has almost 2.5 times better toughness. This is also evident from the fracture of specimens (see Figure 5a). Two of five nylon specimens did not even show any fracture, but only severe bending was evident.

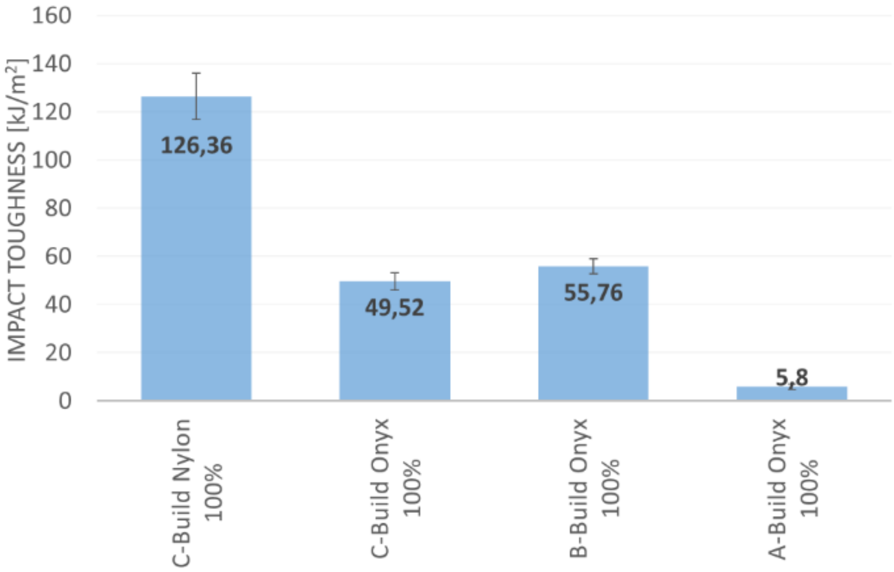

Figure 4. Impact toughness results of specimens built along different axes

Specimens which receive an impact not between deposited layers (#1: C-Build Onyx 100% and #2: BBuild Onyx 100%) exhibit almost 10 times better toughness compared to specimens (#3: A-Build Onyx 100%) which received an impact in between two layers. The effect is also evident from fracture surfaces as shown in Figure 5b. The build directions are shown with an arrow in the figure. Moreover, the build axis is evident from the fracture surfaces of #1: C-Build Onyx 100% and #2: B-Build Onyx 100% specimens. #3: A-Build Onyx 100% specimens get the impact in between two weakly connecting layers due to lack of any pressure while depositing the material. Therefore, it is concluded that the impact toughness results show a very severe anisotropy meaning a reduction of 90% in toughness. The same variance is expected in other mechanical properties due to very weak connection of deposited layers which is evident from very flat fracture surfaces of the #3: A-Build Onyx 100% specimens (see Figure 5b).

The obtained results are well in line with the other studies from the literature. Although they have conducted their study with carbon fiber reinforced ABS and also obtained toughness as a result of tensile properties, Ning et al. [12] concluded that the obtained toughness decreased when the matrix was reinforced even at different fiber loadings. In other study by Ning et al. [27], the effect of various process parameters such as layer thickness and fill speed on toughness obtained via tensile testing are investigated with carbon fiber reinforced ABS. In this study, they also attribute a low toughness value to the weak interlayer connection. They have concluded that the tightly coalesced interlayers generated a great interbonding strength led to a high toughness value [27]. Love et al. [21] also report that reinforcement of polymers has led to a reduction of z-strength probably due to the fact that the filament did not conform to the underlying substrate as it was deposited. This led to reducing the contact area between layers whereas the in-plane specimens showed a 2-fold increase in the tensile strength. The toughness results of specimens built with different densities are shown in Figure 6 along with the results of nylon specimens built only in the same direction given for comparison. The error bars shows the 95% confidence intervals. As evident from the figure, as the density is decreased, the obtained toughness is reduced. However, the amount of reduction is not the same for the same amount of porosity. Reducing the density from 100% to 75%, the toughness is reduced almost 50% from 50 kJ/m^2 to 25 kJ/m^2 . However, when the density is reduced from 75% to 50%, there is only a further reduction of 3 kJ/m^2 . For applications where weight reduction is a major concern but toughness can be tolerated to some extent, 50% density would be more preferable considering the toughness reduction. The repeatability of the toughness tests, especially with Onyx® material is also noticeable for all configurations. The reduced density obtained with triangular infill strategy is visible on the fracture surfaces as shown in Figure 7.

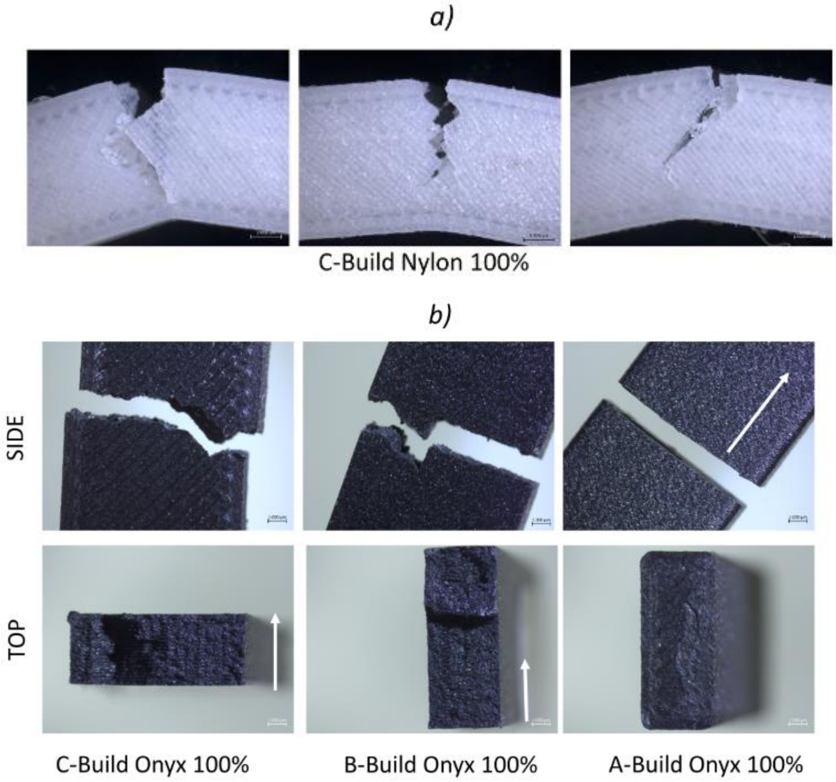

Figure 5. Tested specimens a) from nylon material b) from Onyx® built in different orientations – top and side view

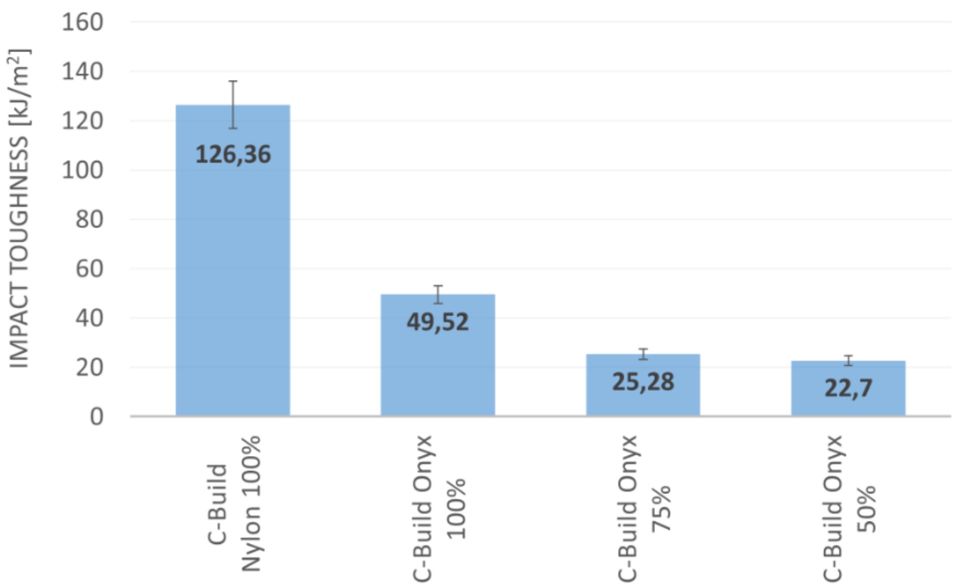

Figure 6. Impact toughness results of specimens built with different densities

From these results, it can be concluded that the specific toughness which can be defined as toughness per weight is higher with lower density PMCs fabricated by FFF. This is mainly attributed to the deposition strategy where the boundary geometry is produced fully dense to ensure dimensional stability and high accuracy whereas the infill density is used to determine how thick the triangular beams shall be. Thus, the boundary of the specimen introduces an additional impact resistance during Charpy testing.

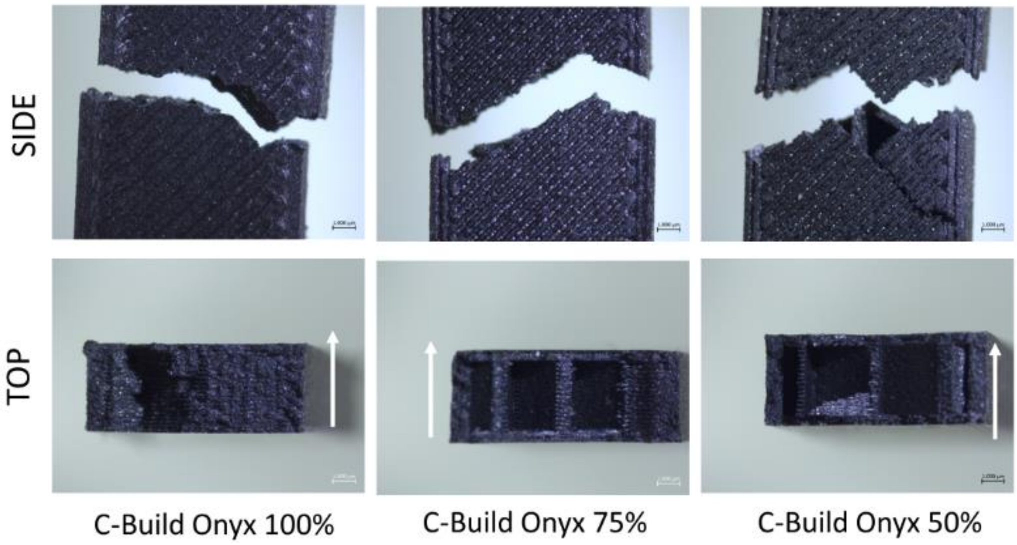

Figure 7. Tested specimens from Onyx® built with different infill strategies and resulting densities– top and side view of tested specimens

4. CONCLUSIONS

This study has been conducted in order to study the impact toughness of chopped carbon reinforced nylon produced by FFF. Although it is the most commonly used AM methodology for manufacturing polymer matrix composites for advanced mechanical properties such as bending properties, the results obtained in this study have shown that there is a severe anisotropy in the toughness properties. The same ansiostropic behaviour is also expected in other mechanical properties because the encountered anisotopy is mainly due to weak connection of successive layers. Due to the nature of the process, 2D layers of extruded material are depositied on top of each other without applying any pressure or any other means for a strong connection. In other AM technologies, especially for metallic materials, a good fusion of successive layers is provided by melting to a depth greater than one layer thickness so that each layer is well fused to the existing part beneath as is the case in Selective Laser Melting. As a result, the weak connection of successive layers is considered as a significant barrier for PMCs especially in load-bearing structural applications. Secondly, the effect of customized density on the impact toughness has been addressed for lightweighting. As expected, it has been seen that changing the density with triangular infill strategy to 75% decreases the toughness by almost 50%. However, a further change of the density by another 25% to 50% density only reduces the toughness less than 5% mainly due to the commonly used FFFdeposition strategy. Moreover, it has been shown that reinforcing nylon with chopped carbon has decreased the toughness significantly. A 2.5-fold toughness was obtained by nylon specimens mainly due to high ductility of nylon.

ACKNOWLEDGEMENTS

The authour would like to acknowledge that the toughness testing took place in TÜBİTAK MAM. Moreover, the author thank Novustek Danışmanlık Mühendislik Sanayi Ticaret Ltd. Şti. for their support to this study.

REFERENCES

[1] Murr LE, Gaytan SM, Medina, F, Lopez H, Martinez E, Machado BI, Hernandez DH, Martinez L, Lopez MI, Wicker RB, Bracke J. Next-generation biomedical implants using additive manufacturing of complex, cellular and functional mesh arrays. Philosophical Transactions of the Royal Society A 2010; 368: 1999-2032.

[2] Jahan SA, Wu T, Zhang Y, Zhang J, Tovar A, Elmounayri H. Thermo-mechanical design optimization of conformal cooling channels using design of experiments approach. Procedia Manufacturing 2017; 10: 898 – 911.

[3] Standard Terminology for Additive Manufacturing – General Principles – Terminology, ISO / ASTM52900 – 15. Accessed July 2018.

[4] Hegab HA. Design for additive manufacturing of composite materials and potential alloys: a review. Manufacturing Rev. 2016; 3: 11, 1-17.

[5] Wang R-M, Zheng SR, Zheng Y-P. Introduction to polymer matrix composites. In: Polymer Matrix Composites and Technology. Woodhead Publishing in Materials, 2011.

[6] Puigoriol-Forcada J M, Alsina A, Salazar-Martin AG, Gomez-Gras G, Perez, MA. Flexural fatigue properties of polycarbonate fused-deposition modelling specimens. Materials and Design 2018; 155: 414- 421.

[7] Baehr F, Westkaemper E. Correlations between Influencing Parameters and Quality Properties of Components Produced by Fused Deposition Modeling. Procedia CIRP 2018; 72: 1214–1219.

[8] Goh GD, Yap YL, Tan HKJ, Sing SL, Goh GL, Yeong WY, Process–Structure–Properties in Polymer Additive Manufacturing via Material Extrusion: A Review, Critical Reviews in Solid State and Materials Sciences 2019: DOI: 10.1080/10408436.2018.1549977

[9] Ligon SC, Liska R, Stampfl J, Gurr M, Mülhaupt R, Polymers for 3D Printing and Customized Additive Manufacturing, Chemical Reviews 2017; 117 (15): 10212-10290.

[10] Tekinalp HL, Kunc V, Velez-Garcia GM, Duty CE, Love LJ, Naskar AK, Blue CA, Ozcan S. Highly oriented carbon fiber-polymer composites via additive manufacturing. Composites Science and Technology 2014; 105: 144- 150.

[11] Zhong W, Li F, Zhang Z, Song L, Li Z. Short fiber reinforced composites for fused deposition modeling. Materials Science and Engineering 2001; A301: 125-130.

[12] Ning F, Cong W, Qui J,Wei J, Wang S. Additive Manufacturing of carbon fiber reinforced thermoplastic composites using fused deposition modeling. Composites Part B 2015; 80: 369-378.

[13] Yao X, Luan C, Zhang D, Lan L, Fu J. Evaluation of carbon fiber-embedded 3D printed structures for strengthening and structural-health monitoring. Materials and Design 2017; 114: 424-432.

[14] Gardner JM, Sauti G, Kim JW, Cano RJ, Wincheski RA, Stelter CJ, Grimsley BW, Working DC, Siochi EJ. 3-D Printing of multifunctional carbon nanotube yarn reinforced components. Additive Manufacturing 2016; 12: 38-44.

[15] Parandoush P, Tucker L, Zhou C, Lin D. Laser Assisted Additive Manufacturing of Continuous Fiber Reinforced Thermoplastic Composites. Materials & Design 2017; 131: 186-195.

[16] Tian X, Liu T, Yang C, Wang Q, Li D. Interface and performance of 3D printed continuous carbon fiber reinforced PLA composites Composites Part: A 2016; 88: 198-205.

[17] Matsuzaki R, 3D Printer Using Continuous Carbon Fiber Composite Materials, http://www.jscm.gr.jp/3Dprinting/images/introduction_CFRP3Dprinter.pdf, last visited on

24.07.2018. 16. Matsuzaki R, Ueda M, Namiki M, et al. Three-dimensional printing of continuous-fiber composites by in-nozzle impregnation. Sci. Rep. 6, 23058; doi: 10.1038/srep23058 (2016).

[18] Dickson AN, Barry JN, McDonnel KA, Dowling DP. Fabrication of continuous carbon, glass and Kevlar fibre reinforced polymer composites using additive manufacturing. Additive Manufacturing 2017; 16: 146-152.

[19] Girdis J, McCaffrey M, Proust G. Additive Manufacturing of Carbon Fiber and Graphene – Polymer Composites using the technique of Fused Deposition Modelling. Solid Freeform Fabrication 2016: Proceedings of the 26th Annual International, August 8-10 2016, Austin, TX, USA, 864-870.

[20] Love LJ, Kunc V, Rios O, Duty CE. The importance of carbon fiber to polymer additive manufacturing. J. Mater. Res. 2014; 29(17): 1893- 1898.

[21] Toughness, NDT Education Resource Center, Ed. Larson B, https://www.ndeed.org/EducationResources/CommunityCollege/Materials/Mechanical/Toughness.htm, last visited on 25.07.2018.

[22] Young D, Wetmore N, Czabaj M. Interlayer fracture toughness of additively manufactured unreinforced andcarbon-fiber-reinforced acrylonitrile butadiene styrene. Additive Manufacturing 2018; 22: 508-515.

[23] Plastics — Determination of Charpy impact properties Part 1: Non-instrumented impact test, ISO 179-1:2010, Accessed October 2017.

[24] van der Klift F. 3D Printed Unidirectional Carbon Fibre Reinforced Polymers for Aerospace Applications. MSc. Thesis, the Delft University of Technology, the Netherlands, 2017.

[25] Bourell D, Kruth J-P, Leu M, Levy G, Rosen D, Beese AM, Clare A. Materials for additive manufacturing. CIRP Annals - Manufacturing Technology 2017; 66: 659-681.

[26] Eiger Software from https://altar.com.tr/donanim/3d-yazici/eiger; last visited on 23.07.2018.

[27] Ning F, Cong W, Qui J, Wang S. Additive manufacturing of carbon fiber-reinforced plastic composites using fused deposition modeling: Effects of process parameters on tensile properties. Composites Part B 2015; 80: 369-378.