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MECHANICAL PROPERTIES AND FAILURE ANALYSIS OF PLA/COPPER COMPOSITES FABRICATED BY FUSED DEPOSITION MODELLING

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Abstract

The Fused Deposition Modelling process is an additive manufacturing process that is influenced by numerous parameters that affect the strength of the components. This paper article is dedicated to the study of the effects of Fused Deposition Modelling parameters on the strength of PLA/Copper infill composites. The influence on tensile, impact and flexural strength was investigated by varying the process parameters. The printer properties, i.e. the Nozzle Temperature and Printing speed, and the processing parameters, i.e. the Layer Thickness and the density of the infill are the most important parameters considered in this study. Mathematical models were developed to predict the strength of the composites as the process parameters were varied. The strength of the composites decreased with increasing layer thickness and printing speed. On the other hand, in the strength of the composites increased when the nozzle temperature and the density of the infill were increased. The composite samples were subjected to failure analysis to determine the fracture mechanisms. Both brittle and ductile failure mechanisms were observed in the samples, which are influenced by the process parameters affecting the layered composite and porosity.

***Keywords**: Mechanical properties; Polymer composites; Additive manufacturing; Fused Deposition Modelling*

1. Introduction

Additive manufacturing (AM) is a rapidly growing technology that facilitates low-cost manufacturing of complex geometric shapes with high accuracy. AM technology is finding its opportunity in wide range of industries like biomedical, mechanical, aerospace, construction, food industries and academic research. AM technology creates a paradigm shift in manufacturing composite materials to construct complex, custom designed parts [1]. The development in 3D/4D printing has tiled ways to develop innovative materials and products in soft robots, biomedical, sensors and actuators, aerospace and other applications. Processes such as synthesis of smart 3D printing materials, manufacturing techniques and post-curing are mutually dependent and are suitable in biomedical applications like bone scaffolds, artificial muscles, cardiovascular stents and so on [2]. Fundamental AM processing methods include direct energy deposition, material jetting, fused deposition modeling, material extrusion, powder bed fusion, vat photo- polymerization, sheet lamination, binder jetting. Fused deposition modelling (FDM) is the most commonly used extrusion-based AM process to fabricate polymer-based components [3]. FDM is the generally used AM technology in a wide variety of applications due to its simplicity in operation and low cost [4]. FDM process is influenced by parameters like build orientation, printing speed, nozzle temperature, layer height, and screw type [5]. However, in large-scale applications, the use of FDM is limited and may not be used as an alternate for conventional techniques such as injection molding [5].

Application of polymers and composites is progressing in diversified industrial and promising applications for FDM. The choice of printable materials is limited due to the factors like rheology, melting point, and other physical properties [6]. Materials like PLA, PC, ABS, PEEK, and PEI are the most common materials for FDM process due to their bonding capabilities [7,8]. Addition of reinforcement particles up to 15% enhances the mechanical properties of the base materials. Beyond 15%, the minor defects created by the metal reinforcements harmfully affect the physical and mechanical properties of the composites [9]. FDM using composite materials faces major challenges in terms of filament preparation, intrinsic agglomeration of nature fibers, moisture, fiber degradation, void

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formation, nozzle clogging, fiber breakage, improper curing, etc. [10].

Process parameters like ambient temperature, printing temperature, infill pattern, printing speed, infill density, flow characteristics, etc., have a significant sway on the mechanical properties of the developed parts. The non-uniform dispersion of reinforcement in the matrix and agglomeration of particles acts as stress concentrating sites and plays an important role in influencing the mechanical properties of the parts [11]. Integrity of the material and material properties are influenced by the existence of pores due to parameters like thermal conductivity, energy received by the material, material layer thickness etc. [12]. Increase in the percentage of metal in polymer increases the strength and flexural modulus while strain of the composites decreases [13]. Addition of reinforcements like graphene in polymers such as ABS, polycarbonate increased the strength while the percentage elongation and surface roughness decreased [14].

High heating temperature, less printing speed, less layer thickness increases the density, decreases the internal defects, improves the binding strength and reduces the surface roughness of FDM parts [15]. Strength of the parts increases with decrease in layer thickness, higher layer thickness increases the porosity across the parts and decreases the mechanical properties [16]. Less layer heights and raster orientation along the longitudinal direction increases the elastic modulus and stress, while the void density decreases [17]. Low printing speed modifies the stability of printing and encourages extrusion and adhesion of the polymer composites. Thin layer thickness leads to tightly packed particles and increases the mechanical properties of polymer composites [18]. Increase in number of raster contours increases the stiffness, elastic modulus and tensile strength, while the percentage of elongation decreases leading to brittle failure [19]. Increase in nozzle temperature during processing reduces the viscosity and creates back pressure along the nozzle leading to thermal degradation and a decrease in the mechanical properties [20]. Mechanical properties of the composites are also subjective to fiber orientation, fiber volume ratio and loading direction [21]. Specific energy of the composites decreases with decrease in shell thickness, infill density while the specific energy decreases with increase in feed rate and layer thickness [22,23]. The impact energy of PLA/graphene composites declines with increase in addition of graphene particles [24].

The primary factors that influence mechanical properties are the presence of voids, weak interfacial bonding and raster orientation [25]. Intrinsic presence of voids and low adhesion lead to decrease the tensile strength and decrease in the stiffness of the parts, which enhances elongation during failure [26]. Agglomeration of polymer particles, voids and difference in viscosity between polymers leads to decrease in mechanical properties [27]. Failure of components due to mechanical loading primarily takes place due to fiber pull-out, fiber -breakage and debonding, while voids acts as feeble areas and initiates failure of the parts. Line-by-line deposition primarily influences the surface roughness while layer-by-layer deposition influences staircase effect [28]. Failure of composites is characterized by matrix cracking, delamination, fiber breakage and fiber/matrix debonding, primarily due to lesser permeability of the molten filament [29]. The literature review indicates that most of FDM studies were carried on polymers and fiber reinforced polymer composites. Very few studies were carried out to analyze the influence of FDM process parameters of polymers composites reinforced with metal particles. The current paper examines the effect of FDM process parameters on the strength of the PLA/copper composites.

2. Materials and Manufacturing

2.1. Material

In this study, PLA/copper composite filament was made-up by Flashforge 3D Technology Co. Ltd as shown in Fig. 1. The filament is a combination of PLA (80%), Polybutylene adipate terephthalate (PBAT) (10%) and copper powder (5%) as shown in Table 1. Filament of 1.75 mm diameter is used in this study. The average size of the copper particles in this study is around 200 μm.

***Figure 1**. PLA/Copper composite filament*

2.2. Fused Deposition Modelling

A CREALITY CR-10 S 5 make fused deposition modeling machine is used in this study to fabricate the samples (Fig.2). Implication among the investigational values and its allied yields can be assessed by Response surface methodology (RSM)

Table 1. *Composition of the composites material*

Sl. No.	Material	Percentage (wt%)
1	PLA	>79.9
2	Copper	10
3	PBAT	10
4	Others	< 0.1

and Design Expert-16 software. The performance of the FDM specimen is influenced by several FDM parameters. Table 2 indicates the details of FDM parameters used in the study.

Figure 2. *Setup of FDM machine*

Table 2. *Input factors and their corresponding values*

Parameters	Units	Symbols	Variable levels		
Nozzle Temperature	Deg	NT	230	240	250
Layer Thickness	Mm	LT	0.1	0.2	0.3
Printing speed	mm/s	PS	50	75	100
Infill density	%	ID	70	80	90

2.3. Evaluation of Mechanical Properties

Tensile test: Composite specimens were subjected to tensile test as per ASTM D3039 standards. Standard sample was used as shown Fig 3(a) with a thickness of 6 mm and width of 20 mm, and the sample was fabricated using FDM as shown in Fig 3(b). Tensile test was conducted with the help of AIMIL make AIM 653-1 UTM machine with a load carrying ability of up to 20 kN. The strain rate was kept constant at 1 x 10^{-4} m/s during the study.

Flexural test: ASTM D7264 standard was followed to conduct the flexural test using a three-point load tester. Tests were conducted at a speed of 1.0 mm/min until fracture. Flat rectangular samples of 127 mm width, 12.7 mm length, and 6 mm thickness were used for the study (Fig 3(c).

Impact test: The impact strength is tested by charpy test adopting ASTM D 256 standard and the dimensions of the specimen is shown in Fig. 3(d). MICROMECH made impact testing machine was used to evaluate the impact strength. At least three samples of each composite were tested and the average strength was calculated using the obtained results and considered.

2.4. Mathematical modeling

The output response variables and their related input parameters can be enunciated as Y = f (LT, RA, ID, PS) where Y designates the reaction while Layer Thickness (LT), Raster Angle (RA), Infill density (ID) and Printing speed (PS) designates the input parameters. Design Expert-R16 was used to develop the Mathematical models for estimating strengths of the composites. Box-Behnken design adopted with four factors, with 27 runs, 3 centers, 1 base block and 27 set of experiments were designed as in Table 3.

3. Results and discussion

3.1. Analysis of mathematical models

The developed mathematical model using the Design Expert-R16 is shown in equations (1), (2) and (3). Significance of the model developed is assessed using ANOVA (Table 4). Sum of squares is the sum of squares between the group means and the grand mean, which quantifies the variability between the groups of interest and the total variability in the observed data.

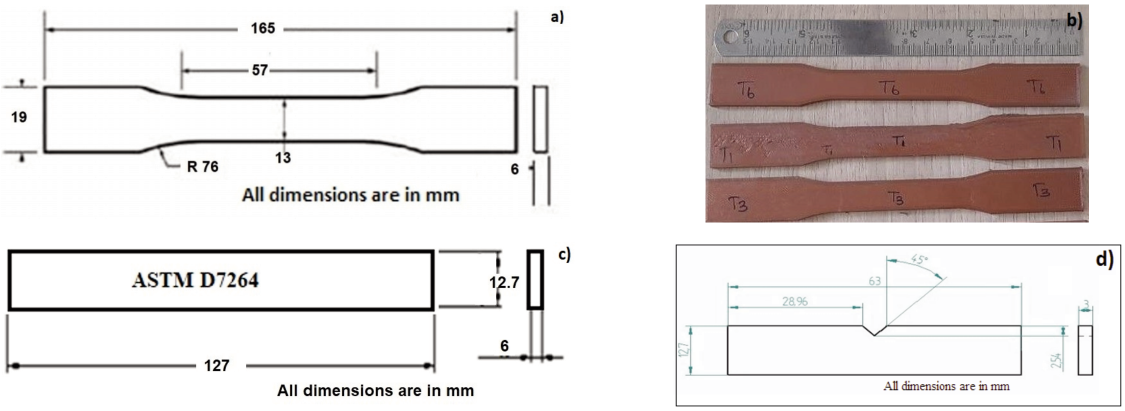

***Figure 3**. PLA/Copper FDM test sample: a) Schematic diagram of tensile test sample; b) Fabricated PLA/Copper tensile test sample; (c) Schematic diagram of flexural test sample; (d) Schematic diagram of impact test sample*

$$Tensile\ Strength = +22.23 - 13.09(LT) - 0.07(NT) + 0.177(ID) - 0.084(PS) - 0.006(LT)(NT) + 0.075(LT)(ID) - 2.04617(LT)^2 \quad (1)$$

$$Flexural\ Strength = -59.58 + 48.85(LT) + 0.25(NT) + 0.19(ID) - 0.107(PS) + 0.057(LT)(ID) - 1.77(LT)^2 \quad (2)$$

$$Impact\ Strength = -0.649 + 0.077(LT) + 0.0038(NT) + 0.0021(ID) - 0.0017(PS) - 0.0015(LT)(ID) + 0.052\ (LT)^2 \quad (3)$$

3.2. EDS Analysis

Existence of copper powder was demonstrated by the Energy Dispersive X-ray analysis (EDS). Presence of copper filler is evident in the EDS spectra (Fig. 4) thus ensuring the presence of copper in the composite filament.

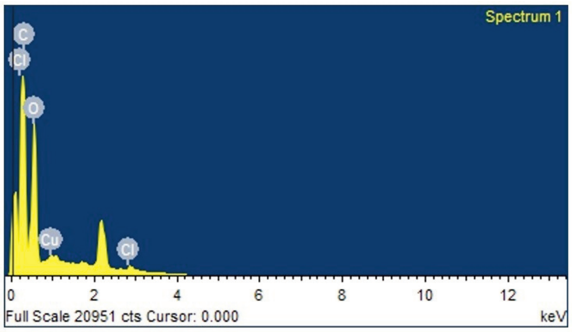

***Figure 4**. EDS of PLA/Copper composite filament*

3.3. Effect of FDM parameters on tensile strength

Impact of FDM factors on the tensile strength of PLA/Copper composites is described in Fig 5. Strength of the PLA/Copper composites revealed a maximum value of 21.99 N/mm^2 and a minimum value of 14.68 N/mm^2. These variations can be attributed to the changes in FDM parameters. Infill density stands tall in inducing the tensile strength of PLA/copper composites and contributes to about 37.86%, followed by other parameters as shown in Table 4. It can be noted (Fig. 6(a)) that the tensile strength diminished with rise in layer thickness. Rise in nozzle temperature from 230°C to 250°C increased the tensile strength, but the variation was minimal and it contributed to only 8.75% in inducing the strength. As the infill density increased, tensile strength of the composites rose (Fig. 5(b)) while rise in printing speed declined the tensile strength. The fractured FDM tensile sample is shown in Fig. 6.

Increase in tensile strength is primarily characterized by the solid interfacial bonding among the PLA matrix and copper fillers. In general, strong interfacial bonding amongst layers leads to increase in tensile strength. Tensile strength also depends on certain parameters like voids and porosity, which can be controlled by optimizing the process parameters. Increase in layer thickness means the probability for formation of voids and porosity is higher that leads to increase in water absorption [16]. Increase in nozzle temperature improves the formability and melting fluidity of the material thereby reducing the gaps and leading to strong interfacial bonding to enhance the tensile strength [18]. Impact of nozzle temperature influences parameters such as layer stratification, bonding strength compaction, forming time, crystallinity that has an effect on the strength [15]. Too low extrusion temperature increases the viscosity and extrusion becomes harder. On the other hand, at high temperature the possibility of dripping is also higher [5]. Printing speed is the relative motion between the nozzle and the platform. Higher the printing speed, the possibility of rough surface and non-uniform deposition of layers is higher leading to the formation of voids. Issues related to adhesion and

Table 3. *Design background and relevant experimental data*

Sl. No	Layer Thickness (mm)	Nozzle Temperature (ºC)	Infill Density (%)	Printing speed (mm/s)	Tensile Strength (N/mm^2)	Flexural Strength (N/mm^2)	Impact Strength (kJ/m^2)
1	0.1	240	70	75	17.89	15.22	0.209
2	0.3	240	80	50	19.5	31.46	0.29
3	0.1	240	80	50	21.4	20.11	0.287
4	0.3	240	90	75	18.93	29.37	0.284
5	0.2	240	70	100	14.68	18.06	0.18
6	0.2	240	90	50	21.99	26.97	0.321
7	0.1	250	80	75	19.54	21.5	0.291
8	0.2	240	80	75	18.75	22.28	0.26
9	0.2	250	80	100	16.19	22.7	0.238
10	0.1	240	90	75	20.25	17.65	0.26
11	0.1	230	80	75	19.24	13.97	0.208
12	0.2	240	70	50	18.95	23.61	0.267
13	0.2	230	90	75	19.87	21.23	0.247
14	0.2	250	80	50	20.46	28.25	0.325
15	0.2	230	70	50	18.96	20.65	0.237
16	0.2	240	90	75	19.86	24.19	0.277
17	0.3	230	80	75	17.42	24.73	0.227
18	0.2	230	80	75	18.35	19.55	0.22
19	0.2	230	80	100	16.21	16.78	0.176
20	0.3	250	80	75	16.67	28.97	0.29
21	0.2	240	70	100	14.68	18.06	0.18
22	0.2	250	80	75	18.33	25.47	0.281
23	0.2	250	80	75	18.33	25.47	0.281
24	0.3	240	90	100	16.8	26.6	0.241
25	0.3	240	90	75	19.87	29.26	0.28
26	0.2	240	70	75	16.82	20.83	0.224
27	0.1	240	80	100	17.13	14.56	0.2

Table 4. *Influence of FDM parameters*

Responses/Variables	Tensile Strength (N/mm^2)		Flexural Strength (N/mm^2)		Impact energy (kJ/m^2)	
	Sum of squares	% contribution	Sum of squares	% contribution	Sum of squares	% contribution
Infill density (%)	73.76	37.86	176.07	23.43	0.0069	27.94
Nozzle Temperature (ºC)	33.12	17	322.34	42.89	0.0019	7.69
Layer Thickness (mm)	17.05	8.75	66.08	8.79	0.0019	7.69
Printing speed (mm/s)	70.9	36.39	186.98	24.88	0.014	56.68
Total	194.83	100	751.47	100	0.0247	100

voids interacts the strength while presence of voids decreases the stiffness and augment to the elongation during failure [26]. Voids are formed during printing process due to the presence of micro cavities in the filament. During printing, voids are formed due to entrapment of air between the layers and beads [28]. Interface of the polymer and metal infill has an effect on the bonding strength, thereby influencing the elongation to failure and intern has an impact on the strength [9]. Addition of ceramic infill in ABS matrix increases the interfacial bonding thereby increasing the thermal stability of the composites. However, addition of ceramics beyond a certain limit leads to poor dispersion, wrapping and agglomeration of particles leading to a decrease in tensile strength [14].

SEM of the fractured tensile test sample is illustrated in Fig. 7. It can be seen that fracture of the composite sample is characterized by mechanisms like micro cracks, pores, layer bonding, gap between layers, removal of infill particles, smearing, stacking of layers and so on. In Fig. 7(a) it can be noted that at higher layer thickness (0.3 mm) the gap between

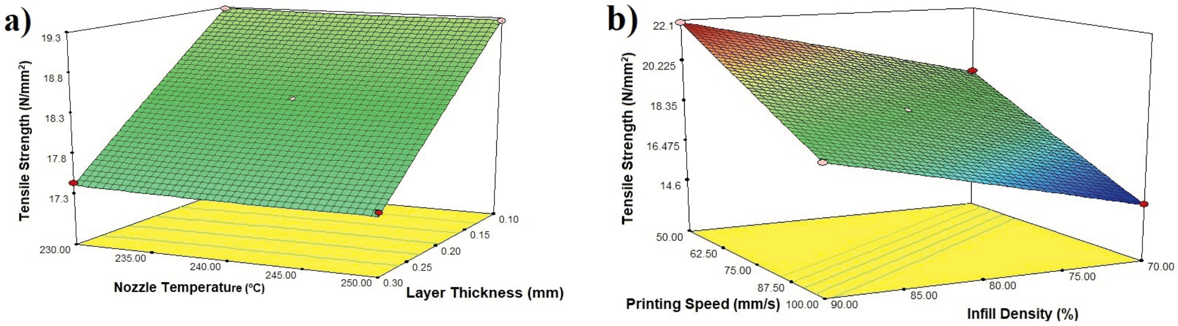

Figure 5*. Influence of process parameters on tensile strength: a) tensile strength vs nozzle temperature and layer thickness; b) tensile strength vs printing speed and infill density*

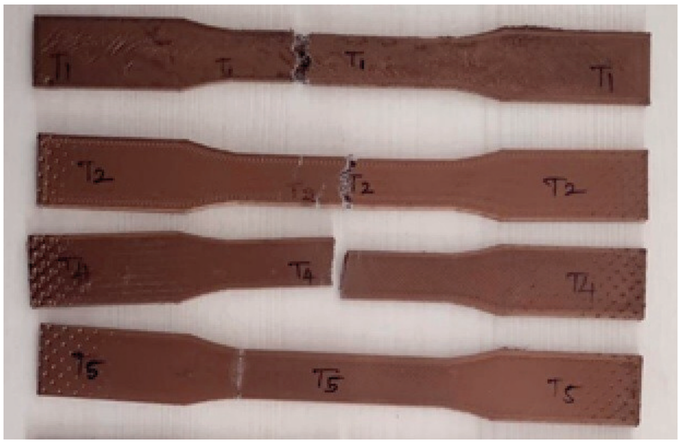

Figure 6. *Fractured tensile test sample*

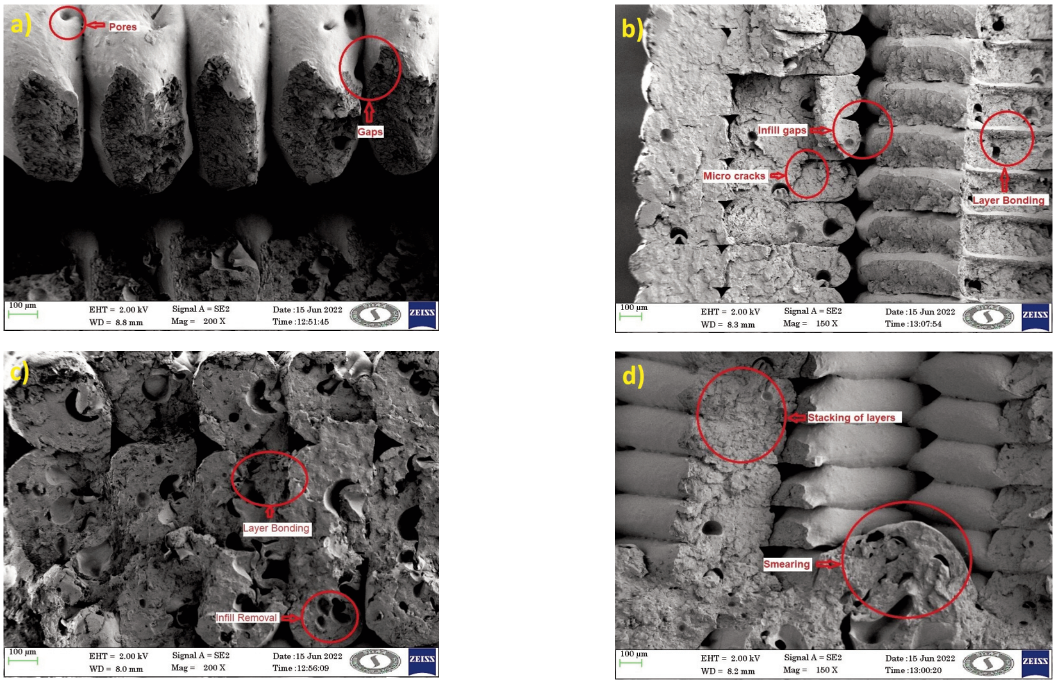

***Figure** 7. SEM image of fractured tensile test sample: a) LT – 0.3 mm, NT – 230°C, ID - 80%, PS-100 mm/s; b) LT – 0.2 mm, NT – 230°C, ID-80%, PS-50 mm/s; c) LT – 0.2 mm, NT – 250°C, ID - 90%, PS-75 mm/s; d) LT – 0.1 mm, NT – 240°C, ID-90%, PS- 50 mm/s* layers is larger and hence the interfacial bonding amongst the layers is also lesser which might decrease the tensile strength. With a layer thickness of 0.2 mm in Fig. 7(b) the gap amid the layers are smaller and hence the bonding between the layers is also healthier. This might lead to an escalation in the tensile strength. Infill density is also another major parameter that influences the strength. In Fig. 7(a) and 7(b) the density between subsequent layers and rosters is higher at 80% infill density. Decreasing the printing speed to 50 mm/s in Fig 7(b) shows a positive indent in layer bonding thereby increasing the tensile strength. As the nozzle temperature increases to 250°C, increase inlayer bonding can be witnessed in Fig. 7(c). However, formation of pores is higher which can be controlled by reducing the printing speed. Decrease in printing speed leads to uniform distribution of layers and solidification. At smaller layer thickness (0.1 mm), printing speed (50 mm/s) and moderate nozzle temperature (240°C) it can be noted that the presence of pores is minimal in Fig. 7(d). Distribution of layer is uniform and hence the tensile strength is also greater. A delamination kind of smearing is observed which influences ductile mode of failure rather than brittle fracture indicating a rise in tensile strength of the sample. Higher nozzle temperature beyond a certain limit influences the viscosity of molten metal coming from the nozzle and thereby influences the tensile strength.

3.4. Effect of FDM parameters on flexural strength

Impact of parameters on flexural strength of PLA/Copper composites is presented in Fig. 8. Flexural strength exhibited a maximum value of 31.46 N/mm^2 and a minimum value of 13.97 N/mm^2. These variations are due to the impact of FDM parameters. Nozzle temperature has a major impact on the flexural strength of PLA/copper composites and it contributes to about 42.89% of the flexural strength shadowed by Printing speed (24.88%), Infill density (23.43%) and Layer Thickness (8.79 %) as shown in Table 4. It can be noted (Fig. 8(a)) that a rise in layer thickness declines the flexural strength. An increase in nozzle temperature from 230°C to 250°C increases the flexural strength. Rise in the infill density increases the flexural strength (Fig. 8(b)) while rise in printing speed decreases the tensile strength, however the variation is very minimal. The fractured FDM flexural sample is shown in Fig. 9.

Rise in nozzle temperature develops the formability and fluidity of materials thus improving the interfacial bonding and flexural strength. Increasing in printing speed declines the volume of material extruded and reduces the printing stability thereby decreasing the flexural strength of the sample. At lesser printing speed the extruded material from nozzle have adequate time to join with the succeeding layers and improves the strength [18]. Changes in the strain rate of materials during bending influences the interlaminar shear strength between layers, induces separation of layers and tends to failure of the materials. This interlaminar shear strength is influenced by parameters such as nozzle temperature, printing speed, layer thickness, etc. [5]. Addition of metal infills in polymer composites enhances the interfacial bonding network leading to improved thermal stability. On the other side addition of metal infills beyond a certain limit results in deprived dispersion, particle agglomeration, wrapping etc. and reduces the strength of the composite sample [14]. Significant adhesion between the polymer matrix and metal infill enhances transfer of stress between them and improves the strength. The gap between adjacent layers increases with increase in layer thickness and increases the porosity thereby decreasing the flexural strength [16].

Fracture surface of the flexural specimen analyzed using scanning electron microscopy is presented in Fig. (10). Flexural strength of the PLA/Copper infill composites is determined by mechanisms such as breaking of layers, delamination, layer merging, and protrusion of layers. It can be observed from Fig.

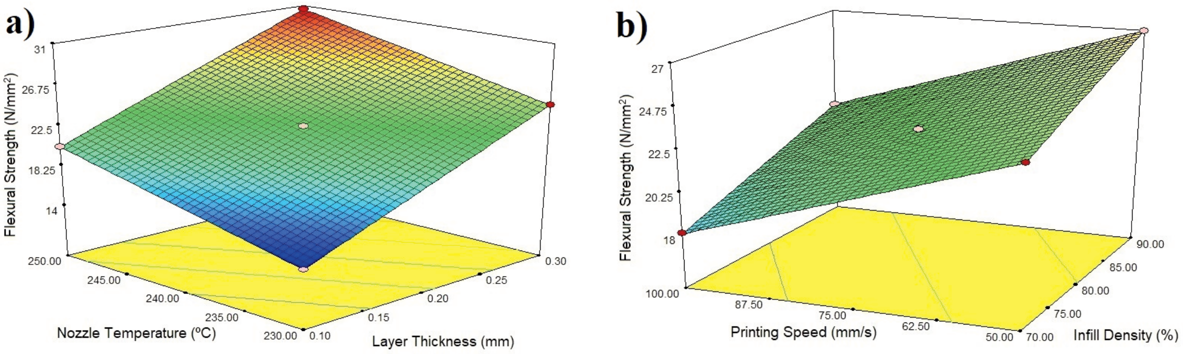

***Figure 8**. Impact of process parameters on flexural strength: a) flexural strength vs nozzle temperature and lLayer thickness; b) flexural strength vs printing speed and infill density*

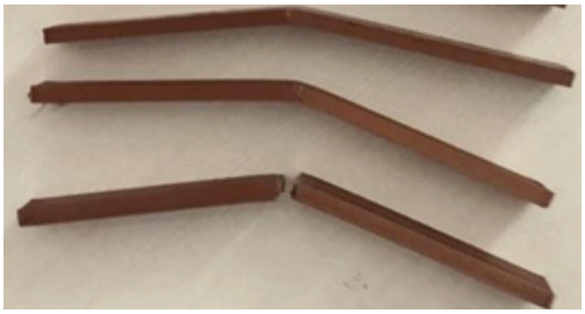

Figure 9*. Fractured flexural test sample*

10(a) that failure of specimen shows brittle fracture at some region. Debonding of one layer from the successive layer due to weak interfacial bonding is also witnessed in Fig. 10(a). Weak interfacial bonding is due to the increase inlayer thickness (0.3 mm) and rise in printing speed (100 mm/s). For the same layer thickness, debonding of layers is smaller in Fig 10(b). This might be due to decrease in printing speed from 100 mm/s to 50 mm/s. Failure of specimen is characterized by delamination of layers in many regions indicating a ductile mode of failure. Decreasing the layer thickness and printing speed, increasing the nozzle temperature (250°C), and infill density (90%) increases bonding of layers (Fig. 10 (c)). This can be witnessed by merging of layers and delamination of the matrix material thereby influencing a ductile mode of failure and increasing the flexural strength. Breakage of layers along with protrusion in the form of fibrillation of matrix material is also witnessed in Fig. 10 (d). In summary both brittle and ductile mode of failure is witnessed along the specimen influenced by the impact of process parameters that stimuluses bonding of the layers and porosity.

3.5. Effect of FDM parameters on impact strength

Impression of FDM process parameters on the energy absorbed by the PLA/Copper composites is presented in Fig. 11. Impact strength of composites exhibited a maximum value of 0.321 kJ/m^2 and a minimum value of 0.176 kJ/m^2. Difference in impact strength can be correlated to the changes in the input FDM process parameters. Impact strength is influenced by printing speed (56.68 %), Infill density (27.94%), Nozzle Temperature (7.69%) and Layer Thickness (7.69%) as shown in Table 4. The influence of Nozzle Temperature and Layer Thickness is less compared to that of Printing speed and Infill density. Increase in layer thickness decreased the impact strength while rise in nozzle temperature from 230°C to 250°C increased the impact strength. Rise in the infill density improved the impact strength while increasing the printing speed decreases the flexural strength. The fractured FDM impact sample is displayed in Fig. 12.

The primary parameter that influences the strength of the FDM composites is the interfacial bonding

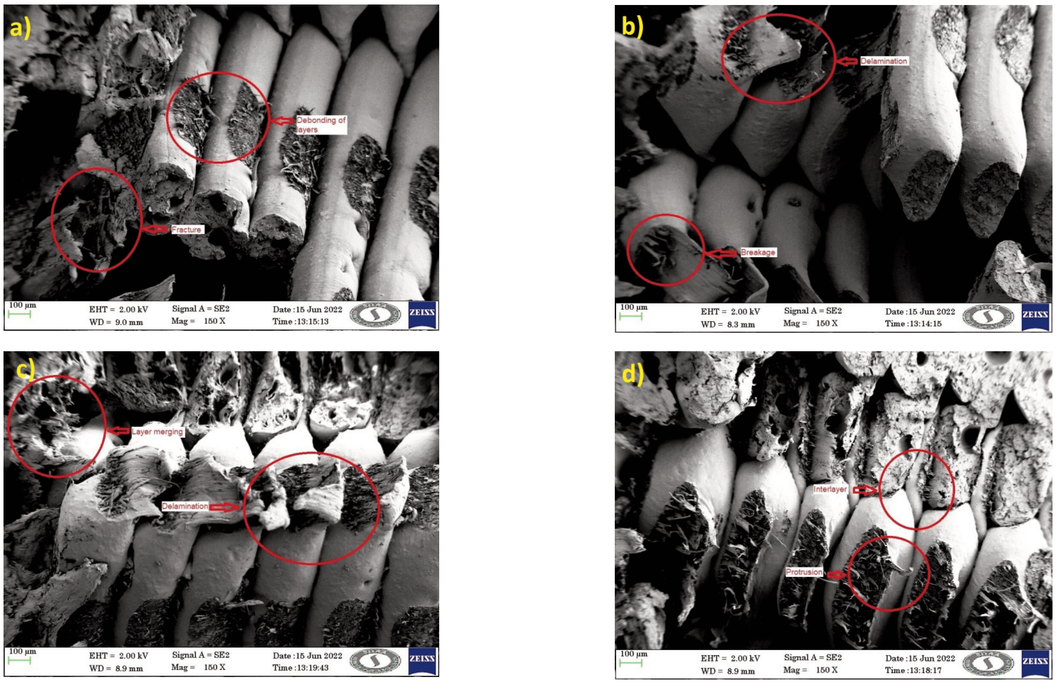

Figure 10*. SEM image of flexural strength: a) LT – 0.3 mm, NT – 230°C, ID - 80%, PS - 100 mm/s; b) LT – 0.3 mm, NT – 230°C, ID - 80%, PS - 50 mm/s; c) LT – 0.2 mm, NT – 240°C, ID - 90%, PS - 50 mm/s; d) LT – 0.2 mm, NT – 250°C, ID - 90%, PS - 50 mm/s*

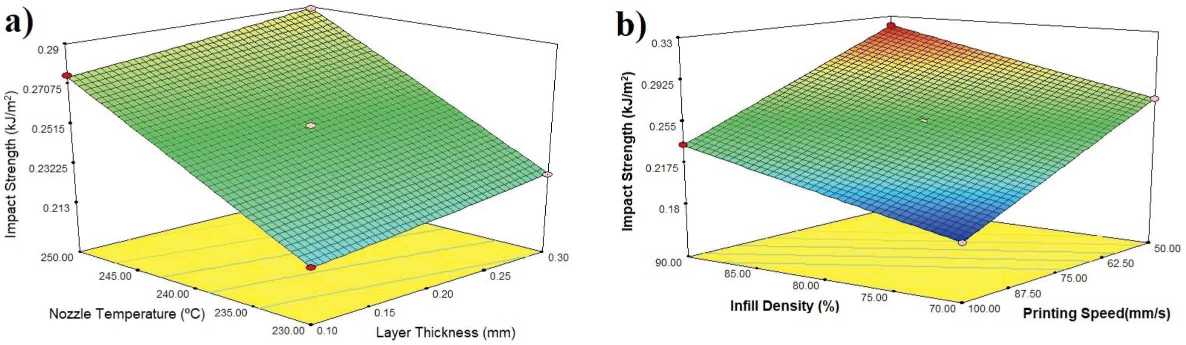

Figure 11. *Impact of process parameters on impact strength: a) impact strength vs nozzle temperature and layer thickness; b) impact strength graph vs printing speed and infill density*

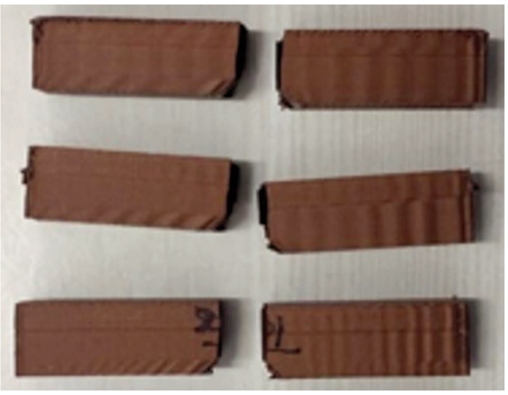

Figure 12. *Fractured impact test sample*

between matrix-reinforcement and layer-layer. The interfacial bonding strength is characterized by defects such as shape distortion formed due to residual stress, micro voids in the filaments and matrix, uneven distribution of fillers in the matrix, surface roughness etc. Residual stress is formed due to the variation in thermal gradient influenced by change in temperature and other printing parameters [28]. Increase in addition of infills in the matrix increases the breaking resistance energy and increases the strength. Addition of copper particles in PLA matrix reduces deformation and mobility of the polymer molecules and also absorbs energy during propagation of cracks thereby increasing the strength of composites [14].

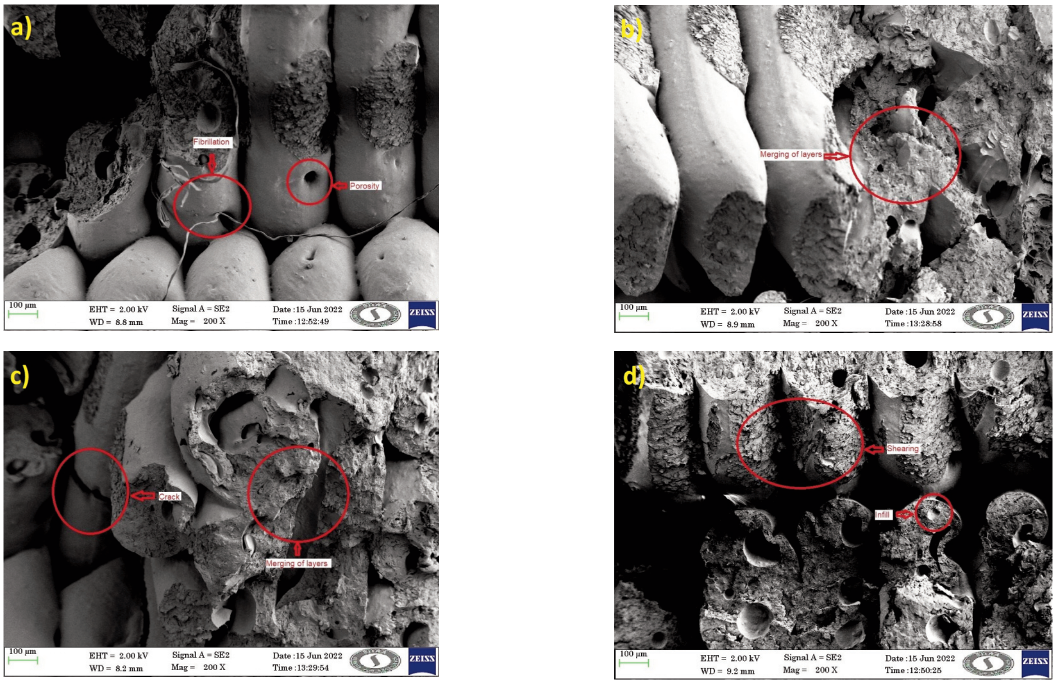

Figure 13. *SEM image of impact strength: a) LT – 0.3 mm, NT – 230°C, ID - 80%, PS - 100 mm/s; b) LT – 0.3 mm, NT – 230°C, ID - 80%, PS - 75 mm/s; c) LT – 0.2 mm, NT – 240°C, ID - 80%, PS - 75 mm/s; d) LT – 0.1 mm, NT – 250°C, ID - 80%, PS - 50 mm/s*

The mechanism of fracture of impact test specimen is presented in Fig. 13. Failure of the specimen is characterized by merging of layers, cracks, merging of layers, fibrillation, porosity, shearing, debonding of infills etc. Extrusion of PLA polymer in the form of fiber/thread is evidenced in Fig. 13(a). Debonding of layers is also witnessed in Fig. 13(a) at higher layer thickness (0.3 mm). Increase in nozzle temperature (240°C) and decrease in printing speed (75 mm/s) enhances bonding of the layers. This can be witnessed by merging of layers in the form of agglomeration of matrix material ((Fig. 13(b)). Failure of the specimen is primarily a brittle fracture evidenced by the formation of micro cracks. Decreasing the layer thickness increases the interfacial bonding characterized by merging of layers ((Fig 13(c)). Merging of layers is also evidenced with the presence of some minor cracks in few places. This indicates the mode of failure is partially ductile and partially brittle. Decreasing the printing speed (50 mm/s) and increasing the nozzle temperature (250°C) increases the interfacial bonding (Fig. 13(d)). Shearing of materials is witnessed indicating a ductile fracture influenced by the process parameters.

4. Conclusion

The following conclusion can be drawn from the study on the influence of FDM parameters on the strength of PLA/copper infill composites:

The tensile strength decreases with increasing layer thickness, while increasing the nozzle temperature increases the tensile strength. Increasing the infill density increases the tensile strength of the composites (Fig 6(b)), while increasing the printing speed decreases the tensile strength.

Increasing the layer thickness decreases the flexural strength, while an increase in nozzle temperature increases the flexural strength. Increasing the infill density increases the flexural strength, while increasing the printing speed decreases the tensile strength, although the deviation is very small.

Increasing the layer thickness reduces the impact strength, while increasing the nozzle temperature increases the impact strength. Increasing the infill density improves the impact strength, while increasing the printing speed decreases the flexural strength.

The fracture of the composite sample is characterized by mechanisms such as micro-cracks, pores, layer bonding, gaps between layers, removal of infill particles, smearing, stacking of layers and so on.

Both brittle and ductile failure modes are observed along the specimen, which are influenced by the process parameters affecting the layer bonding and porosity. The failure of the specimen is characterized by fusion of layers, cracks, merging of layers, fibrillation, porosity, shear, debonding of infills etc.

Authorship contribution

R.V. Kumar: Methodology, Experimentation, Writing – original draft, Investigation, Resources. K.R. Kumar: Conceptualization, Methodology, Writing – review & editing, Project administration, Validation, Formal analysis. N. Soms: Methodology, Software, Writing – original draft, Formal analysis, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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MEHANIČKE OSOBINE I ANALIZA LOMA PLA/BAKAR KOMPOZITA DOBIJENOG TRODIMENZIONALNIM ŠTAMPANJEM SUKCESIVNIM NANOŠENJEM SLOJEVA MATERIJALA

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Apstrakt

Trodimenzionalno štampanje sukcesivnim nanošenjem slojeva materijala (FDM tehnologija) je proizvodni proces koji je pod uticajem brojnih parametara koji utiču na čvrstoću komponenata. Ovaj rad je posvećen proučavanju uticaja parametara FDM tehnologije na čvrstoću kompozita PLA/bakar. Uticaj na zateznu čvrstoću, žilavost i otpornost na savijanje ispitivan je variranjem procesnih parametara. Svojstva štampača, tj. temperatura mlaznice i brzina štampe, i parametri obrade, tj. debljina sloja i gustina punjenja, najvažniji su parametri koji su razmatrani u ovom istraživanju. Razvijeni su matematički modeli kako bi se predvidela čvrstoća kompozita pri variranju parametara procesa. Čvrstoća kompozita opada sa povećanjem debljine sloja i brzine štampe. S druge strane, čvrstoća kompozita se povećava kada se povećaju temperatura mlaznice i gustina punjenja. Uzorci kompozita podvrgnuti su analizi otkaza radi određivanja mehanizama loma. U uzorcima su posmatrani krti i duktilni mehanizmi loma materijala, koji su pod uticajem parametara koji utiču na složeni i porozni kompozit.

Ključne reči: *Mehaničke osobine; Polimerni kompoziti; Proizvodnja aditiva; FDM modeliranje*