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Flextural properties of 3D printed Copper-Filler Polylactic Acid (Cu-PLA)

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Abstract. Fused Deposition Modelling (FDM) technology is among the lowest cost 3D printing technology for processing thermoplastic and composite materials. FDM has been highly used in additive manufacturing due to its ability to process complex parts with accurate dimension and lowest cost possible. FDM technology has limited working temperature; hence the materials used in FDM such as polylactic acid (PLA) have a relatively low melting temperature. The drawback of these thermoplastic printed through FDM is the lack of mechanical strength and properties such as thermal and electrical conductivity to print functional part. These problems have led to the development of new composite filament for FDM technique. In this research, polymer-matrix composite (PMC) with 25 wt.% and 80 wt.% of copper reinforced polylactic acid (PLA) specimens have been printed with different infill patterns (Rectilinear, Grid, Concentric, Octagram-spiral, and Honeycomb) to study its flexural properties. The flexural test was carried out according to ASTM D790. This study found that there is a significant effect of the two parameters towards flexural properties. From the flexural test, the preliminary result of flexural strength and flexural modulus were obtained. The flexural strength is 25.98 MPa achieved by the 25 wt.% Cu composition specimens with Concentric infill pattern. The flexural modulus is 0.3306 GPa achieved by the 80 wt.% Cu composition specimens with Concentric infill pattern.

Keywords. Fused deposition modeling, polymer matrix composite, Copper, PLA, flexural, infill pattern, bending

1. Introduction

Additive Manufacturing (AM) has been evolved in the manufacturing sector due to their time and cost saving advantage. AM is a process of merging several layers of materials to fabricate a three-dimensional (3D) model. The model is usually created by using design software [1, 2]. Designing through computer software allows complex geometry to be created effortlessly compared to traditional fabrication method. AM technologies optimize the usage of raw materials and minimize waste while offering accurate geometry in the final product. Many different methods of AM with advanced working principles have been developed to push through limitation existed in each process and to meet the demand for customized and intricate manufacturing products, including complex geometries. The most commonly used AM methods are fused deposition modeling (FDM), stereolithography (SLA), powder bed fusion (PBF), material jetting (MJ), binder jetting (BJ), and direct energy deposition (DED).

At present, FDM is usually used for printing prototypes due to its cost-effectiveness (reduced wastage of raw materials), ease of material change (since filaments are usually stored as spool) and fabrication of functional parts that can be used for the testing. However, FDM's limitations are the mechanical strength of the final product, limited selection of materials and working temperature. Since FDM technology has limited working temperature; the materials used in FDM are usually thermoplastic such as PLA and ABS that have a relatively low melting temperature. The drawback of these thermoplastic printed through FDM is the lack of mechanical strength and properties such as thermal and electrical conductivity to print functional part. These problems have led to the development of new composite filament for FDM technique. Composite filaments reinforced with metal particles such as iron particles into ABS, nylon, and PLA; copper particles into ABS; bronze particles into PLA; and stainless steel 420 particles into ABS has been developed with the aim to improve the base material mechanical properties.

At present, the studies of these composite filaments have focused on its fabrication process and their best tensile strength. Minimal studies have focused on the mechanical properties of these composite filaments with variation in printing parameters and different composition of filler metals. Printing parameters such as printing speed, layer thickness, printing pattern, melting temperature and fill density have a significant effect on mechanical properties of the final product [3-7]. These parameters can cause distortion in between layers and reported to be the root cause of reduced in mechanical strength of FDM parts [8]. The thickness of layers [9], angle of printing orientation [10, 11], air gap, the position of the printhead [12], the orientation of filament and building direction have attracted a lot of 3D printer manufacturers and also researchers involved in the development of printing materials [13, 14].

Since there have been limited studies on the effect of infill pattern towards the mechanical behavior of FDM printed parts [15-17], the present study has been carried out to focus on the mechanical properties of printed PLA reinforced with copper particles at different weight composition and variation of printing parameters. The copper composition varied with 25 wt.% and 80 wt.% whereas the infill patterns consist of Rectilinear, Concentric, Grid, Honeycomb and Octagram-spiral is studied.

2. Materials and Methods

The WANHAO Duplicator i3 FDM printer with MK10 nozzle of 0.4 mm nozzle diameter was used to process the 1.75 mm Copper-PLA composite filament. A 0.4 mm nozzle diameter was used to print 0.3 mm layer height in order to prevent clogging of the nozzle. The 3D printer runs in open-sourced firmware named Marlin. To command the printing process of the FDM printer, G-code is required. A slicing software named Repetier Host was used to generate G-code from 3D CAD models to carry out the printing process. Several printing parameters were kept constant to avoid major mislead of the result obtained as shown in table 1. The verification of ambient humidity and temperature of printing environment were done to ensure the printing process was carried out in a controlled environment, preventing additional factors from affecting the printing quality. The humidity and temperature were measured using before initiation of each printing process. The printing process was only initiated after making sure that the ambient humidity and temperature were between 70% to 80% and 20℃ to 25℃ respectively.

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Table 1.Constant printing parameters.

No.	Parameters	Constants
1	Initial layer height	0.3 mm
2	Layer height	0.3 mm
3	Horizontal Shell: solid layer	Top: 1 layer, Bottom: 1 layer
4	Outer Perimeter	2
5	Nozzle diameter	0.4 mm
6	Filament diameter	1.75 mm (± 0.05 mm)
7	Extruder temperature	210 °C (± 2 °C)
8	Printing speed	30 mm/s
9	Print bed temperature	60 °C (± 2 °C)

Table 2. DOE combination table.

Combination	Pattern	Copper Composition (wt.%)
1	Concentric	25
2	Rectilinear	25
3	Honeycomb	25
4	Octagram-spiral	25
5	Grid	25
6	Concentric	80
7	Rectilinear	80
8	Honeycomb	80
9	Octagram-spiral	80
10	Grid	80

2.1. Design of experiment
The design of the experiment includes the parameter and its value selected to be investigated. The two chosen parameters are infill pattern (Rectilinear, Concentric, Octagram-spiral, Honeycomb, and Grid) and Copper composition consists of 25 wt.% and 80 wt.% Copper. The infill density is kept constant at 50% throughout this entire research. Total number combinations of parameters are 10 as shown in table 2.

2.2. Fabrication of tensile specimen
The designing of the test specimen is done by using SOLIDWORKS 2017 edition. The dimension of the test specimen is according to the ASTM standards of the respective mechanical test. The CAD model generated using SOLIDWORKS is converted into STL file. In this study, Repetier-Host is the slicing software used for its simple interface and its accuracy in generating g-code. Visual g-code interface and a DTL composer are important elements which allow visualizing the STL file on a plate. The parameter that to need to be varied can be manipulated using the slicing software (except the composition of filler metal that requires a manual change of filament spool).

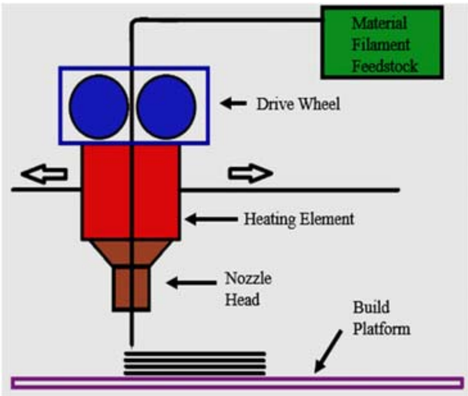

Figure 1. Fused deposition modelling working mechanism.

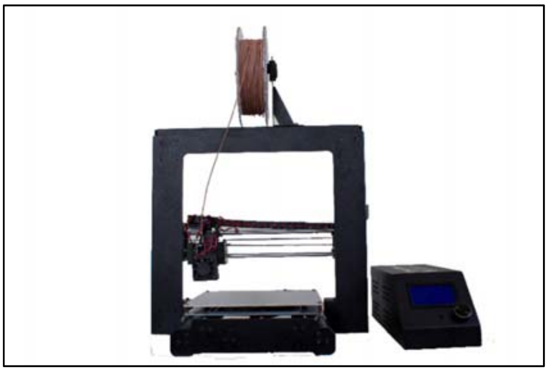

Figure 2. WANHAO Duplicator i3.

The parameters that will require settings in the Repitier-Host are raster angle and infill density. After setting the parameter required, g-code is generated using the g-code generator embedded in the software. The g-code will then be transferred to the 3D printer through an SD card. Through the 3D printer interface, the g-code file is selected to run, and the 3D printer automatically sets the machine parameter according to g-code command. Revalidation of room temperature and humidity is done throughout the printing process. If the ambient condition is found to be out of the controlled range, the printing process is stopped immediately. After the printing process completed, the printed test specimen can proceed to its respective mechanical test.

The selected low-cost 3D printer seen in figure 2 requires manual calibration. The calibration of the 3D printer is done before the start of the printing process. Calibration involves adjusting the alignment of x-axis, y-axis and z-axis. This calibration is important to ensure the nozzle position is sync with g-code command. The X-axis guide rods that are connected at the 3D printed left and right seat to the z-axis guide rods was ensured to be aligned at a perfectly horizontal position which is 180° respect to the horizontal ground axis. This adjustment will automatically correct alignment for z-axis movement. Then, the alignment of hotbed by referring to its distance from the nozzle was done using the feeler gauge. These are to make sure that the distance between the nozzle and the hotbed is consistent all over the hotbed. The main reason for this is to allow the heated filament deposited efficiently without oozing over the previously deposited layer and have constant distance between the nozzle and deposited layers in the process. This calibration will be performed at the beginning of printing each batch of specimens.

During the printing process, the filament is guided by a stepper motor into the hot-end extruder to be melted. The molten material then flows through the nozzle and is deposited layer by layer on to the print bed. The temperature is set at 210 ℃ to melt the filament. Filament is heated to a few degrees higher than its melting point so that the extruded material does not solidify too quickly before exiting the nozzle and allow adhesion to the previously deposited layers. The working mechanism is illustrated in figure 1. A sample of concentric infill pattern with 80 wt. % Copper composition tensile test specimen is shown in figure 3.

2.3. Flextural testing

Tensile test was done using INSTRON 3367 machine. The maximum load which can be applied to this machine is 50 kN. According to ASTM D790 standard, the speed of testing that must be applied is 1.365 mm/min. In figure 3(a), the specimen geometry and the dimension of the specimen is shown [18]. The thickness of the specimen is 3.2 mm. the completed specimen can be seen in figure 3(b). The method is generally applicable to both rigid and semi-rigid materials, but flexural strength cannot be determined for those materials that do not break or yield in the outer surface of the test specimen within the 5.0 % strain limit. For ASTM D790, the test is stopped when the specimen reaches 5% deflection, or the specimen breaks before it.

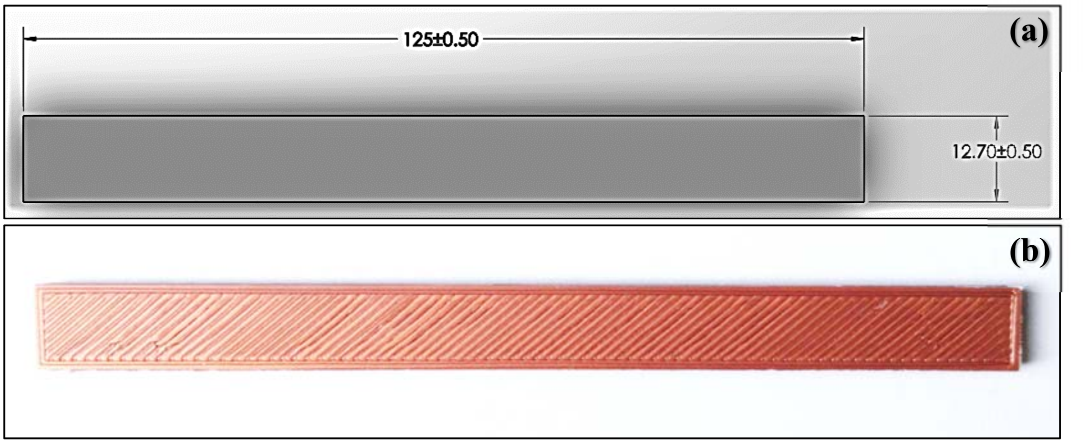

Figure 3. (a) Dimension of the test specimen, (b) 80 wt.% Cu with Concentric infill pattern flexural test specimen, (c) 25 wt.% Cu with Rectilinear infill pattern.

Table 3. Flexural properties

Infill Pattern	Flexural Strength (MPa)		Flexural Modulus (GPa)	
	25 wt.%	80 wt.%	25 wt.%	80 wt.%
Octagram-spiral	23.64	11.22	0.58233	0.71264
Rectilinear	32.64	13.65	0.61353	0.80773
Honeycomb	34.28	14.34	0.66387	0.84453
Grid	33.63	14.91	0.65722	0.93042
Concentric	41.03	17.57	0.73427	0.91677

3. Results and Discussion

The value of flexural strength is obtained from the maximum stress withstood by the specimen, similar to UTS in the tensile test [19-23]. All flexural properties were obtained from raw data generated from the test machine. The flexural properties are tabulated in table 3 and a sample of stress-strain curve with Octagram-spiral infill pattern and 25 wt.% Cu composition is shown in figure 4.

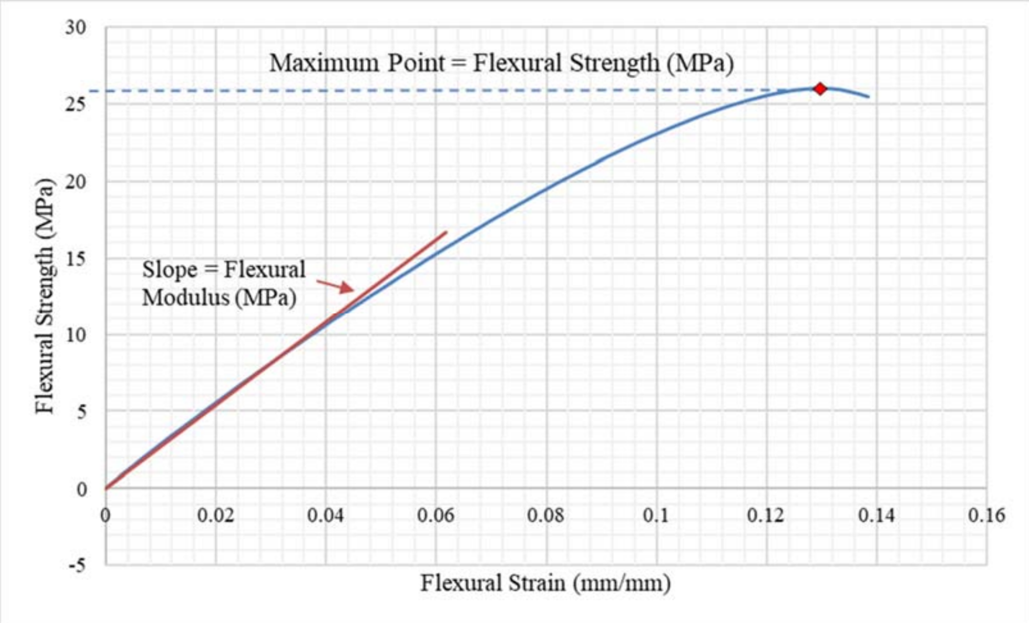

Figure 4. Stress vs strain curve of a sample specimen with Octagram-spiral infill pattern and 25 wt.% Cu composition.

3.1. Flextural strength

According to table 3 and figure 5(a), the highest flexural strength is achieved by the 25 wt.% Cu composition specimens with Concentric infill pattern recording 41.03 MPa while the 80 wt.% Cu achieved 17.57 MPa. The weakest flexural strength was observed in Octagram-spiral recorded 23.64 MPa for 25 wt.% Cu and 11.22 MPa for 80 wt.% Cu. From figure 5, it is observed that flexural strength increases in the following sequence of pattern; Octagram-spiral, Rectilinear, Honeycomb, Grid and Concentric.

The flexural strength of 25 wt.% Cu generally higher than 80 wt.% Cu regardless of infill pattern. This relation can be seen in figure 5(b). Increase of copper particles in the PLA matrix reduces mechanical strength provided by the parent material, PLA. This result can also be seen in other researches that use metal particles as additives for PMC [24-27]. The significant difference in flexural strength also can be observed between 25 wt.% and 80 wt.% Cu was observed, and it can be deduced that higher metal fillers composition reduces the flexural strength of the specimens.

The significance of the printing parameters was further confirmed with the Pareto chart shown in figure 6. From figure 6, it can be seen that the infill pattern, copper composition and the combination of both infill pattern and copper composition have a significant effect on flexural strength.

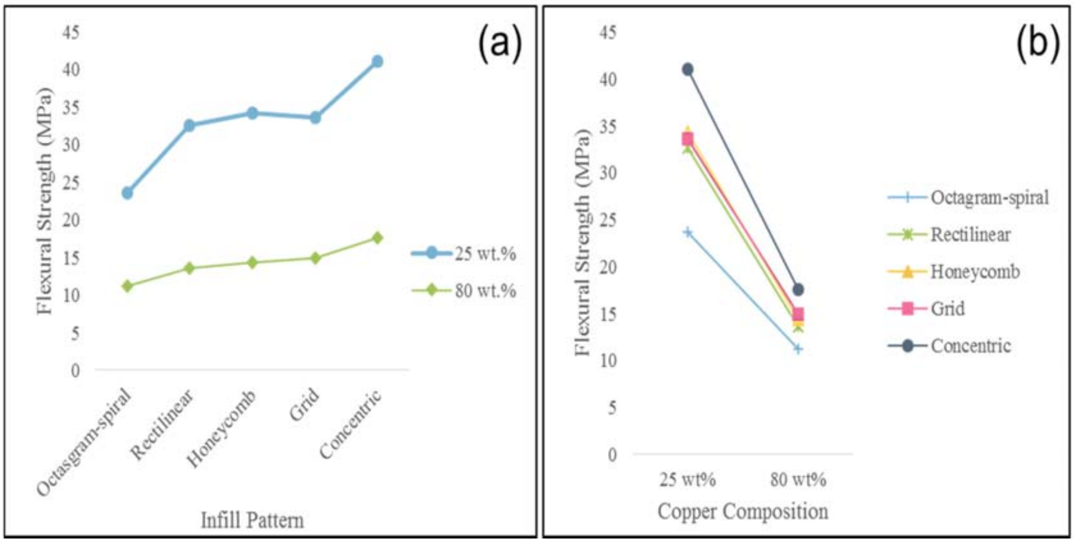

Figure 5. Graph of flexural strength against infill pattern and copper composition.

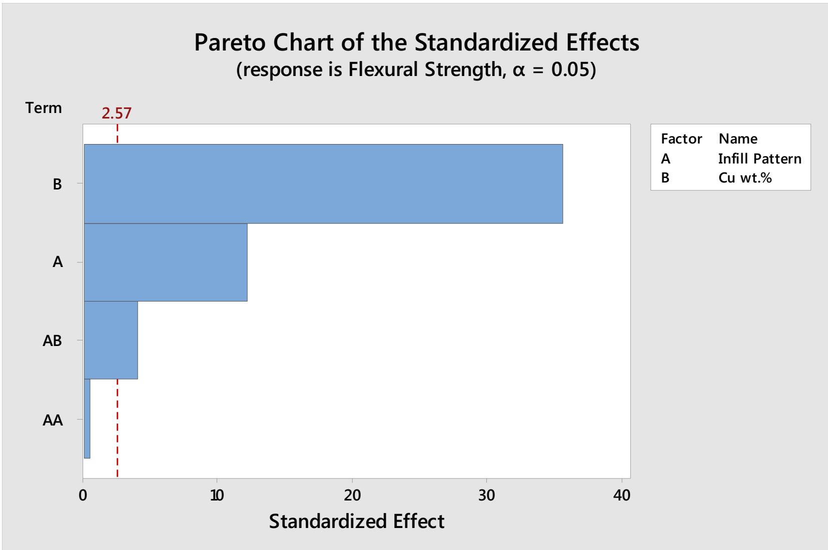

Figure 6. Pareto chart of printing parameters toward flexural strength.

3.2. Flexural modulus

According to table 3 and figure 7(a), the highest flexural modulus is achieved by the 80 wt.% Cu composition specimens with Concentric infill pattern recording 0.9168 GPa whereas for the same pattern of 25 wt.% Cu recorded 0.7343 GPa. The weakest flexural modulus is observed in Octagram-spiral infill pattern with 0.5823 GPa and 0.7126 GPa for 25 wt.% and 80 wt.% Cu respectively. From figure 7, it is observed that flexural modulus increases with the following sequence of pattern; Octagram-spiral, Rectilinear, Honeycomb, Grid and Concentric.

The flexural modulus of 80 wt.% Cu is generally higher than of 25 wt.% Cu regardless of infill pattern. This relationship can be seen in figure 7(b). The significant difference of flexural modulus was also observed between 25 wt.% and 80 wt.% Cu, the higher flexural modulus represents stiffer behavior of the specimen and bend resistant to due to the higher content of metal particles, reducing molecular bond in the polymer matrix. The significance of the printing parameters was further confirmed with the Pareto chart shown in figure 8. From figure 8, it can be seen that the infill pattern, copper composition and the combination of both infill pattern and copper composition have a significant effect on flexural modulus.

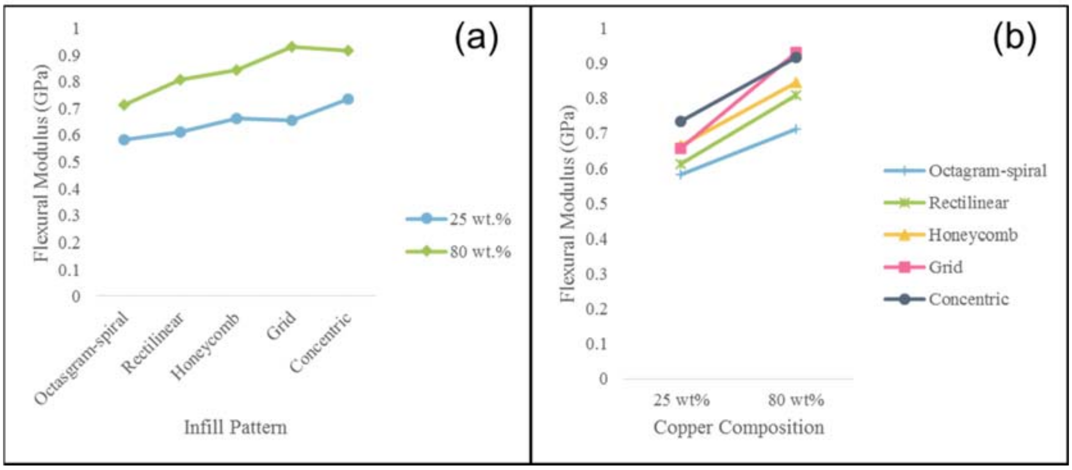

Figure 7. Graph of flexural modulus against infill pattern and Copper composition.

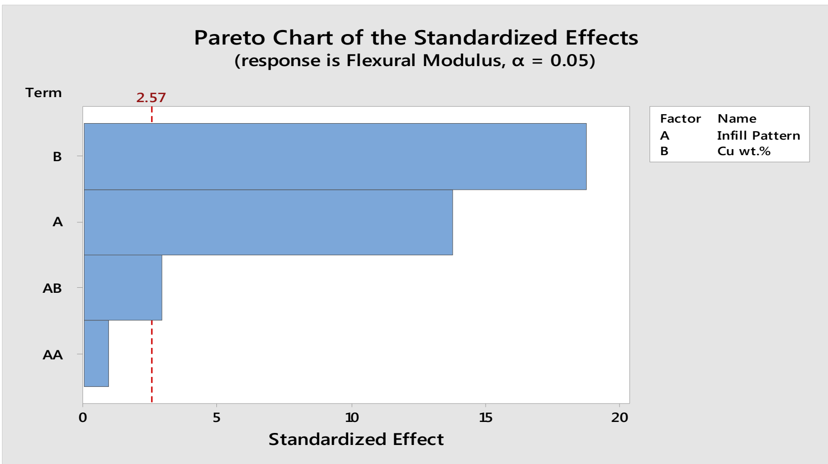

Figure 8. Pareto chart of printing parameters toward flexural modulus.

4. Conclusions

This research first started with identifying Cu reinforced PLA filament available in the market and do not have published research articles. Printing of specimen according to ASTM standards varying infill pattern and different Cu composition using low cost fused deposition modeling printer was successfully done. Mechanical test comprising flexural test has been successfully performed on the printed specimens according to ASTM D790 standard. The mechanical test results were investigated using response surface methodology and reliable modeling for all mechanical properties were proposed.

Flexural test results showed that both flexural strength and flexural modulus, infill pattern, Cu wt.% and interaction between infill pattern with Cu wt.% have a significant effect. The 25 wt.% Cu showed better mechanical strength. The increase of metal particles composition weakens the mechanical strength of the polymer matrix.

The maximum flexural modulus can be obtained parameters combination of Concentric infill pattern with 80 wt.% Cu composition meanwhile, Concentric infill pattern with 25 wt.% Cu composition for maximum flexural strength.

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