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Experimental and Statistical Analysis of the Effect of Process Parameters on Mechanical Properties of 3D Printed Copper Reinforced Composite Samples

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Keywords：3D printing, copper, tensile strength, impact strength, Taguchi.

ABSTRACT

The effects of 3D printing process parameters on mechanical properties of three-dimensional (3D) printing copper reinforced Polylactic acid (PLA) composite samples were analyzed as experimentally and statistically. In this context, tests were carried out with orthogonal array Taguchi method. Control factors were determined by using the Taguchi method for optimum mechanical properties. Two different filament materials (PLA and PLA+20% Copper Reinforced Composite), three different filling structures (Octogram spiral - Os, Archimedian cords - Ac, and 3D Honeycomb - Hc), and three different occupancy rates (10, 30, and 50%) were determined. The results showed that significant improvements in mechanical properties of PLA+20% copper reinforced composite samples were observed. According to the regression equations, optimum mechanical properties were found to be as 29.277MPa at tensile strength, 3.503% at percentage elongation, 3.458kJ/m² at izod impact values. Mechanical properties can be improved by using appropriate 3D printing process parameters. Occupancy rate and filling structure show a similar relationship for tensile strength and izod impact values. Hc filling structure can be selected for products which strength property is important. Os filling structure can be preferred for products when elongation and damping properties are required.

INTRODUCTION

3D printing technology is a process to produce the 3D components (Çevik and Kam, 2020). In this context, Fused Deposition Modeling (FDM) method that provides the most suitable technology, low cost and use of many material types in Additive Manufacturing (Kam et al. 2021; Kam et al. 2022; Ning et al. 2015). The most important advantages of this method; it is possible to produce without preliminary preparation and without creating residual materials and besides, geometric restrictions are not a problem in the product according to traditional production methods (İpekçi et al. 2018; Kam et al. 2017; Kam et al. 2018; Huang et al. 2015; Ford and Despeisse 2016). However, its mechanical properties are slightly lower than traditional manufacturing methods. This situation limits using FDM method for manufacturing (Kohtala 2015; Faludi et al. 2015; Chen et al. 2015; Huang et al. 2013; Kohtala and Hysalo 2015; Turner et al. 2014; Nidagundi et al. 2015). Therefore, it is possible to print by improved mechanical properties with composite filaments formed by adding additives such as copper into plastic materials. Copper reinforcement can increase the strength of the parts and this reinforcement cause a decreasing in flexibility and workability (Çevik and Kam, 2020). In this context, it is widely used in situations requiring of production, such as prototypes, special apparatus or products specific to individual needs (Boschetto and Bottini 2016). Despite all these advantages of the FDM method, there are some disadvantages. One of these disadvantages; because of the shrinkage and twisting of the melted material coming out of the nozzle, it prevents the material from adhering properly to the plane surface. In addition, during production, there are bumps and distortions in the geometrical corners of the part caused by different cooling conditions. Detailed studies have been carried out by many researchers to overcome these disadvantages of the FDM method (Wu et al. 2016; Ramli et al. 2015).

Occupancy rate, filling structure, and layer thickness are the main factors affecting product quality in 3D printers (Ramli et al. 2015). Studies in literature; FDM technology shows success in the manufacture of complex surfaced geometry. In an alternative study,

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researchers changed the way of filling in production and reduced the product cost by reducing the internal volume (Wang et al. 2013). They were focused on strength with the FDM method, production parameters in 3D printing systems, printing techniques and reverse engineering applications, different printer and their applications (Campbell et al. 2012; Piattoni et al. 2012; Kashdan et al. 2012; Vaezi et al. 2013), and development (Lanzotti et al. 2015). Tests of tensile and izod impact are the most important methods used to determine the tensile strength, percentage elongation, and izod impact values of 3D samples. In a different study, they made tensile tests to examine mechanical properties of printed products. They used an open source 3D printer and evaluated their results (Lanzotti et al. 2015). 3D printers are computer aided manufacturing (CAM) systems since they are faster than traditional manufacturing methods, nowadays many industrial areas such as automotive, aerospace, medical, manufacturing, education use 3D printers. Product amounts increases according to increasing requirements. 3D printing process has no waste material left and also products that could not be manufactured by traditional methods or needs of many processes can be printed by 3D printers at once.

Many studies on the FDM method have been conducted in the literature (İpekçi et al. 2018; Kam et al. 2017; Kam et al. 2018; Huang et al. 2015; Ford and Despeisse 2016; Popescu et al. 2018). In these studies, the mechanical properties of the samples were examined by considering many different 3D printing process parameters. Since the samples with composite filaments have good strength and low intrinsic mass properties, their use in industry is increasing rapidly, and they become even more important with their low cost and comparable mechanical properties (Çevik and Kam, 2020). Samples that can be printed from composite materials using FDM method; aerospace and aircraft industry, automotive industry, sports and marine products; it has found a wide area of use due to its desirable properties such as lightness, rigidity, heat resistance, high strength, good wear resistance. Basically, composite materials are used instead of steel and similar metals in products where excess weight is not desired but high strength is desired. To improve the mechanical properties of the product with FDM and to increase the performance, researchers (Liu et al.2019; Zhang et al. 2019; Lebedev et al. 2018; Guan et al. 2018) have developed composite materials that can be used with existing FDM. There has been a great increase in the production of reinforced polymer composites due to the development of new additives in recent years. There are a large number of studies (Guan et al. 2018; Tang et al. 2020; Kam et al. 2020; Ertugrul et al. 2020; Yalcinkaya et al. 2020; Kam et al. 2021; Atakok et al. 2021; Kam and İpekci 2021) that have been made considering the mechanical and thermal properties of these composites. However, a limited number of studies have been conducted in the literature on mechanical properties of products made from composite materials using FDM method (Çantı and Aydın 2018; Çantı et al. 2018; Günay et al. 2020; Kam et al. 2020; Kam et al. 2021; Atakok et al. 2021; Kam and İpekci 2021). In this study, it was investigated the effects of parameters on mechanical properties of produced copper reinforced composite samples.

MATERIAL AND METHOD

3D Printing parameters of the samples were determined as presented in Table 1.

Table 1. Printing process parameters.

Diameter of filament (mm)	1.75
Diameter of nozzle (mm)	0.40
Temperature of extruder (°C)	200
Temperature of table (°C)	60
Width of extrusion (mm)	0.35
Thickness of layers (mm)	0.2
Printing speed (mm/min)	3600
Idle speed (mm/min)	4800
Filament material	PLA
	PLA+%20 Copper
Filling structure	Octagram spiral
	Archimed cords
	3D Honey comb
Occupancy rate (%)	10, 30, 50

The properties of PLA and copper reinforced composite filament materials used for test samples were given in Table 2.

Table 2. Properties of filament materials (Çevik and Kam, 2020).

Material	PLA	PLA+20%Copper
Filament color	Red	Copper
Diameter of filament (mm)	1.75	1.75
Density of filament material (g / cm³)	1.20-1.24	3.41
Tensile Yield Modulus (MPa)	62	18.3
Flexural Modulus (MPa)	2504.4	4210
Elongation at Break (%)	4.44	4.5
Melt Point (ºC)	190-220	195-210
Impact Strength (kJ/m^2)	4.28	9.3
Vacant Softening (ºC)	±60	±65

Figure 1 gives 3D printing of samples using a 3D printer, according to the standard tensile test sample (ISO 527 - Type 2) and izod impact test sample (ISO 180 - Type 1). The filling structures and occupancy rates of the test samples prepared for the experiments were given in Table 3.

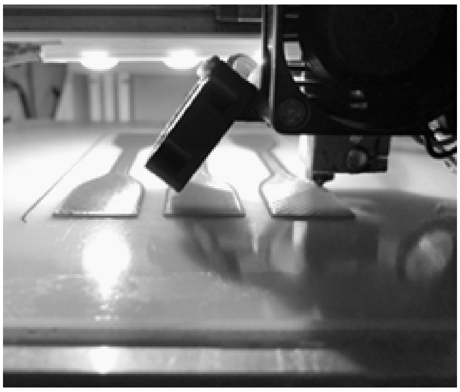


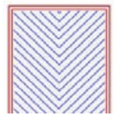
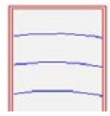
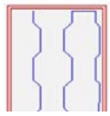
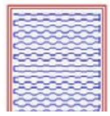
Fig. 1. Printing process of samples.

Tests were carried out in 5 ton tensile testing device. Tensile test speed is taken as 5 mm / min in tensile tests. Tensile test and izod impact test device were presented in Figure 2. Tensile and impact strength tests were repeated three times for each test. Average values were calculated.

Taguchi method was applied to optimize the mechanical properties of test samples. The larger is better criteria is chosen for calculating the Signal/Noise (S/N) ratio carried out with Minitab18. In this context, control factors were shown in Table 4. In Equation (1); y_i is the measured values and n is the number of performed tests.

$$S/N = -10log\left(\frac{1}{n}\sum_{i=1}^{n} 1/{y_i}^2\right) \quad (1)$$

Table 3. Filling structures and occupancy rates of the samples.

Filling structure	Occupancy rate (%)		
	10	30	50
Octagram spiral			
Archimedian chords			
3D Honeycomb			

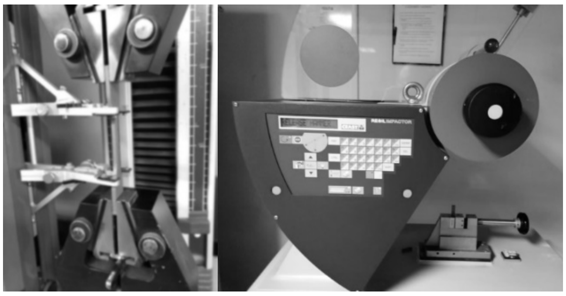


Fig. 2. Tensile test and izod impact test device

Table 4. Control factors

No	Factors	S	U	L1	L2	L3
1	Filament material (PLA:1; PLA+ : 2)	A	-	1	2	-
2	Filling structure (Os: 1; Ac: 2; Hc: 3)	B	-	1	2	3
3	Occupancy rate (10% : 1 ; 30% : 2 ; 50% : 3)	C	%	1	2	3

RESULTS AND DISCUSSION

The effects of the parameters on mechanical properties were determined with analysis of variance (ANOVA) statistical calculations. Average values and S/N ratios were presented in Table 5. ANOVA statistical results were presented in Table 6. The main effect plot and levels of the 3D printing process parameters were given in Figure 3. Response table for S /N ratios in tensile strength were shown in Table 7. The statistical results showed that Taguchi method has been successfully applied to determine the optimum tensile strength values. Regression Equation was given in (2) for estimation of values.

$$\text{Tensile Strength(MPa)} = 3.47 + 3.587(A) + 3.263(B) + 2.948(C) \quad (2)$$

Optimum estimated tensile strength value was obtained as 29.277 MPa according to Equation (2).

Table 5. Test results and S / N ratios.

No	A	B	C	Tensile strength values (MPa)	S/N (dB)	Elongation values (%)	S/N (dB)	Impact strength values (kj/m²)	S/N (dB)
1	1	1	10	16.14	24.15	3.44	10.73	1.65	4.34
2	1	1	30	17.91	25.06	3.35	10.50	2.32	7.30
3	1	1	50	19.65	25.86	3.24	10.21	2.37	7.49
4	1	2	10	16.22	24.20	3.55	11.00	1.72	4.71
5	1	2	30	17.10	24.65	3.35	10.50	2.10	6.44

6	1	2	50	20.34	26.16	3.15	9.96	2.25	7.04
7	1	3	10	19.42	25.76	2.98	9.48	2.05	6.23
8	1	3	30	23.32	27.35	2.87	9.15	2.56	8.16
9	1	3	50	25.24	28.04	2.81	8.97	2.85	9.09
10	2	1	10	16.28	24.23	1.58	3.97	1.79	5.05
11	2	1	30	18.98	25.56	1.52	3.63	2.33	7.34
12	2	1	50	20.56	26.26	1.24	1.86	2.72	8.69
13	2	2	10	19.40	25.75	1.32	2.41	1.92	5.66
14	2	2	30	23.85	27.54	1.17	1.36	2.57	8.19
15	2	2	50	27.86	28.89	1.13	1.06	2.82	9.00
16	2	3	10	22.66	27.10	1.22	1.72	2.45	7.78
17	2	3	30	26.18	28.35	1.15	1.21	3.45	10.75
18	2	3	50	31.85	30.06	1.08	0.66	3.95	11.93

Table 6. ANOVA table.

Source	DF	Seq SS	Adj SS	Adj MS	F Value	P Value	Contribution (%)
Filament material	1	57.89	57.89	57.889	18.50	0.0010	17.56
Filling structure	2	129.81	129.81	64.903	20.74	0.0001	39.39
Occupancy rate	2	104.34	104.34	52.168	16.67	0.0003	31.66
Error	12	37.55	37.55	3.129			11.39
Total	17	329.58					100.00

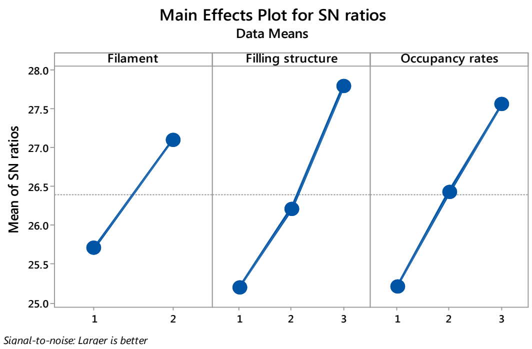


Fig. 3. S / N rates for tensile strength.

Table 7 gives that the effective factors for the tensile strength were the filling structures, occupancy rates, and filament materials. The results were confirmed with ANOVA analysis. The optimum parameters for the tensile strength were the second level of filament material (A_2), the third level of filling structure (B_3), and the third level of occupancy rate (C_3).

The optimum parameters (filling structure, occupancy rate, and filament material) for process parameters were 3D Honeycomb, 50%, and PLA+. The results of ANOVA showed the most effective parameter on tensile strength to be filling structure (39.39%), occupancy rate was the most effective parameter after filling structure at 31.66%, and the filament material (17.56%) was low, respectively. The results obtained from experiments were confirmed with ANOVA analysis.

Table 7. Response table (Tensile strength).

L	A Filament	B Filling structure	C Occupancy rates
1	25.70	25.19	25.20
2	27.09	26.21	26.43
3	-	27.78	27.55
Delta	1.39	2.59	2.35
Rank	3	1	2

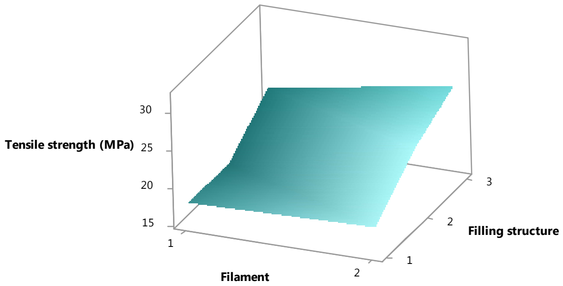
Normal probability plot for tensile strength and surface plot graphs were shown in Figure 4. As the occupancy rates values increase, tensile strength values increased proportionally. The filling structures increase to tensile strength less than other parameters. It was observed that the filling structure of 3D Honeycomb shows more strength than the other filling structures. It has shown similar results in the literature studies with FDM method (Çevik and Kam, 2020; Kam et al. 2020; Kam et al. 2021; Atakok et al. 2021; Kam and İpekci 2021).

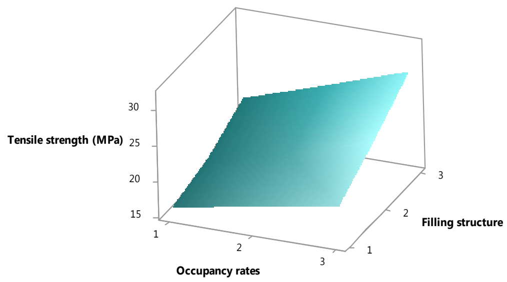
Table 8 shows the ANOVA results. 3D printing process parameters were significant statistically. The main effect plot was presented in Figure 5. Response table for S /N ratios in percentage elongation were presented in Table 9. Regression Equation was shown in (3).

$$\text{Elongation}(\%) = 5.736 - 1.925(\text{A}) - 0.188(\text{B}) - 0.120(\text{C}) \quad (3)$$

Estimated optimum elongation value was obtained as 3.503% according to equation (3).

Table 9 gives that the most important 3D printing factors for percentage elongation were filament materials, filling structures, and occupancy rates. The optimum parameters for the elongation were the first level of filament material (A_1), the first level of filling structure (B_1), and the first level of occupancy rate (C_1). The optimum parameters (filament material, filling structure, and occupancy rate) for elongation were PLA, Octogram spiral, and 10%, respectively.





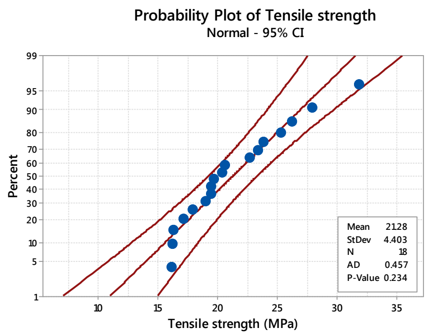


Fig. 4. Surface plots of tensile strength and probability plot of strength.

Table 8. ANOVA table

Source	DF	Seq SS	Adj SS	Adj MS	F value	P value	Contribution (%)
Filament material	1	16.6849	16.684	16.684	1223.83	0.00000	95.52
Filling structure	2	0.4462	0.446	0.223	16.36	0.00037	2.55
Occupancy rate	2	0.1730	0.173	0.086	6.34	0.01319	0.99
Error	12	0.1636	0.163	0.013			0.94
Total	17	17.4677					100.00

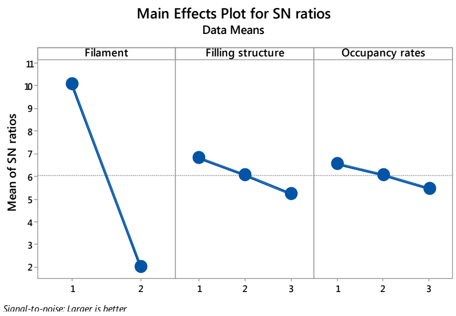


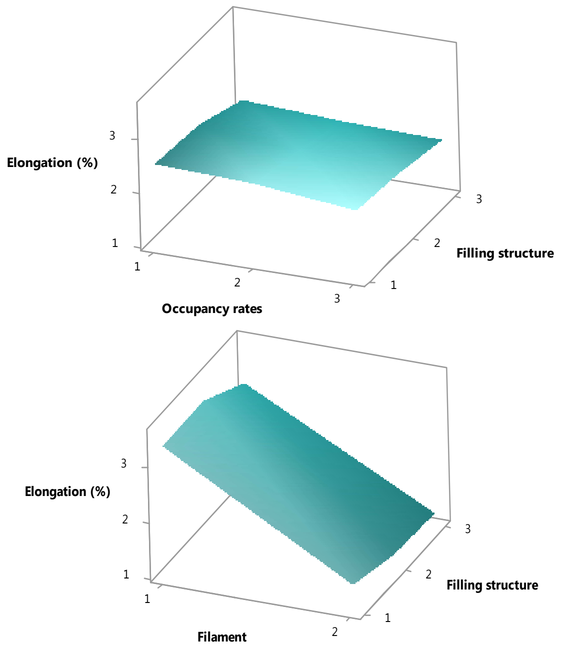
Fig. 5. S / N rates for percentage elongation.

Table 9. Response table (Elongation).

L	A Filament material	B Filling structure	C Occupancy rates
1	10.059	6.820	6.555
2	1.992	6.051	6.062
3	-	5.204	5.458
Delta	8.067	1.616	1.097
Rank	1	2	3

The ANOVA results showed that the most effective parameter on elongation is filament material (95.52 %), filling structure was the most effective parameter after filament material at 2.55%, and the occupancy rate (0.99%) was very low, respectively. Surface plot graphs and probability plot of elongation were shown in Figure 6.

In the surface plot graphs, the occupancy rate and filling structure can be seen ineffective. The filling structures increase to elongation less than other parameters. It was observed that the Octogram spiral (Os) filling structure of shows higher percentage elongation than other other filling structures. It has shown similar results in the literature studies with FDM method (Çantı and Aydın 2018; Çantı et al. 2018; Günay et al. 2020; Çevik and Kam, 2020; Kam et al. 2021; Atakok et al. 2021; Kam and İpekci 2021).



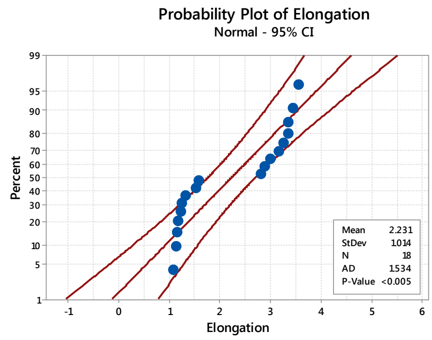


Fig. 6. Surface plots of elongation and probability plot of percentage elongation.

Table 10. ANOVA table.

Source	DF	Seq SS	Adj SS	Adj MS	F value	P value	Contribution (%)
Filament material	1	0.9476	0.9476	0.94761	18.93	0.00094	16.08
Filling structure	2	1.8079	1.8079	0.90394	18.06	0.00024	30.68
Occupancy rate	2	2.5369	2.5369	1.26844	25.34	0.00005	43.05
Error	12	0.6006	0.6006	0.05005			10.19
Total	17	5.8930					100.00

Table 10 shows the ANOVA results. The main effect plot and levels of the parameters were given in Figure 7. Response table for S /N ratios (izod impact value) were given in Table 11. Regression Equation was shown in (4).

$$\text{impact value } (\text{kj/m}^2) = 0.164 + 0.459(A) + 0.3442(B) + 0.4483(C) \tag{4}$$

Optimum izod impact value can be estimated as 3.458 kJ/m² according to Equation (4).

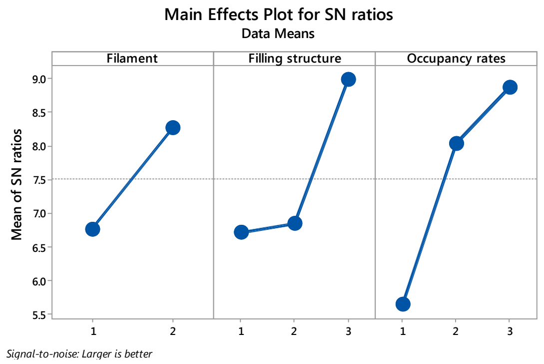


Figure 7. S / N ratios for izod impact values.

Table 11 gives that the most important 3D printing factors for the izod impact values were occupancy rates, filling structures, and filament materials. The optimum parameters for the izod impact values were the second level of filament material (A_2), the third level of filling structure (B_3), and the third level of occupancy rate (C_3).

Table 11. Response table (izod impact value).

L	A Filament	B Filling Structure	C Occupancy rate
1	6.761	6.708	5.634
2	8.271	6.845	8.037
3	-	8.995	8.877
Delta	1.510	2.286	3.244
Rank	3	2	1

The optimum parameters (occupancy rate, filling structure, and filament material) for impact strength were 50%, 3D Honeycomb, and PLA+. The results of ANOVA showed the most effective parameter on izod impact values to be occupancy rate 43.05%, filling structure were the most effective parameter after occupancy rate at 30.68%, and the filament material 16.08% was low, respectively. Normal probability plot for izod impact values and surface plot graphs were shown in Figure 8. As the occupancy rates increase, the izod impact values increased proportionally. It was observed that the filling structure of 3D Honeycomb shows more izod impact values than the other filling structures. It has shown similar results in the literature (İpekçi et al. 2018; Kam et al. 2017; Kam et al. 2018; Huang et al. 2015; Ford and Despeisse 2016). In the experimental and statistical study, verification experiments were carried out and optimum results were obtained.

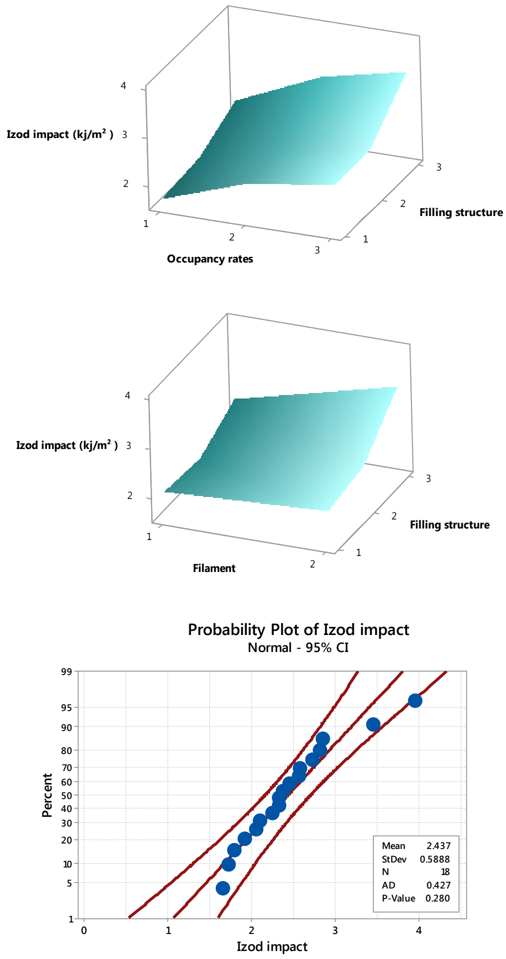


Figure 8. Surface plots of izod impact values and probability plot.

However, tensile strength properties of printed products or samples were not emphasized in this study. In this study, izod impact test has been done and it has been investigated that it can work in vibrating environments. Samples with high impact resistance are predicted to operate in vibrating environments.

CONCLUSIONS

The mechanical properties of copper reinforced PLA composite samples were analyzed as experimental and statistical. The optimum parameters for tensile strength were second level of filament material (PLA+), the third level of filling structure (3D Honeycomb), and the third level of occupancy rate (50%). The ANOVA results showed the most effective parameter on tensile strength was filling structure 39.39%, occupancy rate was the most effective parameter after filling structure at 31.66%, and the filament material 17.56% was low, respectively. The optimum parameters for the elongation were the first level of filament material (PLA), the first level of filling structure (Octogram spiral), and the first level of occupancy rate (10%). The most effective parameter on elongation was filament material 95.52%, filling structure was the secondary effective parameter after filament material at 2.55%, and the occupancy rate 0.99% was very low, respectively. The optimum parameters for the impact strength were the second level of filament material (PLA+), the third level of filling structure (3D Honeycomb), and the third level of occupancy rate (50%). The most effective parameter for izod impact was occupancy rate 43.05%, filling structure was the secondary effective parameter after occupancy rate at 30.68%, and the filament material 16.08% was low, respectively.

The results showed that significant improvements in mechanical properties of PLA+ 20% copper reinforced composite samples were observed. According to the regression equations, the optimum mechanical properties were found to be as 29.277 MPa at strength, 3.503% at percentage elongation, 3.458 kJ/m² at izod impact values in the copper reinforced composite filament (PLA+) with filling structure (3D Honeycomb) and occupancy rates (50%), respectively. Occupancy rate and filling structure show a similar relationship for tensile strength and impact strength. Hc filling structure can be selected for products which strength property is important. Os filling structure can be preferred for products when elongation and damping properties are required. While the occupancy rate can be increased as much as possible for strength and izod impact values, the opposite is true for situations where a percentage elongation is desired.

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