

Chapter 25

Investigation of Mechanical Behaviour and Surface Roughness Properties on Copper Electroplated FDM High Impact Polystyrene Parts



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Abstract Additive manufacturing is an advanced production technique which builds up complex-shaped parts layer by layer, as opposed to subtractive manufacturing methodologies by using the .stl file as input data. The mechanical strength and surface roughness properties of polymer-based additive manufacturing components need to be improved for its efficient use in functional end tooling applications. Many research methodologies were proposed to improve the mechanical strength and surface properties of additive manufacturing components but post-processing characterization is a kind of method, which is highly concentrated in recent years by various organizations. The various coating techniques like D.C sputtering, electroforming, electroless forming and electroplating were selected in this study, and a pilot study was conducted to choose a best technique that provides better adherence of source material over target in different build orientations of 3D-printing process. Among the various techniques in pilot study, the electroplating process was selected for this study because of its better coating properties, simple procedure, low-cost and good surface finish than other technique. In this study, the tensile and flexural test specimens were fabricated with high impact polystyrene material by using fused deposition modelling technique in five different build orientations (0° , 30° , 45° , 60° and 90°). The fabricated parts were electroplated with copper of thickness $250\ \mu$ by using sulphuric acid (H_2SO_4) and copper sulphate ($CuSO_4$) as electrolyte solution. The electroplated and non-electroplated parts were tested for its tensile and flexural properties as per ASTM standards at room temperature to analyze the effect of electroplating over HIPS parts. The portable surface roughness tester was used to analyze the improvement in roughness properties of electroplated parts. The results between electroplated and non-electroplated parts fabricated in five different orientations were compared and validated for its application in functional end tooling applications. The results are showing that electroplating process over 3D-printed HIPS parts significantly

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improved its tensile, flexural and surface roughness properties when comparing to non-electroplated parts.

Keywords High impact polystyrene · Fused deposition modelling · Copper electroplating · Anisotropic behaviour

25.1 Introduction

Additive manufacturing is an unconventional production technique which creates any complex-shaped geometrical parts at a stretch without in need of any additional experimental set-up. The additive manufacturing can be classified based on its nature of raw material usage like powder-based, liquid-based and filament-based technique [1]. The applications of additive manufacturing were expanded beyond the expectations and the limitations of conventional manufacturing are almost replaced by this technique [2]. Additive manufacturing in tooling is highly preferred than conventional tooling methods like CNC machining in terms of speed, difficulty and quality [3]. Post-processing characterization experimentations are performed to improve mechanical strength and surface roughness properties for development of additive manufacturing tooling in sand casting, investment casting and plastic moulding applications [4]. Electroplating has been practiced for many years in industries such as electronics and jewellery manufacturing. The electroplating process contains an anode and cathode in an electrolytic solution which together kept in an electrolytic bath. When potential difference is applied between the anode and cathode the ions from the anode got discharged and bonded to the cathode. This process is repeated till the cathode is completely electroplated by the metal from anode [5]. The cathode must be a conductive material, so the polymer parts must be coated with conductive ink preferably silver paint in most cases for making it conductive [6]. The nickel deposition over the polymer prototypes produced by fused deposition modelling technique showed a significant increase in ultimate tensile strength, young's modulus and impact strength which highly influenced overall strength and stiffness behaviour [7]. The electroplating process carried out with a thickness of 60 μm over the ABS parts showed lower ductility, while 70 and 80 μm samples showed considerable ductility improvement [8]. The electroplating of copper and nickel samples from stereolithography and laser sintering process showed that the samples with higher coating thickness provided more UTS and impact energy but had a poor effect on the ductility of parts [9]. The reaction between butadiene synthetic elastomer and (5–14%) styrene containing crystal polymer creates high impact polystyrene [10]. HIPS material provides very good mechanical resistance comparing to other polymers, which also facilitates excellent machinability as well as dimensional stability. The excellent aesthetic quality along with easy to glue and paint property in low-cost makes it ideal material for various applications like prototypes, covers and tooling in food industries, low strength mould applications, etc. [11].

25.2 Objective of the Study

The objective of this work is to study the mechanical behaviour and surface roughness properties of 250 μ copper electroplated and non-electroplated high impact polystyrene specimens fabricated by using fused deposition modelling process in five different build orientations (0° , 30° , 45° , 60° and 90°). The specimens manufactured as per ASTM standards were tested for tensile, flexural strength and the surface roughness also measured. The results were compared between electroplated and non-electroplated specimens for all the five orientations and based on findings an optimized orientation is suggested for further applications.

25.3 Methodology of the Study

The methodology used in this study is shown in Fig. 25.1 as follows:

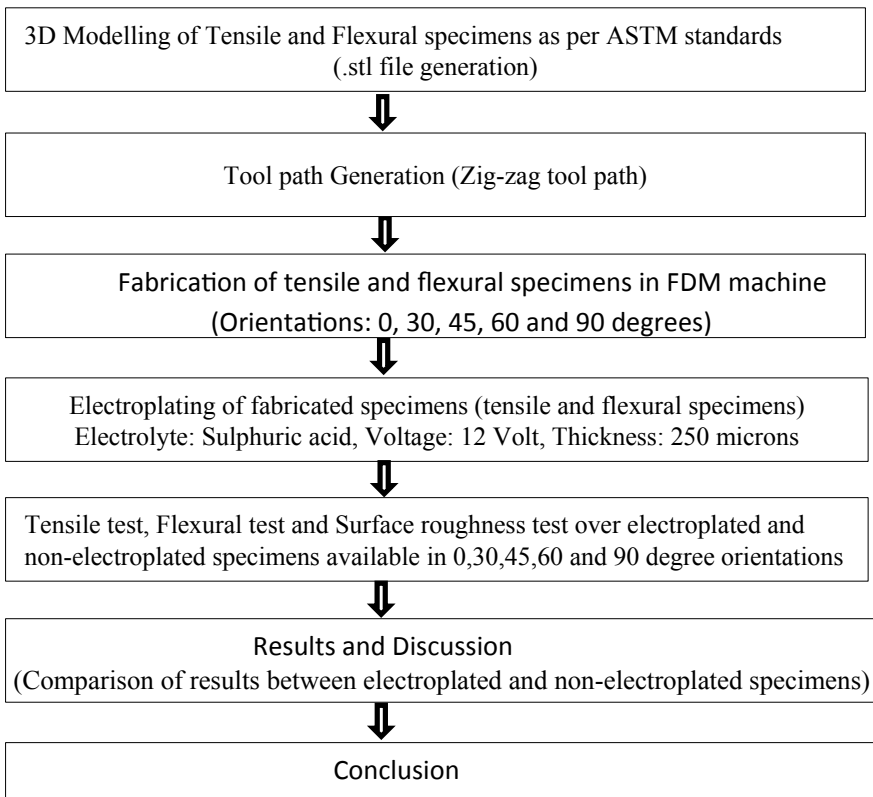


Fig. 25.1 Methodology of the study

25.4 Experimentation

25.4.1 3D Modelling

The material consumption and build time is an important parameter to be considered at the time of selecting standards for printing specimens, so here ASTM standards were accordingly selected to minimize the material consumption and build time as much as possible [12]. The tensile and flexural test specimens were modelled in CATIA software as per ASTM D638 and ASTM D6272 standards. The surface geometry of generated models was encoded by STL file format. The encoded STL file format was checked against standard file generation rules like vertex rule, orientation rule, all positive octant rule, and triangle sorting rule by using ASCII programming module. The ASTM standards and generated 3D models of tensile test specimen and flexural test specimen were shown in Figs. 25.2 and 25.3, respectively.

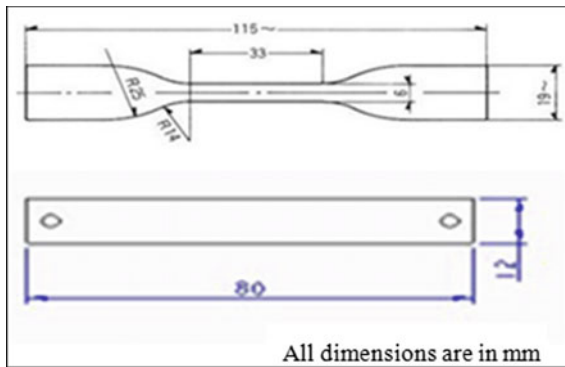


Fig. 25.2 ASTM standards of tensile and flexural specimens

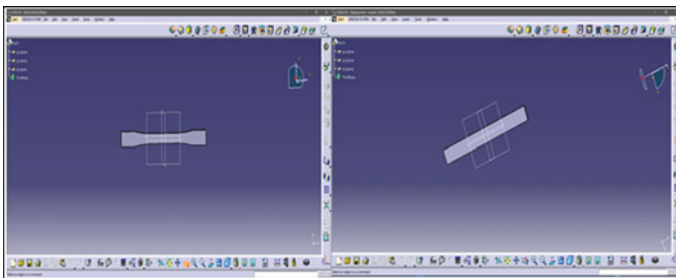


Fig. 25.3 3D models of tensile and flexural specimens

25.4.2 Fabrication

The Flash Forge 3D-printer machine was used for the fabrication of tensile and flexural test specimens. The tensile and flexural test specimens were fabricated in five different orientations (0° , 30° , 45° , 60° and 90°). Figures 25.4 and 25.5 show the different orientations of fabricated specimens. The specimens were fabricated by high impact polystyrene material based on the zig-zag tool path. The support structures were removed after fabrication by immersing in solution. The specifications of Flash Forge FDM machine and HIPS material are shown in Tables 25.1 and 25.2 as follows.

Fig. 25.4 Fabricated tensile specimens

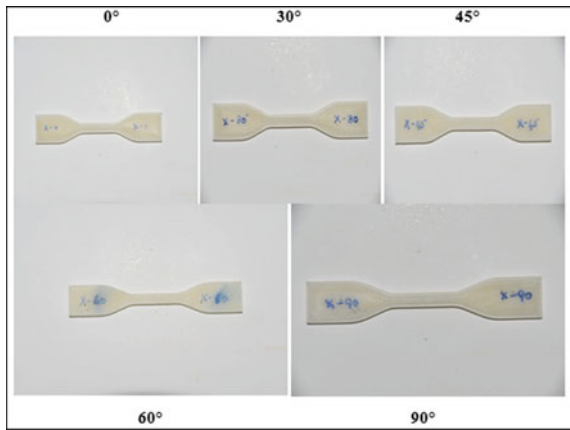


Fig. 25.5 Fabricated flexural specimens

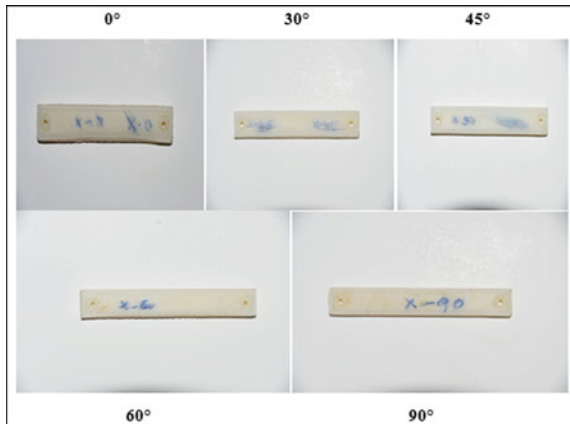


Table 25.1 Specifications of flash forge FDM machine

Model material	High impact polystyrene
Support material	SR 30 soluble
Build size (mm)	203 × 152 × 152
Layer thickness (mm)	0.254
Operating system compatibility	Windows XP/7
Network connectivity	Ethernet TCP/IP 10/100 baseT
Size (mm)	635 × 660 × 787
Weight (kg)	76
Power (VA)	100–127

Table 25.2 Specifications of HIPS material

Commercial name in FDM	HIPS
Glass transition temperature (T_g)	105 °C
Coefficient of thermal expansion	8.82×10^{-05} mm/mm/°C
Extrusion temperature	240 °C

25.4.3 Electroplating

The cleaning of specimens was done after fabrication and the specimens were prepared for electroplating process. The copper ink is painted over tensile and flexural specimens to make it conductive. In the electrolytic bath tank, the source copper material was attached to anode and the copper conductive ink coated specimens were attached to cathode. Sulphuric acid (H_2SO_4) was used as an electrolyte because of its well-known electrical conductivity and a better throwing power. The ability of the electrolyte to get uniform depositions in areas with different current densities is called as throwing power. From the pilot study, it was observed that the addition of more sulphuric acid provided increased throwing power. Based on the theoretical calculations the appropriate voltage and time were chosen. The pilot experiments were conducted based on theoretical calculations in a trial and error basis, which shows that maximum current of 4.5 A/in^2 provides better adherence and the experiments exceeding this value resulted in melting and collapsing of specimens. In electroplating process, the thickness of coating is directly proportional to voltage so in this study voltage was taken as a constant value of 12 V to perform the electroplating of specimens. The average time taken by each specimen of different orientation was 10 min approximately and the thickness of 250μ was achieved over each specimen. Figure 25.6 shows the steps followed in electroplating of specimens.

Fig. 25.6 Electroplating of 3D-printed HIPS specimens



25.4.4 Tensile and Flexural Testing

The electroplating process was followed by testing of electroplated and non-electroplated tensile and flexural specimens of all five different orientations. The tensile and flexural tests were carried out as per ASTM D638 and D690 standards at normal room temperature. The loads were gradually increased in steps and the corresponding stress versus strain graph was recorded for all the orientations. The ultimate tensile and flexural strength of all specimens in different orientations were calculated separately. Figure 25.7 shows the electroplated and non-electroplated specimens of

Fig. 25.7 Electroplated and non-electroplated specimens



Fig. 25.8 Experimental set-up of flexural test



Fig. 25.9 Experimental set-up of tensile test



different orientations used for tensile and flexural testing. The experimental set-up of tensile and flexural tests was shown in Figs. 25.8 and 25.9.

25.4.5 Surface Roughness Measurement

The surface roughness plays a significant role in determining the quality of the material printed in 3D-printing. Since from its introduction, the surface roughness oriented problems like stair-stepping effect in edges would be a major concern in various 3D-printing technologies. Even though this roughness oriented problems are greatly reduced by methods like adaptive slicing, customized tool path generation, etc. but the need for studying the surface roughness behaviour in this kind of electroplated specimens is highly recommended to verify the influence of coating thickness, bond-

Fig. 25.10 Portable surface roughness tester



ing nature between metal and plastics over the surface roughness properties so that for determining the anisotropic behaviour in each orientation. In this study, the surface roughness test was performed over electroplated and non-electroplated specimens by using portable roughness tester. The surface roughness (R_a) was calculated along the two adjacent lateral directions say x -direction (length) and z -direction (width). Figure 25.10 represents the portable surface roughness tester used for this study.

25.5 Results and Discussion

25.5.1 Tensile Test

The tensile test was conducted for the electroplated and non-electroplated specimens in all five orientations at room temperature. The results of tensile test experiment show a great improvement in ultimate tensile strength and ultimate load-bearing capacity of electroplated specimens over non-electroplated specimens. The ultimate tensile strength and ultimate load-bearing capacity of electroplated specimens exhibit a 55.63% and 61.42%, respectively. The % of elongation is very high for electroplated specimens in all orientations, which confirm the establishment of transition between brittle to ductile nature over the surface of non-electroplated high impact polystyrene specimens. This increase in elongation also confirms the perfect bonding of copper molecules over HIPS surface structure for the mentioned experimental conditions used in this study, and this increased percentage of elongation in electroplated specimens provided a great resistance against tensile loading in all directions. Even though the tensile nature is improved greatly for electroplated specimens, the 45° orientation built specimen showed a minimum percentage of improvement comparing other orientations against tensile loading because of its poor anisotropic nature as resulted from weak interfacial bonding between adjacent layers. The 90° built orientation provided a significant improvement in tensile properties because of its strong interface between adjacent layers facilitated by the good adhesion of copper molecules at the time of electroplating. Tables 25.3, 25.4 and 25.5 shows the maximum load-bearing capac-

Table 25.3 Maximum load-bearing capacity of tensile specimens

S. No	Orientation (°)	Ultimate tensile strength (MPa)	
		Non-electroplated	Electroplated
1	0	18.11	62.90
2	30	18.64	41.88
3	45	19.16	29.76
4	60	18.89	31.79
5	90	13.04	52.80

Table 25.4 Ultimate tensile strength of tensile specimens

S. No	Orientation (°)	Ultimate tensile load (KN)	
		Non-electroplated	Electroplated
1	0	0.41	1.52
2	30	0.44	0.85
3	45	0.46	0.76
4	60	0.44	0.85
5	90	0.31	1.52

Table 25.5 Elongation percentage of tensile specimens

S. No	Orientation (°)	% of Elongation	
		Non-electroplated	Electroplated
1	0	2.51	12.56
2	30	2.08	9.96
3	45	0.60	3.12
4	60	3.12	3.40
5	90	0.72	2.52

ity, ultimate tensile strength and percentage of elongation between electroplated and non-electroplated specimens in all orientations. Figures 25.11, 25.12 and 25.13 show the comparison graphs of ultimate tensile strength, maximum load-bearing capacity and % of elongation between electroplated and non-electroplated specimens for all the five different orientations, respectively.

25.5.2 Flexural Test

The three-point bending test was used to test flexural strength of the electroplated and non-electroplated specimens at room temperature. Since the specimen shape, loading geometry and strain rate plays a major role in determining the flexural strength of the material utmost care was taken to establish gradual loading condition over the specimens. Table 25.6 shows the results of flexural test in different orientations. The

Fig. 25.11 Ultimate tensile strength versus orientation

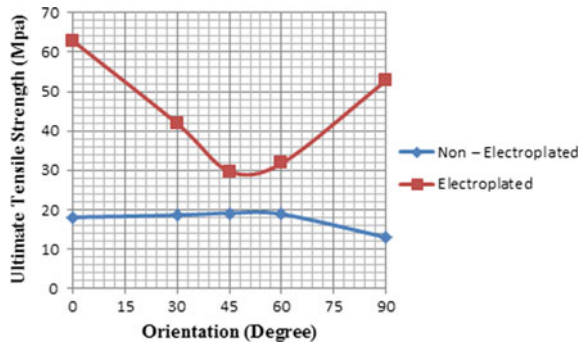


Fig. 25.12 Ultimate tensile load versus orientation

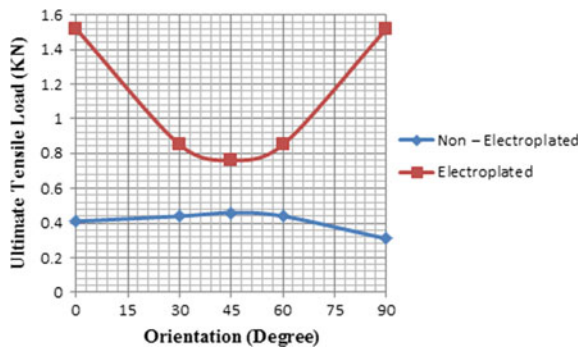


Fig. 25.13 Percentage of Elongation versus orientation

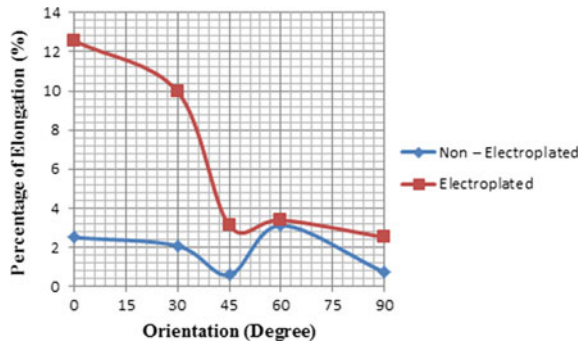
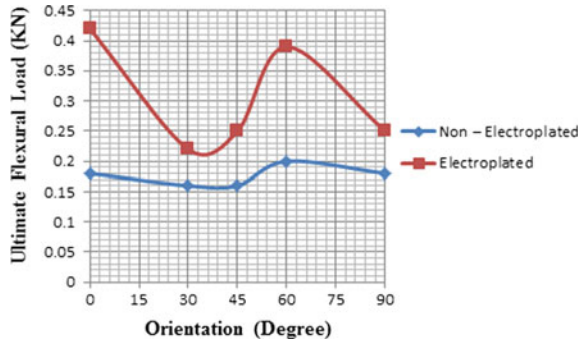


Table 25.6 Ultimate flexural load-bearing capacity of specimens

S. No	Orientation (°)	Ultimate flexural load (KN)	
		Non-electroplated	Electroplated
1	0	0.18	0.42
2	30	0.16	0.22
3	45	0.16	0.25
4	60	0.20	0.39
5	90	0.18	0.25

Fig. 25.14 Ultimate flexural load versus orientation



results are similar to tensile test as the electroplated specimens provided more flexural strength on the average of 39.41% than non-electroplated specimens. The electroplated specimen with 0° orientation provided maximum flexural strength because of its flat horizontal exposure of zig-zag tool path perpendicular to the direction of loading as shown in standard loading conditions. The electroplated specimen with 90° orientation shows minimum flexural strength over non-electroplated specimen because of its vertical exposure of zig-zag tool path perpendicular to the direction of loading. Figure 25.14 shows the comparison graph of specimens against respective orientations.

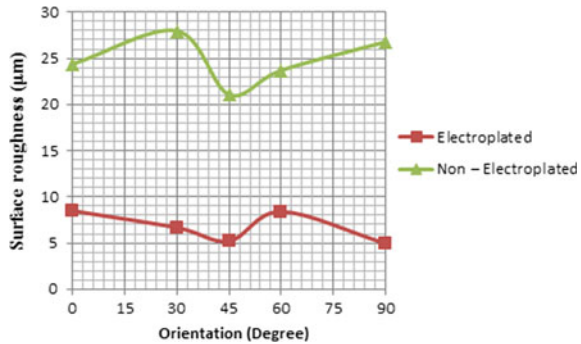
25.5.3 Surface Roughness Test

The high frequency, short wavelength component of a measured surface is called surface roughness. The surface roughness is a component of surface texture, which is quantified by the deviations in the direction of the normal vector of a real surface from its ideal form. The roughness is very high if deviations are large and surface is smooth if deviations are small. The surface roughness of electroplated and non-electroplated specimens was measured using portable roughness tester and the results indicated an average reduction of 72% surface roughness in electroplated parts comparing to non-electroplated parts because of the uniformed distribution of copper molecules over HIPS surface parts. The surface roughness is reduced about 60% in all orientations. Table 25.7 shows the surface roughness values of electroplated and non-electroplated parts. Figure 25.15 depicts the comparison of surface roughness between electroplated and non-electroplated parts.

Table 25.7 Surface roughness test results

S. No	Orientation (°)	Surface roughness (µm)	
		Non-electroplated	Electroplated
1	0	24.37	8.50
2	30	27.97	6.67
3	45	21.08	5.22
4	60	23.71	8.41
5	90	26.79	4.94

Fig. 25.15 Comparison of surface roughness



25.6 Conclusion

The study on electroplating of 3D-printed HIPS parts in five different orientations is novel and unique in this study. From the obtained results it is clearly understood that the electroplating of a 3D-printing HIPS material has significant impact over mechanical and surface properties of non-electroplated specimens. The results from this study can be further utilized for other materials in 3D-printing. Among the five orientations tested in this study, the each and every build orientation has its unique anisotropic property because of its complex tool path nature for material deposition over different spatial coordinate positions. The 90° orientation provided good tensile properties, while 0° orientation provided better flexural properties and regarding surface roughness the electroplating imparted high smoothness over surface by levelling deviations in all orientations but in electroplated specimens there is also a smaller amount of noise level deviation in frequency at lateral direction (z-direction) because of its stair-stepping phenomenon which shows that stair-stepping phenomenon is not fully compromised with this technique. The results of this study will help to meet the requirements for using 3D-printing technique in real end functional production of parts. The study also promises the improvement of aesthetics in 3D-printed complex-shaped parts which can be utilized in ornamental industry for creating customized designs.

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