Investigation of the effect of built orientation on mechanical properties and total cost of FDM parts

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Abstract

Fused deposition modeling (FDM) is one of the rapid prototyping methods that produce prototypes from plastic materials such as acrylonitrile butadiene styrene (ABS) by laying tracks of semi-molten plastic filament onto a platform in a layer wise manner from bottom to top. In FDM, one of the critical factor is to select the build up orientation of the model since it affects the different areas of the model like main material, support material, built up time, total cost per part and most important the mechanical properties of the part. In view of this, objective of the present study was to investigate the effect of the built-up orientation on the mechanical properties and total cost of the FDM parts. Experiments were carried out on STRATASYS FDM type rapid prototyping machine coupled with CATALYST software and ABS as main material. Tensile and Flexural specimens were prepared as per the ASTM standard with different built-up orientation and in three geometrical axes. It can be concluded from the experimental analysis that built orientation has significant affect on the tensile, flexural and total cost of the FDM parts. These conclusions will help the design engineers to decide on proper build orientation, so that FDM parts can be fabricated with good mechanical properties at minimum manufacturing cost.

1. Introduction

The competition in the world market for manufactured product has intensified tremendously in recent years.
It has become important, if not vital for new product to reach the markets as early as possible, before the competitors. To bring the product to the market swiftly, many of the processes involved in the design, test, manufacture, and market of the product have been squeezed, both in terms of time and material resources; Wheelwright (1992). Generative production techniques have the advantage of manufacturing parts via an additive process without needing a forming tool. One of these additive manufacturing technologies is “Fused Deposition Modelling”. It is one of the most used additive manufacturing processes to produce prototypes and end-use parts. This technology began as a process for creating prototype parts; recently it has found new utility in the production of manufacturing tools and as a manufacturing process for end-use parts. In order to be used as a part for serial production, the components must possess the required mechanical properties. Bakar et al. (2010) carried out the analysis over the performance of the fused deposition modelling parts. In this they discuss the process parameters of FDM prodigy plus in which six test model were built with the varying parameter like layer thickness, contour width, internal raster, which include the feature like slots, cube, cylinders and ring. Over this the accuracy and the roughness were analysed by using coordinate measuring machine and surface tester respectively. Sood et al. (2011) have been studied the effect of important process parameters viz., layer thickness, orientation, raster angle, raster width, and air gap. The responses considered in this study are mechanical property of FDM produced parts such as tensile, bending and impact strength. Marcincinova and Marcincin (2012) presented different types of test in area of materials properties of selected methods of rapid prototyping technologies. Brooks et al. (2012) worked on variable fused deposition modeling, in which they adapted additive manufacturing system which gives the variable diameter nozzle for fused deposition of polymer which optimised the print resolution and built up time independently. Dani et al. (2013) studied on the cost optimization in the manufacturing of the prototype of connecting rod using fused deposition modeling. In this they fabricated the model at different orientation varying from 0° to 90°, due to which the variation occurred in other factors like number of layers, built time, built material and support material which directly affects the manufacturing cost has been studied.

Aim of the present study was to investigate the effect of the built-up orientation on the mechanical properties and total cost of the FDM parts. The responses considered in this study are mechanical property of FDM produced parts such as tensile and bending strength. The specimens are prepared as per the ASTM standard at three different orientations (0°, 45°, 90°) and in three different axes with the axis of rotation parallel to the larger length of the specimen and perpendicular to the other two sides i.e. breath and thickness of the specimen.

2. Experimental Details

Specimens are fabricated using the FDM U-print machine. The parts are modeled in CATIA V5 software and exported as STL file. STL file is imported to FDM software (CATALYST). The material used for specimen preparation is acrylonitrile-butadine-styrene (ABS) P400. For measuring tensile (ASTM D638) and flexural (ASTM D790) respective standard specimens having respective dimensions 63 mm× 9.53 mm × 3.5 mm, 127 mm × 13 mm × 3.5 mm are prepared (fig. 1 and 2).

![Fig.1. a) Tensile test specimen before slicing](image1)
![Fig.1. b) Tensile test specimen after slicing](image2)

After fabricating the samples, these specimens were tested. Tensile and three point bending test (flexural test) is
conducted on Instron 1195 machine. In tensile test, cross head speed is maintained at 1.0 mm/min whereas it is maintained at 2 mm/min for flexural test. The loading of the specimen on machines for test purpose is shown in fig. 3 and specimens after fracture are depicted in fig. 4.

Fig.2. a) Three point bending specimen before slicing  
Fig.2. b) Three point bending specimen after slicing

Fig.3. a) Tensile test setup  
Fig.3. b) Three point bending test setup

Fig.4. a) Tensile specimen after test  
Fig.4. b) Bending specimen after test
3. Results and Discussions

The tensile data of ABS sample with different level of process parameter are shown in Table 1. As in case of tensile test the load is increased until the specimen gets break and in case of flexural (three point bending test) load is applied up to deflection approximately 7.8 mm and in each test the load is noted down at their maximum stress. The bending test data of ABS sample with different level of process parameter are shown in Table 2.

| Sr. No. | Rotational about axis | Orientation (degrees) | Time (hrs) | Main Material in³ | Support Material in³ | No. of Layers | Tensile Strength (MPa) | Total Cost (Rs) |
|---------|-----------------------|-----------------------|------------|-------------------|----------------------|---------------|------------------------|----------------|
| T1      | Y                     | 0                     | 0.10       | 0.10              | 0.05                 | 14            | 35.45                  | 116.03         |
| T2      | Y                     | 45                    | 0.26       | 0.11              | 0.13                 | 36            | 28.52                  | 274.07         |
| T3      | Y                     | 90                    | 0.17       | 0.11              | 0.05                 | 38            | 34.31                  | 181.99         |
| T4      | Z                     | 0                     | 0.19       | 0.10              | 0.01                 | 249           | 19.00                  | 193.64         |
| T5      | Z                     | 45                    | 0.18       | 0.09              | 0.01                 | 249           | 22.51                  | 182.49         |
| T6      | Z                     | 90                    | 0.19       | 0.10              | 0.01                 | 249           | 17.14                  | 181.99         |
| T7      | X                     | 0                     | 0.17       | 0.11              | 0.05                 | 38            | 33.00                  | 193.64         |
| T8      | X                     | 45                    | 0.26       | 0.11              | 0.13                 | 36            | 30.28                  | 274.07         |
| T9      | X                     | 90                    | 0.10       | 0.10              | 0.05                 | 14            | 30.74                  | 116.03         |

| Sr. No. | Rotational about axis | Orientation (degrees) | Time (hrs) | Main Material in³ | Support Material in³ | No. of Layers | Flexural Strength (MPa) | Total Cost (Rs) |
|---------|-----------------------|-----------------------|------------|-------------------|----------------------|---------------|------------------------|----------------|
| F1      | Y                     | 0                     | 0.22       | 0.34              | 0.12                 | 14            | 34.462                 | 278.552        |
| F2      | Y                     | 45                    | 1.01       | 0.37              | 0.38                 | 45            | 28.01                  | 672.66         |
| F3      | Y                     | 90                    | 0.34       | 0.37              | 0.06                 | 52            | 39.61                  | 386.756        |
| F4      | Z                     | 0                     | 0.49       | 0.36              | 0.01                 | 500           | 28.20                  | 516.28         |
| F5      | Z                     | 45                    | 0.45       | 0.33              | 0.01                 | 500           | 27.44                  | 474.12         |
| F6      | Z                     | 90                    | 0.49       | 0.36              | 0.01                 | 500           | 36.41                  | 516.28         |
| F7      | X                     | 0                     | 0.35       | 0.37              | 0.06                 | 52            | 45.20                  | 395.916        |
| F8      | X                     | 45                    | 1.02       | 0.37              | 0.35                 | 45            | 38.62                  | 681.82         |
| F9      | X                     | 90                    | 0.22       | 0.34              | 0.12                 | 14            | 30.67                  | 278.552        |

As per the industrial references the total cost of FDM parts includes following components and equation (1) is used for calculating total cost of FDM parts;

Main material cost per in³ = 184 Rs.

Support material cost per in³ = 120.60 Rs.

Machine cost per minute = 9.16 Rs.

Total Cost = [Main material (in³) x main material cost per in³ (Rs)] + [Support material (in³) x support material cost per in³ (Rs)] + [Built up time (min) x Machine cost per min (Rs)]

Figure 5 (a) shows the graph between tensile strength and built orientation. It can be seen from the graph that tensile strength value is low for the specimen fabricated about z-axis and shows a maximum value of 22.51 MPa at 45° built orientation. About the x-axis the tensile strength value is almost constant with a maximum value of tensile strength of 33 MPa at 0° built-up orientation. Out of three axes y-axis shows the maximum tensile strength with a
maximum value of 35.45 MPa at $0^\circ$ built orientation. Figure 5 (b) shows the graph between total cost and built orientation. About z-axis the total cost of the FDM parts are constant with a minimum value of Rs.182.49. About the x-axis the minimum total cost of the FDM part is at $90^\circ$ built orientation of Rs.116.03. About the y-axis the minimum total cost of the FDM part is at $0^\circ$ built orientation of Rs.116.03.

Figure 6 (a) shows the graph between flexural strength and built orientation. About x-axis, with increase in built orientation the flexural strength value decreases. But about z-axis the flexural strength value increases with the increase in built up orientation. About y-axis the flexural strength value decreases up to $45^\circ$ built up orientation and then increases with built up orientation. Figure 6 (b) shows the graph between total cost and built orientation. About z-axis the total cost of the FDM parts are constant with a minimum value of Rs.474.12. About the x-axis the minimum total cost of the FDM part is at $90^\circ$ built orientation of Rs.278.522. About the y-axis the minimum total cost of the FDM part is at $0^\circ$ built orientation of Rs.278.522.

4. Conclusions

In the present work, the effect of built orientation on the mechanical properties and total cost of the FDM parts was investigated. The responses considered in this study are mechanical property of FDM produced parts such as tensile and bending strength. Test specimens were fabricated on STRATASYS FDM type rapid prototyping machine coupled with CATALYST software and ABS as main material. Also the effect of main material required,
support material required, number of layers and built time is considered in the evaluation of the total cost of FDM parts. Thus the minimization of main material and support material is also implicitly included in this work. The slicing is also used in the determination of optimum built orientation. The values of build time and number of layers required are determined for varying built orientation. Based on the results it can be concluded that about y-axis at 0° built up orientation FDM parts has good tensile strength and minimum cost. And about x-axis 0° built up orientation FDM parts has good flexural strength and medium cost. This is a useful conclusion which will help Rapid Prototyping users in selecting the best build orientation of the part and create optimal process planning.

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