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Effect of process parameters on the impact strength of fused filament fabricated (FFF) PLA parts

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ABSTRACT

Fused Filament Fabrication (FFF), a well-known additive manufacturing (AM) process has been widely used in developing prototypes as well as functional parts for various sorts of industrial applications because of its ability for creating parts with sophisticated design in the stipulated time along with less wastage of material. Selecting input process parameters in FFF is a tedious task as they directly affect the performance. In this experimental investigation, efforts have been made to select the best parameter setting as per the impact strength perspective. Three important process parameters such as layer thickness, build orientation, and infill density have been considered to study their effects on the impact strength of FFF-printed polylactic acid (PLA) test specimen, using design of experiment (DOE). All the test specimens for impact strength are made according to ASTM D256 standard.

Keywords: Fused Filament Fabrication (FFF); Design of experiment (DOE); Polylactic acid (PLA)

Introduction

Additive manufacturing (AM) was initially developed for manufacturing of prototypes and models and is based on rapid prototyping technique. In recent decades the rise and rapid maturity of AM processes have brought many benefits to engineering design, opening up an entirely new series of possible manufacturing processes. Based on the manufacturing method and the material used the AM processes can be listed as stereolithography (SLA), laser engineered net shaping (LENS), fused deposition modeling (FDM), laminated object manufacturing (LOM), selective laser sintering (SLS), digital light processing (DLP), direct metal deposition (DMD), inkjet modeling (IJM), and electron beam melting (EBM) [1]. In all the AM technologies 3D CAD data is used to create solid objects from the 3D printers. As AM involves manufacturing of objects by adding one layer over the another, they differ from conventional manufacturing methods in terms of material wastage and time to built the part. Fused filament fabrication (FFF), one of the trendiest AM technology, has been widely used in the recent decade to produce models and prototypes due to its simplicity and low cost. FFF involves building of solid model using 3D CAD information by extruding a thermoplastic material onto the build platform. However, as any other 3D printing process, FFF is also susceptible to some issues like shrinkage and raster bonding which leads to a substantial decrease in the mechanical strength and surface quality of the build parts [2]. It is possible to improve the impact strength of 3D printed parts by varying the the input process variables, and to expand the field of application of FFF parts researchers have recently tried to determine the influence of process parameters on the impact strength of FFF parts. Huang et al. [3] experimentally investigated the influence of layer thickness, printing speed, raster angle, and building orientation on the mechanical properties and surface roughness of acrylonitrile-butadiene-styrene (ABS), and found that layer thickness and build orientation had a notable effect on the impact properties of ABS samples made by FDM. Anoop et al. [4] used central composite design (CCD) technique to study the effect of five parameters (air gap, raster angle, build orientation, raster width, and layer thickness) on the mechanical properties of FDM built ABS P400 material and concluded a higher impact strength at a high value of orientation , but after a certain value of orientation the impact strength decreases. Liu et al. [5] investigated the effects of layer thickness, deposition orientation, deposition style, raster gap and raster width on the mechanical properties of FDM built PLA parts. They found that with an increase in the layer thickness, the impact strength of part increases. Camargo et al. [6] studied the impact of infill, and layer thickness on the tensile, flexural, and impact strength of FDM made PLA graphene parts using CCD. They reported that the impact energy decreases with the increase of infill. Vega et al. [7] studied the influence of layer orientation on toughness and mechanical properties and found that the arrestor and short transverse orientation had the highest impact energy. Wang et al. [8] studied the effect of two parameters namely plate temperature and layer height on the impact strength of the FDM built PLA material and found that at higher value of plate temperature the impact strength of FDM printed PLA was higher than PLA made by injection molding using conventional parameters of molding.

Based on the previous researches on FDM, it can be concluded that the surface quality and mechanical properties of FDM built specimens can be improved, so to improve the impact strength of printed PLA by fused filament fabrication three parameters (layer thickness, build orientation and infill density) are considered in this experimental investigation. Three levels of each factor have been selected. Taguchi method, which is based on statistical design of experiment (DOE) is applied at the parameter design strategy to establish optimum process setting [9]. L9 orthogonal array has been used in this study.

Experimental details

Specimens are fabricated using Prusa i3 MK2S, which is an open-source type of 3D printer. The parts are modeled in Creo Parametric 5.0 software and then converted into stereolithography (STL) files. STL file is then imported to FFF software Slic3r. Polylactic acid (PLA) is the material used for sample preparation, and all the samples are made of ASTM D236 Type E standard with dimensions 63.5 mm x 12.7 mm x 3.2 mm. ASTM D256 Type E standard uses a reverse notch, and the pendulum hits the unnotched side of the specimen. Figure 1 shows the impact test specimen before the test, and figure 2 shows the sample after the test.

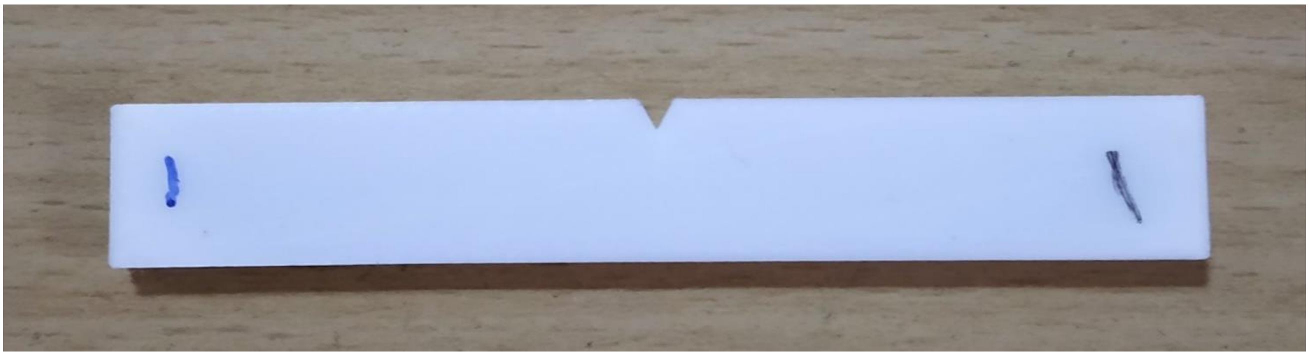

Figure 1. Specimen before test.

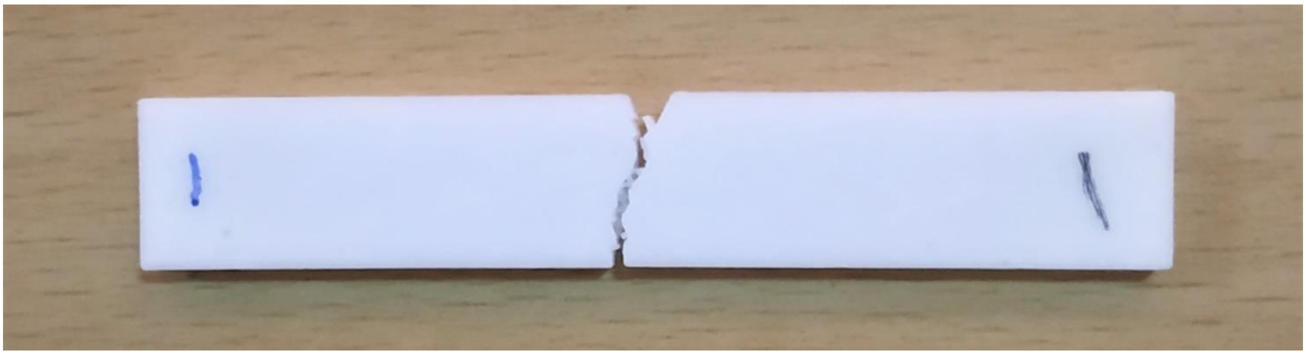

Figure 2. Specimen after test.

The selected input parameters with their three levels are shown in table 1.

Parameters	**Low level (-1)**	**Zero level (0)**	**High level (1)**
Layer thickness (mm)	0.1	0.2	0.3
Build orientation (^{o})	0	30	60
Infill density (%)	20	50	80

Table 1. Various input parameters

The impact strength (E) can be calculated by using the equation (1):

$$E = \frac{\mathrm{I}}{\mathrm{tb}} \times 1000 \qquad (1)$$

where, I is the absorbed impact energy in joules; t is the thickness of the sample and b is the breadth of the sample.

Results and discussions

The impact strength data with various combination of parameters is shown in table 2. L9 orthogonal array is constructed according to the Taguchi method, and the values of the test are tabulated and presented in table 2.

S. No.	Layer thickness (mm)	Build orientation (Degrees)	Infill density (%)	E (KJ/m^2)
1	0.1	0	20	10.52
2	0.1	30	50	11.78
3	0.1	60	80	13.10
4	0.2	0	50	11.78
5	0.2	30	80	13.78
6	0.2	60	20	10.52
7	0.3	0	80	12.46
8	0.3	30	20	11.78
9	0.3	60	50	12.45

Table 2. Taguchi L9 table with results

A plot between the impact energy and the mean effect of selected parameters is presented in figure 3 to understand how these parameters affect the impact strength.

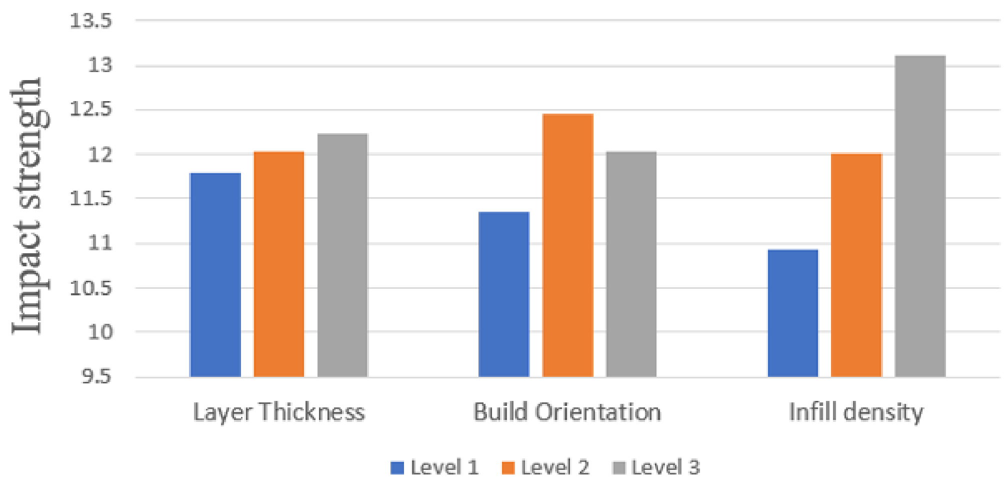

Figure 3. Impact strength vs selected input parameters

From figure 3 the realation between the process parameters and the selected response (impact strength) can be obtained. With increase in the layer thickness, the number of layers required to build the specimen decreases, because, with a high value of layer thickness the material deposition becomes thicker, so to create the specimen of fixed thickness the number of layers required will be much less, which leads to the occurrence of lesser number of interlayer bonding. It further leads to a reduction in the number of cooling and heating involved in building the part. Similarly after layer thickness, the effect of build orientation and infill density is discussed on the impact strength values. As the build orientation increases from 0^o to 30^o the impact strength increases and then from 30^o to 60^o the impact strength decreases. Infill density is the most influential factor, which directly affects the impact strength. At infill density of 20%, the least value of impact strength is obtained, and at 80% infill, the maximum value of impact strength is obtained. It is because, the increase in infill density leads to lesser voids in the part, and thus, more amount of material is deposited with the increase in infill density, which definitely increases the part strength.

Conclusion

In the present study, the effect of three input parameters (layer thickness, build orientation, and infill density) on the impact strength of FFF-printed part is presented. The test specimens were created using a Prusa i3 MK2S machine and PLA is chosen as the build material. Taguchi L9 orthogonal array was employed for the design of experiment. A higher value of layer thickness contributed to the higher average value of the impact strength of samples. Specimens with a higher degree of orientation showed better impact strength than parts made with 0^0 orientation. Parts built with a higher value of infill density showed greater impact strength compared to parts with lower infill density. Based on the results it can be concluded that the maximum impact strength of FFF-printed PLA parts can be obtained by taking mid-level of layer thickness (0.2 mm), mid-level of orientation (30^0), and the maximum infill density (80%).

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