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Effect of the build orientation on the mechanical behaviour of polymers by stereolithography

Haorui Liu[*], Nana Yang, Yitong Sun, Laidong Yang and Ni Li

Department of Mechanical Engineering, LongDong University, Qing yang, China

*Corresponding author e-mail: 178212596@qq.com

Abstract. The use of Rapid Prototyping techniques for the production of end-use parts is increasing in rapid manufacturing. The mechanical properties of stereolithography parts become the most important factor restricting its wide application. The mechanical properties of stereolithography parts can be not only influenced by the material characteristics, but also by the parameters of manufacturing. The purpose of this study is to investigate the influences of the build orientation on mechanical properties of stereolithography parts. Specimens were fabricated with different build orientations related to layout (flat or on an edge), axis and build angle. Mechanical testing including tensile, compressive and impact tests on stereolithography specimens were conducted. The results indicated that layout had a significant effect on tensile and impact properties, and the axis had no significant effect on tensile and impact properties. Also, build angles play an important factor in the compressive strength. From these results, it appears that related characteristics of layer interface have a significant influence on mechanical properties of stereolithography specimens.

1. Introduction

In rapid manufacturing (RM), functional parts and components are directly manufactured using AM (additive manufacturing) technologies. One of AM technologies that improved for transition into RM is stereolithography (SL). In order to accomplish this transition, the 3D-printed parts should withstand various amounts of mechanical and environmental stresses required for RM. Furthermore, SL used for RM must be capable of providing superior fabrication accuracy and reproducible parts [1-3].

The stable and high-strength SL materials are required to meet the functional requirements of application. The SL material industry has been making significant progress to improve the mechanical properties. However, the manufacturing process introduced variability on mechanical performance resulting in inconsistency of part quality when different SL systems or process parameters are used [4-5]. Accordingly, the process parameters affecting the part quality includes build orientation, layer thickness, post processing, etc. Among these factors, build orientation plays a significant role in part accuracy, mechanical property, the volume of support structure, build time and cost [6-8].

For additively manufactured parts, mechanical properties are generally anisotropic due to the Layer-based manufacturing process. There have been some studies that were carried out to investigate the effect of build orientation on mechanical properties of polymers. Studies by Hague et al. (2004) have shown differences in mechanical properties in parts built in a number of orientations and subjected to tensile testing [9]. Dulieu-Barton and Fulton (2000) found that the variation in the material property between the layer orientations is much greater than the variation for a single orientation based on tensile tests [10]. Quintana et al. (2010), using a statistical design of experiments (DOE) approach, showed that axis and position had no significant effect on ultimate tensile strength and elastic modulus, but layout had a statistically significant effect on the resulting mechanical properties [2]. Nattapon Chantarapanich et al. (2013) studied the effect of build orientation on the ultimate tensile strength (UTS) and elongation of commercial SL resins. The results indicated that the larger differences of mechanical properties were found between main the main build orientation compared with sub-build orientation [4]. Dayakar L. Dayakar L. Naik and Ravi Kiran proposed that the effect of build orientation on mechanical properties of specimens built 'on edge' (0°-90°) is insignificant, but the flat specimens exhibited relatively lower modulus, UTS and higher fracture strains [11]. The authors found that distinct mechanical performance was based on the particular positioning of the design, and the influence of build orientation on mechanical properties usually was studied by tensile test.

In this study, the mechanical properties (tensile properties, compressive strength, and impact toughness) of the as-built epoxy-based SL samples fabricated in different orientations were discussed. By doing so, it was possible to investigate the effect of the building orientation on the mechanical properties and fracture mechanism of the components.

2. Experimental methods

2.1. Materials

The material used in this study was the commercially available epoxy based photo-curable resin NH-09 (Necotech, Inc., China.). The NH-09 is optically white, having a viscosity of 240 cps at 30^{o}C, and a density of 1.12 g/cm^3 at 25^{o}C. The resin is used for solid-state laser systems (355-nm laser wavelength) with a recommended critical exposure (Ec) of 10 mJ/cm^2 and penetration depth (Dp) of 110um. The processing parameters were as follows: Laser power: 200mW, Laser scanning speed: 5000mm/s, Laser thickness: 0.1mm.

2.2. Mechanical tests

Mechanical tests were conducted to investigate the influence of build orientation on tensile, compressive and impact properties. Tensile tests were performed on dumbbell samples, according to ISO 527-1, at room temperature at 5 mm/min crosshead speed. Fig. 1 shows "ISO 527-1" which is used for polymers. Impact tests were conducted, according to ISO 180, using a Pendulum Charpy Test and notched samples with dimensions of 10×80×4 mm^3. Compressive tests were conducted according to ASTM D695 at 1.0 mm/min loading rate with dimensions of 25.4 mm in length and 12.7 mm in diameter

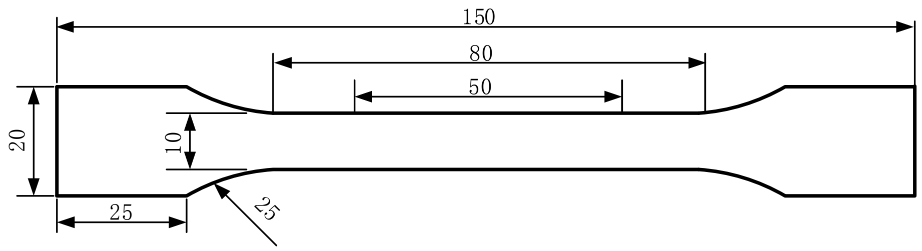

Figure 1. ISO 527-1 tensile test specimen

2.3. Build orientation experiments

In order to investigate the directional dependence properties of SL specimens, the specimens were fabricated in various build orientations as shown in Fig. 2. There are two main build orientations which are flat and edge. Each of main build orientations has two sub-build orientations separately which are 0 degree and 90 degrees to the x-axis. Also, Flat specimens with slope degrees of 0°, 30°, 60° and 90° were tested. To guarantee the reliability of the experiment, three replicates were produced for each layout. After the fabrication process, the samples were removed from the platform, cleaned with isopropyl alcohol, and support material was removed by tools. All the specimens were post-cured outside under sunny day. Finally, light sanding was made to remove surface imperfections and support marks.

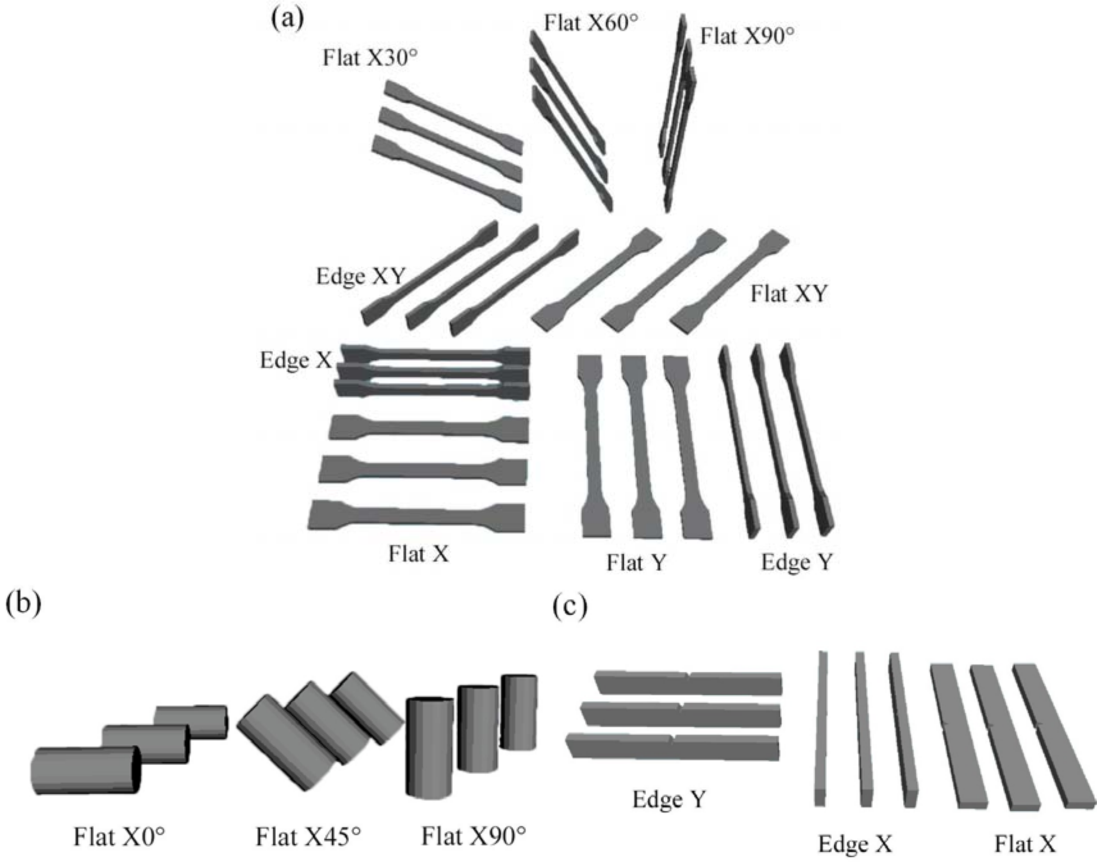

Figure 2. Build orientations of tensile, compressive and impact tests

3. Results and discussion

3.1. Influence of Build Orientation

The main aim of this paper is to investigate the influence of build orientation on Young's modulus, ultimate tensile strength (UTS) and fracture strain from tensile tests, compressive strength from compressive tests and impact strength from impact tests. The UTS and strain are obtained directly from stress-strain curves. The linear part of engineering stress strain curve is used in order to evaluate the Young's modulus of the specimens which is calculated as the slope of a linear least-squares regression line in the strain interval between 1.0% and 0.5%.

The averaged Young's modulus, UTS and fracture strains for all the specimens with same build orientation is illustrated in Table 1. According to the results, it can be noticed that the UTS and Young's modulus of edge build orientation specimens are obviously higher than flat build orientation specimens. On the other hand, the 'Edge' series of specimens exhibit lower elongation at UTS and failure compared with 'Flat' series of specimens. However, the 'XY' sub-build orientation specimens only present lower elongation at failure than the 'X' and 'Y' sub-build orientation specimens from the results of both edge and flat orientations. The Young's modulus, UTS and elongation at UTS are not significantly different between sub-build orientations. As it can be seen from the results of 'Flat X' angle orientations, the average UTS was observed to increase monotonically with an increase in build orientation from0°-90°, and the Young's modulus exhibits similar trend except for 30° build orientation. The elongation at UTS and failure of 90° sub-build orientation are the lowest among the tested specimens.

Table 2 shows impact strength of SL specimens fabricated in different build orientation related to axis (X and Y) and layout (Flat and Edge). We can observe that axis (X and Y) has no significant effect on impact strength. However, whether a sample is built flat or edge is shown to have a statistically effect on impact strength.

Table 3 shows compressive strength of SL specimens fabricated on different angles with X-axis. It is obvious that the specimens of 45° with X-axis exhibits the lowest compressive strength, and other two angles have no significantly difference.

Table 1. Tensile properties of SL specimens fabricated in different build orientation

Build orientation	E(MPa)	UTS (MPa)	Elongation at UTS (%)	Elongation at failure (%)
FlatX angle				
0°	689	26.4	11.2	43.8
30°	465	33.5	12.1	31.3
60°	797	36.5	10.2	35.3
90°	908	37.1	8.76	29
Flat				
X	689	26.4	11.2	43.8
Y	717	28.8	11.5	45.1
XY	716	28	11.6	27.5
Edge				
X	710	41.8	10.6	36.6
Y	751	39.9	10.3	38.8
XY	803	37.2	10.2	20.2

Table 2. Impact strength of SL specimens fabricated in different build orientation

Build orientation	Edge X	Edge Y	Flat X
Impact energy(KJ/m2)	22.8	21.5	14.6

Table 3. Compressive strength of SL specimens fabricated in different build orientation

Build orientation	Flat X0°	Flat X45°	Flat X90°
Compressive strength(Mpa)	25.9	13.7	22.8

3.2. Discussion

This study presents an effort to understand the influence of processing parameter (build orientation) on the mechanical properties of SL specimens. As illustrated in Section 3.1, the obtained results present that the 'Flat' specimens exhibited lower Young's modulus, UTS and larger fracture strains. This is attributed to the higher volume of resin that has to be cured to build a layer for the 'Flat' specimens. It can be explained that larger area leads to more partially cured zones and higher internal stresses which reduce the Young's modulus, UTS and increase the fracture strains [11].

From the result of the impact tests, it revealed that 'Flat' orientation exhibited the weakest impact strength. This result can be explained that the higher number of layers leading to a greater impact strength due to the interface is the resistance of crack growth. According to the result of the compressive tests, specimens of 45° with X-axis exhibited the worst compressive strength. This can be explained by the orientation of individual layers, since the maximum shear stress is parallel to the interface between layers which is weak link [12].

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4. Conclusion

The influence of build orientation on the mechanical properties of photo-cured epoxy resin is investigated in this study, and the main conclusions are as follows:

The assessment of tensile properties was evaluated by Young's modulus, UTS, elongation at UTS, and elongation at failure. It can be concluded that building the specimens flat produced parts exhibited better Young's modulus, UTS compared with building the specimens on edge. When the angle with X-axis was changed, the average UTS was observed to increase monotonically from0°-90°. However, the effect of build orientation on axis relative to X-Y plane was insignificant. Also, whether a sample was built flat of on an edge was shown have a significant effect on impact strength. The result from compressive tests revealed that build angles play an important factor in the compressive strength.

Investigation from tensile, compressive and impact tests concluded that the specimens prepared from different build orientations exhibited a directional dependence of the mechanical properties. Based on these results, it appears that the number, area and orientation of the layer interfaces govern the anisotropy of mechanical behavior in SL fabricated parts.

Acknowledgments

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