Springer

KSME

Journal of Mechanical Science and Technology 31 (5) (2017) 2197~2201
www.springerlink.com/content/1738-494x(Print)/1976-3824(Online)
DOI 10.1007/s12206-017-0415-7

Effect of layer thickness and print orientation on strength of 3D printed and adhesively bonded single lap joints[†]

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(Manuscript Received April 28, 2016; Revised November 30, 2016; Accepted December 31, 2016)

Abstract

Three-dimensional printing is the common name given to various techniques used to manufacture different objects. Fused deposition technique is a commonly used additive manufacturing technology in prototyping and production. Fused deposition modelling systems are limited in terms of shape and size of parts. Printing parts with less support material, for parts too large to print in a single operation or for parts with fine details, sectioning and adhesively bonding is the solution for manufacturing. According to adhesion theory, the strength of adhesively bonding between three-dimensional printed parts is affected by surface roughness. Effects of layer thickness and print orientation on adhesion strength of parts manufactured with three-dimensional printing were experimentally studied. As a result of the study, it was found that the edgewise orientation had the highest bonding strength in lower layer thicknesses, while flatwise orientation had the highest bonding strength in higher layer thicknesses.

Keywords: 3D printing; Layer thickness; Print orientation; PLA; Bonding strength

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1. Introduction

Additive manufacturing (AM) is a process in which Computer-aided design (CAD) tools are used to add material layer-by-layer to manufacture a solid part. Previously, AM technologies were mostly used for prototyping purposes. With improvements in technology, the focus shifted to mechanical properties and surface roughness. In this way, it has become possible to manufacture artificial bones, metallic structures, complex foam-like structures and many more with AM processes [1, 2]. According to ASTM F2792 standard, Fused deposition modelling (FDM), which is one of the 7 AM process categories [3], is a relatively new technology dated back to 1990s. Since then, many process parameters have changed with the development of FDM machines and most researchers have focused on mechanical properties.

Masood et al. [4] examined Polycarbonate (PC) specimens manufactured with FDM and found that the tensile strength was 75 % higher compared to PC specimens manufactured with injection moulding. Ahn et al. [5] conducted a similar experiment using Acrylonitrile butadiene styrene (ABS) and found an increase of about 8 % in tensile strength, while printing platform raster angle changed from 45°/-45° to 90°/0° and raster thickness changed from 0.508 mm to 1 mm. Increased printing time and improved surface quality were also noted by the authors. Montero et al. [6] found that the tensile strength of axially manufactured specimens was increased about 200 % compared to transversely manufactured specimens. Bellini and Guceri [7] investigated mechanical properties of ABS specimens manufactured in XYZ, XZY and ZXY orientations. The specimens manufactured in XZY orientation had the highest tensile strength with 15.99 MPa and the highest elastic modulus with 1653 MPa. On the other hand, the specimens manufactured in ZXY orientation had the lowest tensile strength with 7.60 MPa and the highest elastic modulus with 1391 MPa.

These studies show the differences between results obtained by using different printing parameters. Studies show that the tensile strength of parts manufactured with FDM is lower compared to parts manufactured with injection moulding. A method to increase mechanical properties of parts manufactured with FDM should prove benefits from an engineering application's perspective, which requires specific performance criteria.

Currently, there are different options for extrusion-based FDM machines. Several process parameters are available for each of these machines such as print orientation, layer thickness, raster angle, and raster thickness. Process parameters may be the key factor in improvement of FDM systems when

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focused on mechanical properties. It may be possible to manufacture parts with improved mechanical properties using appropriate process parameters in FDM systems. Eventually, FDM systems may soon compete with conventional injection moulding in terms of mechanical properties and surface roughness.

FDM systems are quite limited in terms of shape and size of parts that can be manufactured. Printing FDM parts in sections and bonding them adhesively must be considered as a solution for manufacturing parts with less support material, for parts too large to print in a single operation or for parts with fine details. The strength of bonding between FDM parts is affected by surface roughness. The relationship between surface roughness and bonding strength can be explained with the notch effect and surface area. Lee et al. [8] performed fatigue tests on adhesively bonded cylindrical joints and identified a rapid decrease in fatigue strength after $R_a = 2.5$ μm. Shaid and Hashim [9] reported that the tensile strength of rough-surfaced steel specimens was lower in comparison to polished specimens.

According to our literature review, no study has been conducted on the relationship of adhesively bonding strength with layer thickness and print orientation in single-lap joints of FDM parts. The purpose of this study is to explain effects of layer thickness and print orientation on adhesively bonding strength of FDM parts under static loads.

2. Material and method

Polylactic acid (PLA) is a widely used material in FDM systems. PLA is a bio-degradable thermoplastic synthesized from renewable sources such as sugarcane and maize starch. Being an amorphous plastic makes it a perfect option for FDM systems. Its strong mechanical properties and high glass transition temperature allow parts manufactured from PLA to be used in a wide variety of applications. Test specimens manufactured from PLA were used in experimental part of this study.

Tensile test specimens were manufactured using RapMan 3.2 3D printer. The machine has a 270 mm×205 mm×210 mm printing chamber. The dimensional accuracy of X and Y axes is ±0.2 mm and the dimensional accuracy of Z axis is equal to half of layer thickness. A manufacturing temperature of 190 °C was selected for PLA specimens. The specimens were printed in dimensions compatible with the ASTM D3165 [10] standard and with three different print orientations: YXZ, YZX and ZYX (Fig. 1). In terms of printing parameters of manufactured specimens, three different layer thicknesses (125 μm, 250 μm and 500 μm) were examined for each orientation.

Specimens manufactured using different layer thickness parameters had different surface roughness values. Surface roughness values of all manufactured specimens were taken from a previous study conducted by the authors of this paper. The manufactured specimens were cleaned with Loctite 7061 all-purpose cleaner. After the cleaning, Loctite 9464 was applied to surfaces of the specimens for bonding and attention was paid to make sure surfaces were completely wet. The bonding was achieved by applying the load recommended by the manufacturer to adhesive-applied specimens with equal pressure and the excessive adhesives were cleared from the edges of specimens. Using ASTM D3165 type joints and applying adhesive under same bonding pressure, way of adhesive applications has not effect on the joint strength. Then the bonded specimens were kept at room temperature for at least 24 hours for curing. Loctite 9464 is a two-component epoxy based adhesive that requires high adhesion strength used for various applications. Loctite 9464 is ideal for a wide variety of surfaces such as metals, ceramics and plastics.

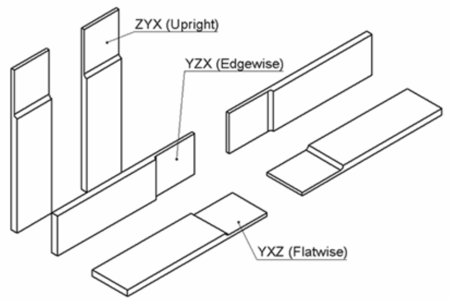


Fig. 1. Three different print orientations used in tensile tests in accordance with ASTM F2921 terminology.

Tensile tests were performed in accordance with ASTM D3165 standard using Instron 8801 tensile test machine. A load cell of 5 kN was used in tensile tests, which is appropriate for testing components with low strength. A loading speed of 300 N/min was used in accordance with the standard. The displacement between grips was measured during the experiment to calculate elongation. Tensile properties (e.g. tensile strength, elastic modulus, and elongation) were calculated with the Bluehill software on the device. At least three specimens were tested for each parameter set.

3. Results and discussion

The duration of manufacturing with 3D printer may vary depending on the FDM machine and process parameters such as layer thickness. Also, the printing duration considerably varies depending on dimensions of the part. The effect of layer thickness may be seen as a good surface quality and resolution at the end of manufacturing, but a considerable time increase shows up due to higher number of layers. Fig. 2 shows the manufacturing duration of three different print orientations and three different layer thicknesses used for each orientation. The manufacturing duration was found to be 194 min for 125 μm layer thickness, 81 min for 250 μm layer thickness and 32 min for 500 μm layer thickness. As is seen, although the manufacturing duration considerably increases with decreased layer thickness, the change in print orientation does not lead to a notable change in manufacturing duration.

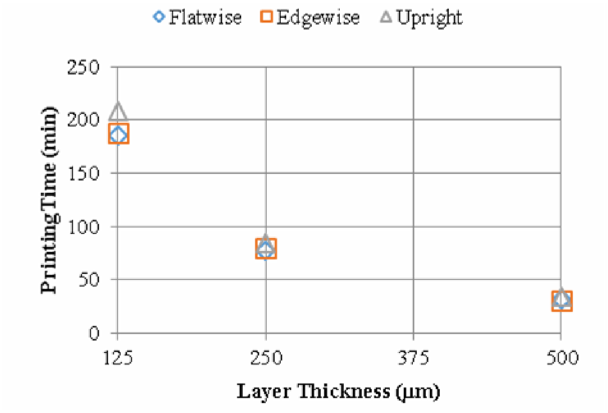
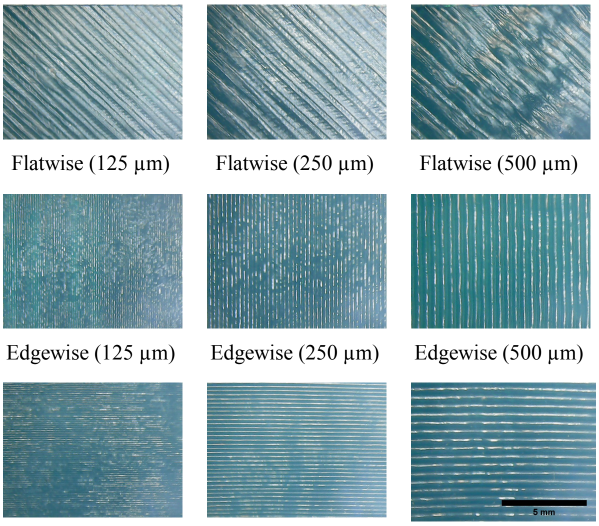


Fig. 2. Manufacturing durations of specimens with different print orientations and layer thicknesses.


Flatwise (125 µm) Flatwise (250 µm) Flatwise (500 µm)

Edgewise (125 µm) Edgewise (250 µm) Edgewise (500 µm)

Upright (125 µm) Upright (250 µm) Upright (500 µm)

Fig. 3. Adhesion surfaces of specimens with different print orientations and layer thicknesses (loading orientation ↕).

Fig. 3 shows optical views of specimens with different print orientations and layer thicknesses according to load direction. Gaps in between raster and contours were more visible and significant in 500 µm layer thickness for all print orientations. The use of 125 µm layer thickness provided the least amount of gaps in between raster and contours for all print orientations. Since FDM extrusion tip covers a smaller geometric area, denser raster occurs in this print orientation. Thus, very small gaps or no gaps occur between raster images. Also, relationships between different raster orientations and different loading orientations resulting from different print orientations of specimens are clearly seen in Fig. 3.

Surface roughness values of manufactured specimens were taken from a previous study in the literature, in which the authors used the same material and the same 3D printer [11]. In that study, surface roughness was measured with a profilometer. Obtained R_a surface roughness values were 11.9 µm for 125 µm layer thickness, 16 µm for 250 µm layer thickness and 24.8 µm for 500 µm layer thickness.

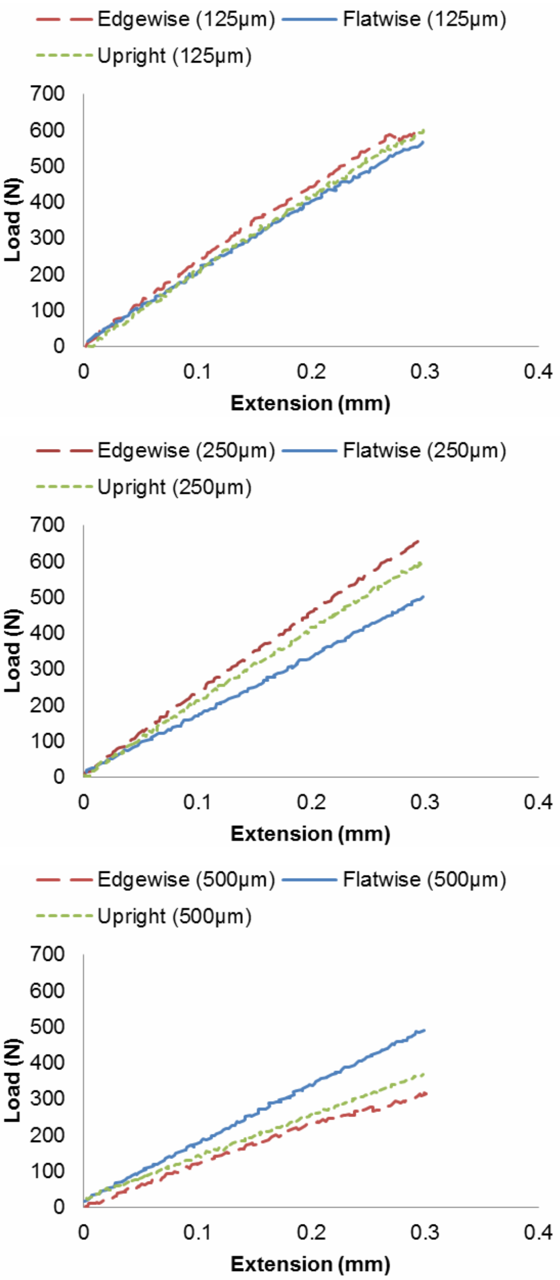


Fig. 4. Characteristic load-elongation curves for three different layer thicknesses.

The characteristic load-displacement curves drawn using the experimental results mentioned above are given in Figs. 4 and 5. Fig. 4 was drawn using average values for three different layer thicknesses (125 µm, 250 µm and 500 µm) and Fig. 5 was drawn using average values for three different orientations. Figures show that elastic modulus changed when a different layer thickness or a different print orientation was used. As clearly seen in Fig. 5, the decrease in layer thickness increased the elastic modulus for all print orientations, while also increasing the manufacturing duration. 125 µm layer

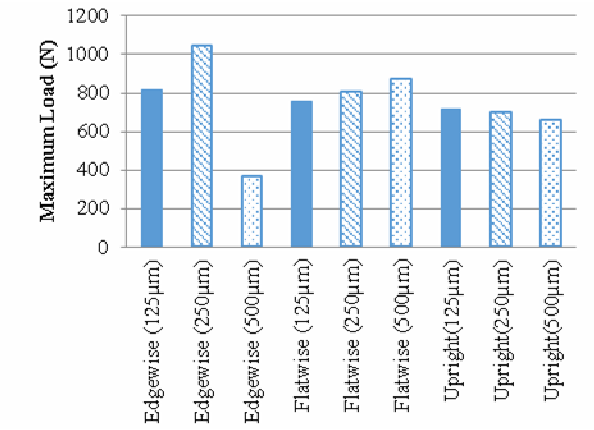


Fig. 5. Maximum load values for all experimental parameters.

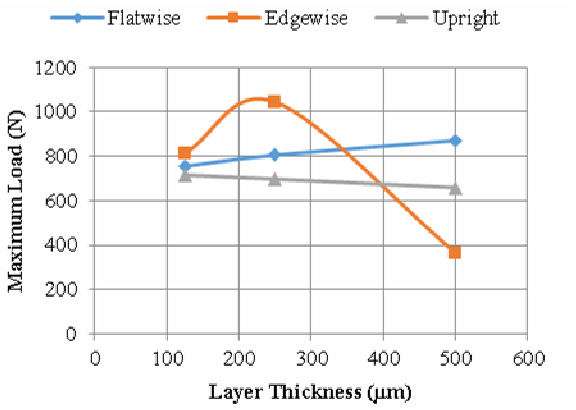


Fig. 6. Highest adhesion strength values for different print orientations and layer thicknesses.

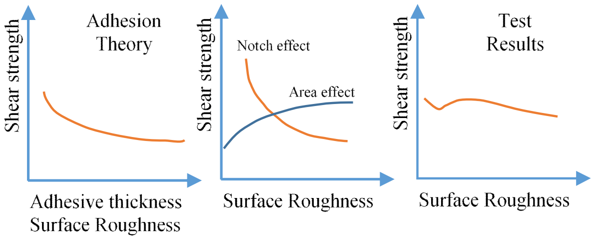


Fig. 7. Adhesive bonding strength as a combination of notch effect, area effect and surface roughness [12].

thickness had the highest elastic modulus for all print orientations, whereas 500 µm layer thickness had the lowest elastic modulus for all print orientations. The elastic modulus obtained for 250 µm layer thickness varied depending on print orientation, 500 µm layer thickness showed a lower elastic modulus for flatwise print orientation, whereas 125 µm layer thickness showed a higher elastic modulus for edgewise and upright print orientation. As is seen in graphs drawn for different layer thicknesses given in Fig. 4, 125 µm and 250 µm layer thicknesses showed the highest elastic modulus for edgewise print orientation, followed by upright print orientation, whereas they showed the lowest elastic modulus for flatwise print orientation. Specimens with 500 µm layer thickness showed an opposite result. 500 µm layer thickness showed the highest elastic modulus for flatwise print orientation, followed by upright print orientation, whereas it showed the lowest elastic modulus for edgewise print orientation.

The highest bonding strength values obtained for different print orientations and layer thicknesses can be seen in Fig. 6. Due to different raster orientations resulting from print orientations and different raster thicknesses resulting from layer thicknesses, it is seen from the figure that adhesion strength was influenced by both print orientation and layer thickness. The highest change was observed in the adhesion strength of specimens printed in edgewise orientation. The highest bonding strength was 1044 N, which was obtained for specimens with 250 µm layer thickness printed in edgewise orientation. The bonding strength of specimens printed in edgewise orientation was observed to change with increased or decreased layer thickness. The bonding strength of specimens printed in flatwise orientation or upright orientation did not display a significant change depending on layer thickness. As seen in the figure, specimens printed in edgewise orientation had the highest bonding strength for 125 µm layer thickness, followed by flatwise orientation and upright orientation. However, the bonding strength of specimens printed in edgewise orientation rapidly decreased with increased layer thickness and eventually showed the lowest adhesion strength. 500 µm layer thickness, the highest layer thickness used in the experiment, showed the highest bonding strength when printed in flatwise orientation, followed by upright orientation and flatwise orientation.

With regard to adhesion strength, the experimental results show that there is an optimum surface roughness value producing the maximum adhesion strength for all orientations and layer thicknesses. Fig. 7 schematically explains the notch (print gaps) effect arising from different print orientations and layer thicknesses and different shapes of adhesion strength curves due to surface roughness. Fig. 7(a) shows the theoretical value of strength of adhesion bond. According to the adhesion theory, the shear strength is inversely proportional to the adhesive thickness. Surface roughness has almost the same effect with the adhesive thickness. For this reason, the surface roughness is shown on the horizontal axis on the figure. Fig. 7(b) shows the change in the adhesion strength depending on area and notch effect. The actual relationship between the surface roughness and adhesion strength can be obtained by combining theoretical values (Fig. 7(a)) with two effects mentioned above (Fig. 7(b)), and this is shown in Fig. 7(c). Different adhesion strength curves obtained for different print orientations and layer thicknesses arise from differences resulting from the combination of these three components. Different layer thicknesses result in parts with different surface roughness and different adhesion strengths due to the notch effect. The use of different print orientations cause surface roughness profiles in different orientations and result in different adhesion strengths due to the notch effect as well.

4. Conclusions

As a result of the study, it was found that layer thickness and print orientation have very important roles to improve bonding strength of parts manufactured with FDM. As a result of optical image analyses, it was observed that gaps between rasters during 3D printing had negative effects on adhesion properties. Eliminating these gaps was found to improve adhesion properties. As another result of the study, it was found that the edgewise orientation had the highest adhesion strength in lower layer thicknesses, while flatwise orientation had the highest adhesion strength in higher layer thicknesses. The fact that 125 µm showed the lowest Ra roughness value compared to other two layer thicknesses seems to be the reason behind this, however print orientation seems to have a considerable effect as well. Taking the above mentioned points into account would allow for higher joint strength when adhesively bonding parts manufactured with FDM for engineering applications.

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