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Original Article

Study of the mechanical properties of photo-cured epoxy resin fabricated by stereolithography process

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Abstract

Stereolithography process enables various freeform geometries to be manufactured, which are beneficial to many research and development fields, particularly on medicine. The mechanical properties of stereolithography models can be generally but not only influenced by the material characteristics, but also by the method of manufacturing. Since the stereolithography process involves building three dimensional objects by depositing material layer-by-layer as well as the post-curing by ultraviolet light, it is therefore possible for stereolithography models to exhibit a directional dependence of the mechanical properties. The objectives of the study focused on the influence of build orientations and ultraviolet post-curing period on the mechanical properties. In the experiments, Watershed 11122 commercial epoxy photo-curable resin was used. The in-house developed stereolithography machine of the National Metal and Materials Technology Center of Thailand was used to fabricate tensile test specimens (American Society for Testing Materials Standard D638) with different build orientations. Main build orientations included flat and edge. Each main build orientation contained three sub-build orientations which were 0 degree, 45 degrees, and 90 degrees to the x-axis. The mechanical properties including elastic modulus, ultimate tensile strength, elongation at ultimate tensile strength, and elongation at break were evaluated by tensile test with a universal testing machine. The results indicated that the mechanical properties of specimens were slightly different among the sub-build orientations. The larger differences of mechanical properties of specimens were found between main build orientations. The mechanical strength of specimens improved corresponding to the increase of UV post-curing period ranged from 0 to 4 hours whereas the post-curing period using 4 hours onward, the mechanical properties of specimens were nearly constant.

Keywords: stereolithography process, build orientation, ultraviolet post-curing process and mechanical properties

1. Introduction

Solid freeform fabrication or additive manufacturing is a production process where physical prototypes are created based on the concept of layer manufacturing technology. The invention of the technology has been preliminary fulfilled the engineering applications, especially for products, which have complex shape and internal structure. Some additive manufacturing utilizations in industries include the fabrication of molds and dies (Jeng and Lin, 2001; Song *et al.*, 2002), production of aircraft component prototypes for aerodynamic analysis (Zhu *et al.*, 2011; Kroll and Artzi, 2011), and the making of full-size automobile instrument panels (Wohlers, 2009).

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The principle of additive manufacturing processes relies on the constructing physical model from a three-dimensional computer aided design (CAD) model by laying down successive layers of material (Levy *et al.*, 2003; Chen and Feng, 2011). Various additive manufacturing systems are currently available, which generally can be classified into three categories according to the characteristics of processing material (Chua *et al.*, 2010), 1) the solid-based system (i.e. laminated object manufacturing and fused deposition machine), 2) the powder-based system (i.e. selective laser sintering/melting and three-dimensional printing), and 3) the liquid-based system (i.e. stereolithography). A wide range of materials can be processed by the additive manufacturing technology. Different materials require certain additive manufacturing systems to build the prototypes. Metals and ceramics are typically proper for selective laser sintering/melting (SLS/SLM) system as the powder of these materials requires high energy in rising the temperature to be above the glass transition or the melting point in order to allow the powder to deform and bond to adjacent powders (Vandenbroucke and Kruth, 2007; Tolosa *et al.*, 2010). For polymeric materials the powder-based materials, such as polyamine, utilize the SLS system (Zarringhalam, 2009), whereas liquid-based polymers (i.e. photo-curable resin) are processed by the stereolithography (SL) system.

Besides industrial applications, progress of digital imaging devices, for example computed tomography (CT) scanner and magnetic resonance imaging (MRI) machine, enables manifold opportunities for the additive manufacturing in medical applications. The anatomical data obtained from CT or MRI is used to manipulate the three-dimensional models in CAD/CAM software, which synchronizes well to additive manufacturing devices. Ordinarily, anatomical shapes are complex, which are difficult to manufacture by conventional subtractive processes, such as milling and turning, due to the limited accessibility of devices and high tooling cost (Sitthiseripratip, 1997). Producing prototypes by means of the additive manufacturing concept can eliminate manufacturing constraints of conventional manufacturing techniques. Among aforementioned additive manufacturing systems, SL system has gained popularity in medical applications due to its advantages in low operating cost, unlimited freeform shape production, and its ability in processing medical-graded materials (Melchels *et al.*, 2010). Various surgical tools and implants employ the SL process for producing especially patient specific surgical instruments such as cutting template, drilling guide, and craniofacial implant (Petzold *et al.*, 1999; Seitz *et al.*, 2004; Hafez *et al.*, 2006). Additionally, in biomedical research, the SL process has also been used to create physical bio-models and implants using for the assessment of biomechanical performance (Kakarala *et al.*, 2006) and the verification of numerical investigations, respectively.

Since the SL process relies on deposition material layer- by-layer, therefore, the mechanical behavior of bio-models fabricated by SL process can be influenced not only by their material properties, but also by the manufacturing method itself. Consequently, the SL prototype may exhibit the directional dependence material properties. In addition, prototypes after SL process are often post-cured in ultraviolet (UV) radiated environments, which also can change material properties (Cheah *et al.*, 1997). In order to understand how SL manufacturing and post-curing processes influence the mechanical properties of photo-curable resin after processed by SL system, this study investigated the effect of the SL build orientation as well as the UV post-curing period on the mechanical properties of SL parts. The obtained results will be beneficial and provide the critical information for the medical device and implant developers who employ SL technology as a research and development tool.

2. Stereolithography Process

SL constructs the physical prototypes according to three-dimensional CAD model, which uses the dissipated energy from laser in UV wavelength or visible light, to solidify the liquid photo-curable monomer (Kruth *et al.*, 1998). The process of SL begins by slicing CAD model at constant interval to obtain a series of two-dimensional cross section contours. The structural supports are also designed and attached to the CAD model to ensure the stability of the physical prototype during fabrication process. After the set of slicing data is loaded to SL machine, a building platform is lowered from its initial position which is equal to the predetermined slice thickness in CAD data. In the meantime, photo-curable resin spreads on the building platform. The wiper then sweeps to adjust the resin surface level before the laser selectively cures the liquid mono-polymer resin through photo-polymerization (a process of linking small molecule into the larger molecule chain) according to close loop geometric contour of current slice. When the current slice is finished, the building platform is again lowered and photo-curable resin spreads on, allowing the successive layer to be constructed. The process repeats layer by layer until the last slice is completed. In addition, the complete SL part is post-cured in an UV chamber to solidify the uncured liquid photo-curable resin. Figure 1 shows schematic diagram of the SL process.

3. Materials and Methods

3.1 Photo-cured epoxy resin

The material used in this present study was the commercially available epoxy based photo-curable resin Watershed XC 11122 (DSM Somos, Inc., U.S.A.). The Watershed XC 11122 is optically clear, having a viscosity of 260 cps at 30°C, and density of 1.12 g/cm^3 at 25°C. The major mechanical properties of Watershed XC 11122 as described in the product data sheet are provided in Table 1 (DSM Somos, 2008).

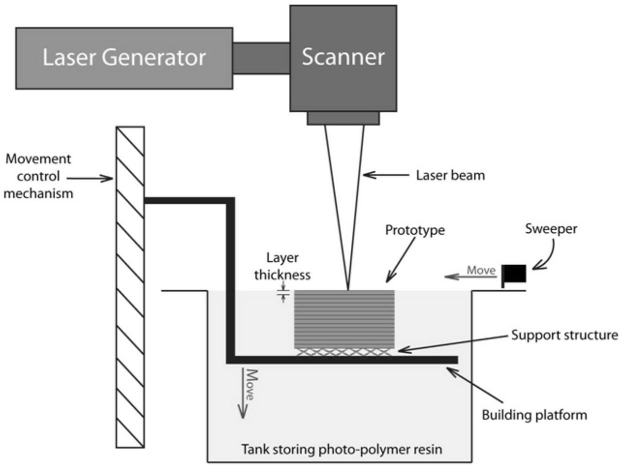

Figure 1. Stereolithography process

Table 1. Mechanical properties of Watershed 11122.

Description	Elastic modulus(MPa)
Tensile strength	47.1–53.6 MPa
Elongation at break	11–20%
Elongation at yield	3.0%
Elastic modulus	2,650–2,880 MPa

3.2 Specimens, SLA device and material processing parameters

Geometry of specimens for tensile test used in this study was created according to the 'Standard Method for Tensile Properties of Plastic' of American Standard for Testing Materials (ASTM, D638-01). All specimens were fabricated on an in-house developed SL machine, of the National Metal and Materials Technology Center (MTEC) of Thailand, as shown in Figure 2. The volume of the build envelop for the machine is 270 mm × 270 mm × 240 mm. The temperature of photo-cured resin was set at 37°C. The fabrication was performed in dark room to prevent undesired curing process initiated by external light sources. The processing parameters were as follows: Layer thickness: 0.175 mm, Laser scanning speed: 3200 mm/s, Laser spot size: 0.08 mm, Laser scanning strategy: cross hatching (Figure 3), and Laser Power: 2.5 watts.

3.3 Build orientation experiments

As mentioned earlier, SL process is based on the layer manufacturing concept which different build orientations may produce dissimilar mechanical properties. In order to investigate the directional dependence properties of SL parts, the specimens were fabricated in various build orientations as shown in Figure 4. In this figure, there are two main build orientations which are flat and edge. Each of main build orientations has three sub-build orientations which are 0

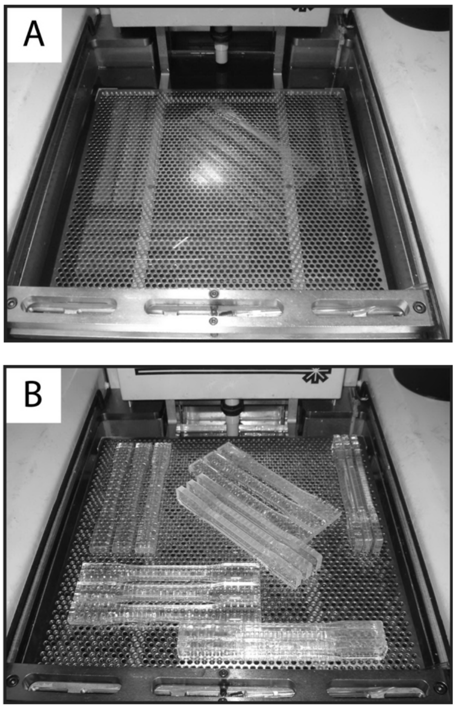

Figure 2. Fabrication of specimens, (A) during SLA process and (B) finished specimens

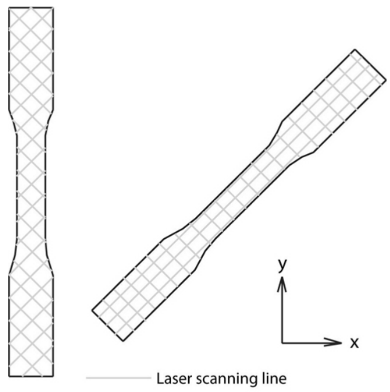

Figure 3. Cross-hatching laser scanning strategy

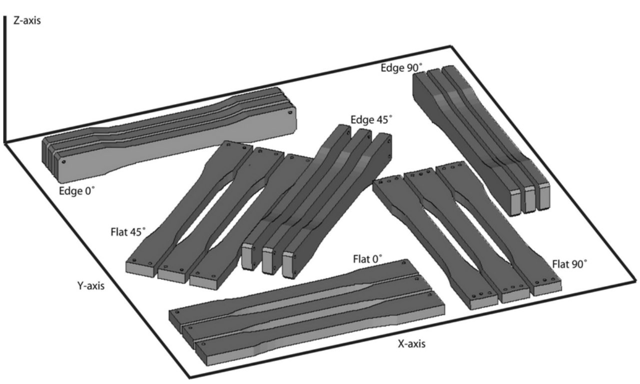

Figure 4. Build orientation

degree, 45 degrees, and 90 degrees to the x-axis. After the fabrication process, all specimens were cleaned with isopropanol alcohol (IPA) to remove excessive resin and structural support, prior post-curing for one hour under UV light.

3.4 UV Post-curing period experiment

In this experiment, influence of different UV post-curing process to the change of mechanical properties was considered. Fifteen specimens were only fabricated on edge build orientation to control the variation of mechanical properties. After cleaning with IPA, the specimens were equally divided into five groups. One of them was the controlled specimens which would not be undergone post-curing process. For the remained groups, the specimens were post-cured for 2 hours, 4 hours, 6 hours, and 8 hours, respectively.

3.5 Tensile test

All specimens were examined the tensile mechanical properties with the Universal Testing Machine (UTM) (Instron 5500R, Instron Inc., U.S.A.). In the tensile test, both ends of specimens were attached to the grip and the extensometer was placed on one side of specimen to measure the displacement, as shown in Figure 5. The testing protocol was controlled the tensile velocity at 5 mm/min until the specimen broke down. The focused mechanical properties including elastic modulus, ultimate tensile strength (UTS), elongation at UTS, and elongation at break could be obtained from the stress-strain curves of each specimen. The stress-strain curve obtained from one specimen was compared to the other specimens to investigate the difference in the mechanical properties of specimens fabricated in each build orientation and different UV post-curing period.

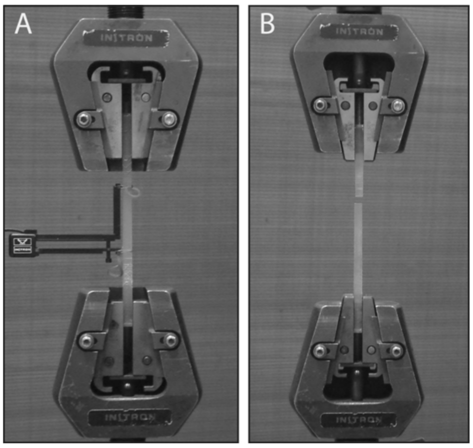

Figure 5. Tensile test, (A) Set up and (B) Failure of specimen

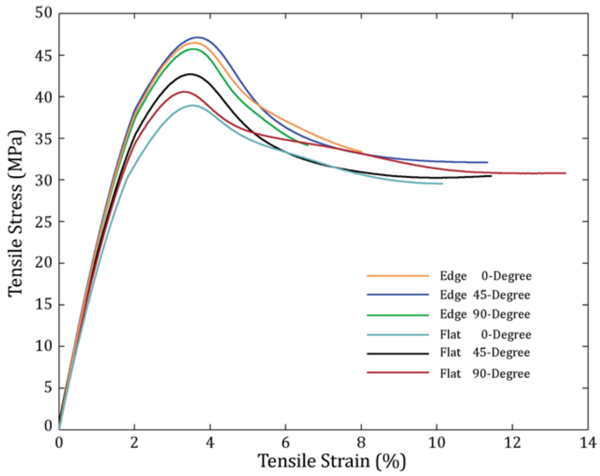

Figure 6. Stress-strain curves of specimens from different build orientation

4. Results

4.1 Influence of build orientations to the mechanical properties

Representative stress-strain curves of specimens at each build orientation are shown in Figure 6. Table 2 also provides the average value (μ) and the standard deviation (S.D.) of elastic modulus, ultimate tensile strength (UTS), elongation at UTS, and elongation at break of the specimens obtained from tensile test. According to the results, it can be noticed that 45 degrees sub-build orientation specimens present the greater mechanical properties than the 0 and 90 degrees sub-build orientations specimens. The elastic modulus and UTS of edge build orientation specimens are slightly

Table 2. Average values and standard deviation of elastic modulus, UTS, elongation at UTS, and elongation at break of specimens fabricated in all build orientations ($\mu \pm$ S.D., n=3).

Build orientation		Elastic modulus (MPa)	UTS (MPa)	Elongation at UTS (%)	Elongation at break (%)
Flat	0 degree	2,038.29±65.35	37.75±1.82	3.45±0.11	11.67±4.97
	45 degrees	2,204.74±3.80	43.25±0.98	3.51±0.03	7.60±3.48
	90 degrees	2,121.16±109.64	38.24±2.22	3.26±0.08	8.53±4.29
Edge	0 degree	2,339.23±20.09	46.07±0.99	3.54±0.07	9.27±1.10
	45 degrees	2,409.02±15.40	47.70±0.52	3.65±0.02	9.00±3.57
	90 degrees	2,337.82±15.09	45.72±0.48	3.50±0.05	6.60±0.30

higher than flat build orientation specimens. In addition, the elongation at UTS of flat build orientation specimens is not significantly different to edge build orientation specimens.

4.2 Influence of UV post-curing effect to the mechanical properties

Representative stress-strain curves of specimens at different UV post-curing periods are shown in Figure 7. Table 3 shows the average values (μ) and the standard deviation (S.D.) of elastic modulus, UTS, elongation at UTS, and elongation at break of the specimens, which were undergone different post-curing period. According to the results, it is obviously shown that the UV post-curing process improved the mechanical properties of SL specimens. Less than 4 hours of UV post-curing, the elastic modulus, UTS, and elongation at UTS were improved corresponding to the increase number of UV exposure periods. However, from 4 hours onwards of UV post-curing process, these mechanical properties were almost constant. Additionally, there was no improvement in the value of elongation at the break after UV-post curing process.

5. Discussion

The progress of various engineering technologies, especially the laser material processing, the reverse engineering instruments, and the CAD/CAM makes it possible for human organs to be modeled and fabricated through the additive manufacturing technology. Various additive manufacturing systems have been utilized in medical applications to produce personalized surgical instruments as well as the implants. Among the systems, SL is considered to be the most effective technology as its system does not require particular controlled processing environments. In contrast, for SLS and SLM systems, it is necessary that the materials are processed in a vacuum chamber with inert gas shielding environment. (Das, 2004; Santos *et al.*, 2006). According to these reasons, the operating cost of SL system is lower than of SLS and SLM systems. Apart from the intensive use of SL system for clinical implementation, the system has also found applications in medical research, for example, the use for constructing bio-models for biomechanical evaluation and computational model validation.

This study presented the factors in SL process which contributed to the mechanical properties of SL specimens, focusing on two aspects, which were build orientation and UV post-curing period. The present study revealed that the build orientation is considered to be significant parameters, which can lead to the variation of mechanical properties of the specimens. Moreover, an increase of the UV post-curing period improved the mechanical properties of specimens. From Figure 6 and 7, the obtained stress-strain curves exhibit the identifiable yield point and majority of the specimens have an elongation at break beyond 5 percents strain; therefore, Watershed 11122 processed by SL technique can be classified as ductile material (Budynas *et al.*, 2008).

For the effect of build orientations, the obtained results presented that the specimens with 45 degrees sub-orientation exhibited the greater mechanical properties than the specimen with 0 and 90 degrees sub-orientations. This is because of the cross-hatching laser scanning strategy, where the laser solidified the photo-curable resin in 45 and -45 degrees to the x-axis of the building envelop. Based on this scanning strategy, the curing direction was parallel to the direction of applied load in the tensile test. The laser scanning direction may be comparable to fiber in composite material that increased the strength in the direction of reinforcement. Table 2 also shows that the mechanical properties of the

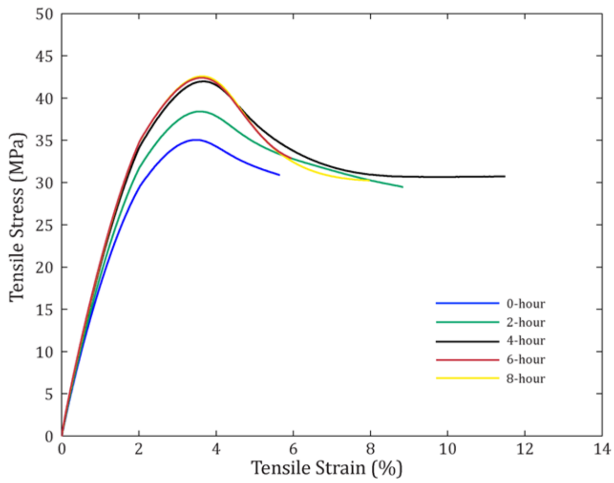

Figure 7. Stress-strain curves of specimens post-cured at various period

Table 3. Average values and standard deviation of elastic modulus, UTS, elongation at UTS, and elongation at break of specimens after different post-curing period ($\mu \pm$ S.D., n=3).

Post-curing period	Elastic modulus (MPa)	UTS (MPa)	Elongation at UTS (%)	Elongation at break (%)
0 hours	1,932.12±91.98	33.61±1.53	3.34±0.14	8.39±2.37
2 hours	2,093.37±28.71	38.13±0.28	3.54±0.02	9.74±0.86
4 hours	2,228.07±40.16	41.69±0.29	3.67±0.01	8.58±2.53
6 hours	2,234.90±26.17	42.30±0.22	3.63±0.04	7.96±4.86
8 hours	2,263.12±42.90	42.90±0.42	3.62±0.02	8.26±1.91

specimens built in edge orientation are slightly greater than the specimens built in flat orientation. This can be explained that the specimens built in edge orientation had a number of built layers parallel to the direction of applied tensile load and more than the specimens built in flat orientation. Due to the fact that the adhesion of the material within the layer (xy-plane) is more robust than between the layers (z-axis) (Kulkarni *et al.*, 2000), a higher number of layers lead to a greater mechanical strength. In order to analyze the isotropic/anisotropic mechanical properties, the elastic modulus, UTS, elongation at UTS, and elongation at break of the specimens prepared from different build orientations were compared using percentage difference, as shown in Table 4 to 7. From the pair wise comparison, the differences of elastic modulus, UTS, and elongation at UTS between sub-orientations were lower than the ones between the main orientations. Although the elongation at break presents the large differences at both between the sub-orientations and between the main orientations, the Watershed 11122 is considered to be a ductile material. Thus, the elongation at UTS is more significant in the design process than the elongation at break. Therefore, considering only three parameters i.e. elastic modulus, UTS, and elongation at UTS, the Watershed 11122 after SL process is a transverse isotropic material.

The photo-polymerization in the SL process typically produces the partial-cured and uncured photo-curable resin inside SL parts, which can be further cured under UV light. From the experiments, there is an improvement in the mechanical properties of the specimens corresponding with the UV post-curing period from 0 to 4 hours whereas a period beyond 4 hours of post-curing indicates a slight improvement of the mechanical properties. The slight improvement of the mechanical properties after 4 hours of UV post-curing can imply that the remaining uncured and partial-cured Watershed 11122 required at least 4 hours to be fully cured. Furthermore, first the external surface of the prototype absorbed the UV radiation and the inner layers afterwards; therefore a thicker prototype requires a longer post-curing period. As a result, it should be noted that the position of the UV generating source in the chamber also influences the degree of curing. With the same period of post-curing, sides of the SL part that were close to the UV sources are expected to be cured more efficiently than the remaining sides.

The specimens prepared from different build orientations exhibited a directional dependence of the mechanical properties. Therefore, the preparation of a building envelop needs to be considered for functional use. For biomedical engineering researches, the problems are usually complicated due to the geometry of human organ, complex material properties and test conditions, which may be prohibitively expensive or difficult to be performed by means of a physical experiment (Chantarapanich *et al.*, 2009). The computational techniques, for example, finite element (FE) method, are employed to investigate the biomechanical behavior. Nevertheless, the numerical techniques are considered to be approximation computational methods; at least some testing conditions are required to verify the mechanical experiments. In order to obtain good agreements between mechanical and

Table 4. Percentage of difference of elastic modulus for each compared pair of build orientations.

Build Orientation		Flat			Edge		
		0 degree	45 degrees	90 degrees	0 degree	45 degrees	90 degrees
Flat	0 degree	-	7.8	4.0	13.7	16.7	13.7
	45 degrees	7.8	-	3.9	5.9	8.9	5.9
	90 degrees	4.0	3.9	-	9.8	12.7	9.7
Edge	0 degree	13.7	5.9	9.8	-	2.9	0.1
	45 degrees	16.7	8.9	12.7	2.9	-	3.0
	90 degrees	13.7	5.9	9.7	0.1	3.0	-

Table 5. Percentage of difference of UTS for each compared pair of build orientations

Build Orientation		Flat			Edge		
		0 degree	45 degrees	90 degrees	0 degree	45 degrees	90 degrees
Flat	0 degree	-	13.6	1.3	19.9	23.3	19.1
	45 degrees	13.6	-	12.3	6.3	9.8	5.5
	90 degrees	1.3	12.3	-	18.6	22.0	17.8
Edge	0 degree	19.9	6.3	18.6	-	3.5	0.8
	45 degrees	23.3	9.8	22.0	3.5	-	4.3
	90 degrees	19.1	5.5	17.8	0.8	4.3	-

Table 6. Percentage of difference of elongation at UTS for each compared pair of build orientations.

Build Orientation		Flat			Edge		
		0 degree	45 degrees	90 degrees	0 degree	45 degrees	90 degrees
Flat	0 degree	-	1.8	5.6	2.5	5.8	1.6
	45 degrees	1.8	-	7.4	0.7	4.0	0.2
	90 degrees	5.6	7.4	-	8.1	11.4	7.1
Edge	0 degree	2.5	0.7	8.1	-	3.3	0.9
	45 degrees	5.8	4.0	11.4	3.3	-	4.2
	90 degrees	1.6	0.2	7.1	0.9	4.2	-

Table 7. Percentage of difference of elongation at break for each compared pair of build orientations.

Build Orientation		Flat			Edge		
		0 degree	45 degrees	90 degrees	0 degree	45 degrees	90 degrees
Flat	0 degree	-	42.2	31.0	22.9	25.8	55.5
	45 degrees	42.2	-	11.6	19.8	16.9	14.1
	90 degrees	31.0	11.6	-	8.2	5.3	25.6
Edge	0 degree	22.9	19.8	8.2	-	2.9	33.6
	45 degrees	25.8	16.9	5.3	2.9	-	30.8
	90 degrees	55.5	14.1	25.6	33.6	30.8	-

numerical experiments, it is necessary to attribute the correct material's constitutive law in computational models. From the result, Watershed 11122, a photo-cured epoxy resin, is considered to be anisotropy after processed by SL system. If the Watershed 11122 after processed by SL system is used to produce the physical model for verification a numerical analysis, it is desirable to assign directional dependent properties to the FE models. However, the average percentage of the difference in the elastic modulus of the specimens processed by SL system is 10.77±3.70 percent; the material properties used in FE analysis may be assumed to be isotropic to simplify the analysis.

6. Conclusion

This paper presented the investigation of the mechanical properties of Watershed 11122, which is a photo-cured epoxy resin, after fabrication by SL process. Two aspects included in the present study were the influence of build orientations and the influence of UV post-curing period. The assessment of mechanical properties was evaluated by elastic modulus, UTS, and elongation at UTS, and elongation at break. The experimental data revealed that the specimens prepared at different orientations (edge and flat orientations) influenced the variation of mechanical properties, whereas the mechanical properties of specimens prepared by sub-build orientations are slightly different. The Watershed 11122 after SL process is considered as a ductile material since most of the tested specimens presented the elongation at break beyond 5 percent strain. The elastic modulus used in numerical analysis may be assumed to be isotropic because the elastic modulus of specimens preparing from different main orientations is approximately 10 percent. The period of UV post-curing played an important role in the improvement of the mechanical properties. The experiment showed that the mechanical strength improved corresponding to an increase of the UV post-curing period ranging from 0 to 4 hours. The mechanical properties of specimens after 4 hours period of UV post-curing were relatively constant.

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Conflict of interest

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

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