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The evaluation of effect of post processing process on parts printed using photopolymer resin by stereolithography additive manufacturing

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***Abstract*— Stereolithography is an additive manufacturing process where liquid photopolymer resin is cross linked and converted to solid. It is basically a rapid prototyping process in which complex parts of plastic monomers are directly built by the photo polymerization process with the help of light or laser source. Printed part strength could be further improved by post processing techniques such as exposure to UV lights and or dipping into the water solution. The aim of this research is to look into a different method for strengthening the parts by dipping into hot tap water. The mechanical properties were measured and compared. The experiments were conducted based on an L8 orthogonal array with three parameters and two levels to identify the parameters influencing the strength of the SLA printed specimen. The results show that there is a decrease in the tensile strength of the printed specimens after curing when compared to uncured specimens. Furthermore, ANOVA and S/N ratios are calculated to identify the percentage contribution of each process parameters and to get the optimum process parameter for better mechanical strength. S/N ratio shows density as the most influencing parameter for the tensile strength of the specimen followed by layer height and point size.**

Keywords—*Additive Manufacturing, SLA, Photo polymerization, Post Processing, L8 Orthogonal Array, ANOVA, S/N ratio.*

I. INTRODUCTION

A process of creating the product from the ground up layer by layer is known as Additive manufacturing. It starts with a 3D model usually created in CAD. The 3D model created is then processed by slicer software, slicing it into an individual layer. Stereolithography is the oldest layer- manufacturing process and continues to construct conceptual models in a few hours or days. Stereolithography is a technique, where a laser beam is focused to a free surface of a photosensitive liquid to build polymerization of the liquid in that region and transform it to a polymerized solid. Parts printed from SLA can be easily painted, machined, dyed, shielded and can also be used to make cavities in silicone molds, serve as patterns for investment or plaster casting [1], [2]. Basically, photo polymerization is a process of formation of cross linked of polymers under exposure of laser light, usually of wavelengths in the ultraviolet spectrum [3][4]. When photo reactive resins get exposed to UV light photo initiator molecules break down into two parts and thereby form two reactive radicals [5]. These reactive radicals are then transferring to other active groups on the monomer which reacts with other active groups forming longer chains. Monomers and Oligomers are the carbon chains which make the solid parts. Photo initiator molecules respond to UV light and initiate the reactions. The SLA process comprises three phases. The first phase is the preparative phase where support structure creation and slicing are executed. The second phase is the building phase where specimens are printed. And the final phase is the finishing phase where cleaning and post curing of specimens are done [6], [7].

The curability and mechanical properties of the photopolymer was studied. It was observed that “Laser exposure density” and “layer height” are the leading factors that have effects on the properties (mechanical) of the stereolithography printed parts. It was found that “laser exposure density” has an impact on ultimate tensile strength and modulus of Elasticity of the printed specimen as the part built by larger exposure to laser results in increase in polymerization process [8]. During SLA printing, specific areas of resin are exposed to a laser which causes them to cure. The cured resin is a cross-linked macromolecule,

which means that every part of it is directly connected to every other part of it. The main function of post curing is to enable parts to reach its highest possible strength and become more stable. Both heat and light are used in this process where heat accelerates the process resulting in increasing its material properties [9].

II. METHODOLOGY

A. Effects of Post Curing

After printing, the SLA printed specimen remains on the build platform in a "green state", which means the part has reached its final form but polymerization has not been completed yet. The reason for performing post curing is to improve the functionality of a part and ensure that they meet the required specification; it enhances the part's surface quality, geometric accuracy and mechanical properties. To improve the mechanical properties of specimens, many researchers have found out different aspects of SLA post curing techniques [9][10]. Different post-curing processes can have varying effects on component efficiency. When using an Ultraviolet and a microwave oven, for example, ultimate tensile strength can be increased by 70.83 percent and 15.01 percent, respectively. Furthermore, using proven models, optimal post-curing strategies under various constraints are determined, providing valuable insights for post-curing process planning and optimization [9].

B. Science of Post Curing

Photopolymer resin is a long chain of Monomers and Oligomers which are highly cross-linked. While printing, they are printed in the continuous molecules but there are some open reactive chains left that can be cross-linked further [11][12]. As more cross-linking takes place, material properties, such as tensile strength and modulus improves. The main intent of the post curing process is to join as many open reactive groups to bring a part to its maximum material properties [13].

C. Specimen preparation

Post curing starts with the heat as rise in the temperature increases the energy and therefore, the rate of polymerization increases. Exposure to light activates the photo initiator that leads to the formation of permanent bonds between reactive groups, cross-linking them together. The curing of the photopolymer resins depends upon how well their open reactive groups bond with each other and hence, this increases with increase in molecular mobility. Application of heat increases the molecular mobility of the open reactive groups and results in permanent bonding to improve the strength and stiffness of the printed specimen [14]. The tensile test specimens The ranges of variable parameters as shown in Table 1 were chosen according to the printing requirement were printed as per ASTM D-638 type-V by designing the model in the solid works. A set of three fixed parameters considered are slope multiplier, height above the raft and raft thickness. Similarly, the layer height, point size and density are considered as variable parameters in the experiment. L_8 orthogonal array is used to study the effect of several control factors [15][16]. After the conversion of the 3D model into STL file it is uploaded to SLA (Formlab) printer with the help of the software (Preform) that helps to create the required supports for the test specimen to be printed.

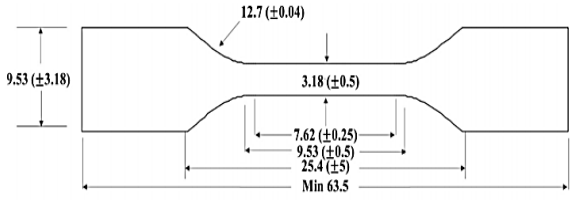

Fig1: Test specimen according to ASTM D638 Type V [19]

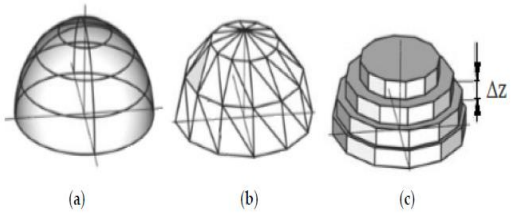

Fig 2: Scheme of the stereolithography (SLA) printing process: (a) CAD model, (b) STL model, and (c) division into slices. ΔZ—layer thickness [17].

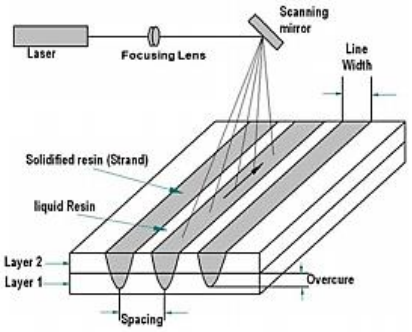

Fig 3: SLA printing process [15]

Table 1: Fixed and Variable parameters

S. No	Fixed parameters		Variable Parameters	Level 1	Level 2
1	***Slope multiplier***	1	***Layer height***	0.05	0.1
2	***Height above the raft***	5	***Point size***	0.6	1.3
3	***Raft thickness***	2	***Density***	1	1.5

given by ASTM D638 type V for printability [18][19]. The optimum layer height that is suitable for start printing the specimen is 0.05 for high resolution and 0.1 for fastest printing. Point size is chosen according to the printability as point size below (0.6) leads to the failure of the specimen [18], L8 orthogonal array was used for variable parameters of two levels as shown in Table 3.

Table 2: L_8 Orthogonal Array

Run	POINT SIZE (mm)	DENSITY (kg/m^3)	LAYER HEIGHT (mm)
1	0.6	1	0.1
2	0.6	1	0.05
3	0.6	1.5	0.05
4	0.6	1.5	0.1
5	1.3	1	0.1
6	1.3	1	0.05
7	1.3	1.5	0.05
8	1.3	1.5	0.1

D. Post printing process

Post-processing of SLA parts typically consists of a solvent hence, after printing, the specimens were submerged in the container filled with Isopropyl Alcohol (IPA) for 10 minutes to remove the uncured layer and reduce any residual stickiness [20]. Alternatively, a squeezed bottle filled with IPA is used to remove the extra resins. The next step is to detach the supports from the specimen gently by cutting it with the help of a model cutter.

Fig 4: (a) SLA Printed specimen (b) Specimen w rapped in black paper (c) Specimen during curing.

In this study, SLA printed specimens of 16 in total were post cured into hot water. Three vessels were filled with tap water and heated using a hot furnace (model-Essac) at 45°C for 15 minutes. After 15 minutes, three specimens were dropped in their respective vessels (at room temperature) and kept inside the furnace for another 15minutes maintaining the same temperature. These three vessels were taken out after 15 minutes and allowed to cool down and the time taken by each specimen to come back to its room temperature was noted. The specimens were dried out and wrapped with a black paper avoiding exposure to light which may cause some change in the mechanical properties.

Fig 5: Measuring Ultimate Tensile Strength

Table 3: Tensile strength measured, post curing parameters and S/N ratio

RUN	CURING TEMP. (°C)	CURING TIME (min)	TIME TO REACH ROOM TEMP. (min)	TENSILE STRENGTH		S/N RATIO	
				BEFORE CURING (MPa)	AFTER CURING (MPa)	BEFORE CURING	AFTER CURING
1	45	15	10	27.5	34.5	28.7478	30.6220
2	45	15	10	27.5	30	28.7478	29.5279
3	45	15	12	46.5	29.5	33.3113	29.3927
4	45	15	10	39.5	25.5	31.8295	28.1257
5	45	15	10	33	29.5	29.7792	29.3927
6	45	15	12	34	27.4	29.9008	28.7478
7	45	15	10	37	33	30.7497	30.3583
8	45	15	10	33	27	29.7792	28.5557

III. Results and Discussion

This research involves a different approach of post curing process for 3D printed specimens, printed using SLA technology. In this research the effect of post curing method on the tensile strength of the specimens and comparing the results for before and after curing was studied. The results shows which printing parameter has the most influence on the mechanical properties of the SLA printed parts. Table 1 showing

the three printing parameters that are point size, density and layer height taken in 2 levels as variable parameters and slope multiplier, height above the raft and raft thickness are taken as fixed parameters. The specimens were modeled as per the ASTM standards D638 type V in Solidworks as shown in Fig 1. Table 2 shows the L8 orthogonal array designed according to the 2 levels of the variable printing parameters. In the previous research, it was found that there is an increase in the mechanical properties of the SLA printed specimen [21]. However, in this experimental study it was found that, there is no such markable effect of post curing on the specimen. Table 3 shows the post curing parameters, values for measured tensile strength and signal to noise ratio for each run before and after curing. Fig 6 clearly demonstrates the comparison of the measured values of the tensile strength for before and after curing of the SLA printed specimens where x-axis display the run numbers and y-axis display the tensile strength values in MPa. Table 4 shows signal to noise ratio. Since the key goal was to see the increase in tensile strength of parts produced by the SLA process the S/N ratio was considered as larger the better. As a result, the level with the highest S/N ratio is chosen as the optimum level, which adds the most strength to the part. The ranking of the parameters shows that tensile strength is mostly influenced by density followed by layer height and point size. Layer height and density have minute differences in their delta values. Therefore, the optimum levels contributing to the higher strength of the part before curing are density (1.5), layer height (0.05) and point size (0.6). The optimum levels contributing to the higher strength of the part after curing are density (1), layer height (0.05) and point size (0.6).

Table 4: Parameters Ranking

S/N RATIO	Before Curing			After Curing		
	POINT SIZE	***DENSITY***	***LAYER HEIGHT***	***POINT SIZE***	***DENSITY***	***LAYER HEIGHT***
LEVEL-1	30.65915	29.29396	30.03397	29.41712	29.57264	29.17406
LEVEL-2	30.05227	31.41747	30.67746	29.26365	29.10813	29.50670
DELTA	0.60688	2.123511	0.643496	0.15347	0.464511	0.33264
RANK	**3**	**1**	**2**	**3**	**1**	**2**

The parameters that had more effect on tensile strength are recognized through calculation of ANOVA. Some researchers have proposed the ANOVA technique as a very useful method for calculation of contribution and consequently the importance of a parameter [6]. Hence, for identifying the percentage contribution from the 3 factors an ANOVA for before curing and after curing were calculated using MINITAB software shown in Table 5 and 6.

Table 5: Shows the % of contribution of the parameters to the measured tensile strength before curing along with the estimated ANOVA (*Significance, $p < 0.05$)

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F- Value	P-Value
Point Size	1	144.50	52.07%	144.50	144.500	25.69	0.007*
Density	1	98.00	35.32%	98.00	98.000	17.42	0.014*
Layer Height	1	12.50	4.50%	12.50	12.500	2.22	0.210
Error	4	22.50	8.11%	22.50	5.625		
Total	7	277.50	100.00%				

Table 6: Shows the % of contribution of the parameters to the measured tensile strength after curing along with the estimated ANOVA (*Significance, $p < 0.05$)

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F- Value	P-Value
Point Size	1	5.120	7.98%	5.120	5.120	4.33	0.106
Density	1	19.845	30.94%	19.845	19.845	16.78	0.015*
Layer Height	1	34.445	53.70%	34.445	34.445	29.13	0.006*
Error	4	4.730	7.37%	4.730	1.182		
Total	7	64.140	100.00%				

Analysis of Variance (ANOVA) helps in identifying which process parameters are significantly contributing towards the response variable and has the highest contribution. From Table 5, the point size and density are significantly contributing towards tensile strength before curing, point size (52.07%) having the highest contribution followed by density (35.32%). From the Table 6, the density and layer height are significantly contributing towards tensile strength after curing, layer height (53.70%) having the highest contribution followed by density (30.94%).

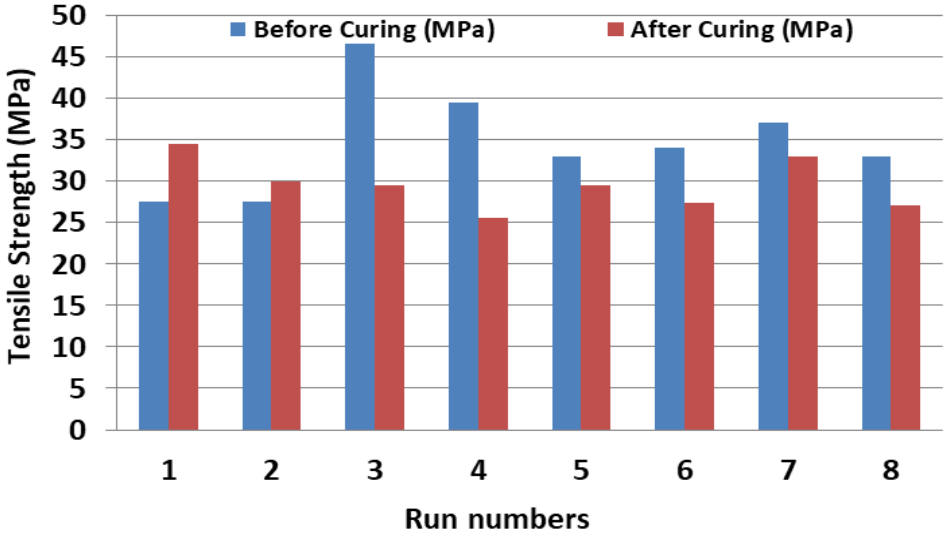

Fig 6: Comparison of Ultimate Tensile Strength

Fig 6 shows the mixed trend of ultimate tensile strength of the SLA printed specimen before and after curing. There is a significance improvement measured on the specimen run number 1 & 2 after curing. However, there is a decrease in strength was measured from run numbers 3 to 8 after curing. The tensile strength of the run numbers 3-8 is higher before curing. The reason for the mixed strategy has to be analysed in details further. From ANOVA and S/N ratio calculations the percentage contribution of the parameters and their significant role to the response can be seen. Similarly, in case of run number 3 specimen, the tensile strength value of before curing is the highest of all, the process parameters present are at the levels having highest S/N ratios (point size-0.6 & S/N ratio-30.65), (density-1.5 & S/N ratio = 31.41747), layer height-0.05 & S/N ratio-30.6774) and having the highest value of tensile strength can be seen in bar graph Fig.6. This work is extended further to analyse the reasons in microscopic level for mixed strategy.

IV. Conclusion

In this paper, a different approach is employed for the post curing of the SLA printed specimen by dipping them into tap water at 45°C for 15minutes. After the post curing it was found that there is no such significant increase in the tensile strength except two of the specimens. Furthermore an attempt is made to analyze and found out the optimum process parameters that could influence the strength aspect of the SLA printed parts the most. With the completion of this experiment, the authors are arrived to the following conclusions, the hot water dipping as per the experimental condition of 45C° for 15mins may not be suitable to cure by cross-linking the monomers. It was observed that the density is a key factor to increase the mechanical strength of the printed components. The density of the raw material also could influence the measured mechanical properties before printing. The reason for the lesser mechanical properties after curing could be the variation in density, however, needs to analyse them with microscopic imaging.

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