Solid Freeform Fabrication 2017: Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

Effect of Process Parameters and Shot Peening on the Tensile Strength and Deflection of Polymer Parts Made using Mask Image Projection Stereolithography (MIP-SLA)

G. Madireddy, M. Montazeri, E. Curtis, J. Berger, N. Underwood, Y. Khayari, B. Marth, B. Smith, S. Christy, K. Krueger, M.P. Sealy[1], P. Rao

Dept. of Mechanical and Materials Engineering, University of Nebraska, Lincoln, NE, U.S.A.

Abstract:

Mask Image Projection Stereolithography (MIP-SLA) is an additive manufacturing technique in which a liquid photopolymer resin is hardened from exposure to ultraviolet (UV) light. Shot peening is a surface treatment to improve the mechanical properties of components. The goal of this work was to quantify the effect of SLA print process parameters, namely layer height and UV exposure, and shot peening on the longitudinal tensile strength of ASTM D638 Type 5 test artifacts. Test parts were created using a central composite experimental plan on a B9 Creator desktop SLA machine. Deflection of the pseudo-Almen strips after shot peening was measured using a digital camera to identify desired peening condition. Post-shot peening tensile strength was measured for the ASTM D638 Type 5 parts. Shot peening generally decreased the strength of MIP-SLA parts.

Keywords: stereolithography, shot peening, polymer, strength, deflection

1. Introduction

The most common application of 3D printed polymer parts is rapid prototyping. In rapid prototyping, builds allow for design visualization, assembly verification, and functional testing. However, these parts are not commonly used for fully functional applications because of limited mechanical properties. In order to use these polymer parts as functional parts, there is a need to have a better understanding of how process parameters affect build quality and mechanical properties as well as a method to improve them.

To improve mechanical properties of polymers, post processes like infiltration, cryogenic treatment, electroplating can be used [1-4]. An alternative method is mechanical surface treatments. Surface treatments such as laser shock peening, shot peening, burnishing, and ultrasonic peening are well known for improving properties of a material. This is done by inducing compressive residual stresses in subsurface of parts through plastic deformation. Usually, these surface treatments are performed on metals. However, the effect of these surface treatments on a 3D printed polymer is not well known.

There are two objectives for this paper: (1) determine the effect of mask image projection stereolithography (MIP-SLA) process parameters on dimensional accuracy and tensile strength of

[1] Corresponding author: sealy@unl.edu (M. Sealy)

polymer parts and (2) determine the effect of shot peening on mechanical properties (tensile strength) of parts made by MIP-SLA (**Fig. 1**). For shot peening these polymers, pseudo-Almen strips were printed on B9 Creator desktop SLA system. Pseudo-Almen strips were used to measure deflection after shot peening to find the saturation point. Saturation is the point at which further peening produces little to no change in the deflection. Once the saturation point is determined, ASTM D638 Type 5 samples were shot peened to find its effect on mechanical properties (*i.e.*, tensile strength) of the photopolymer.

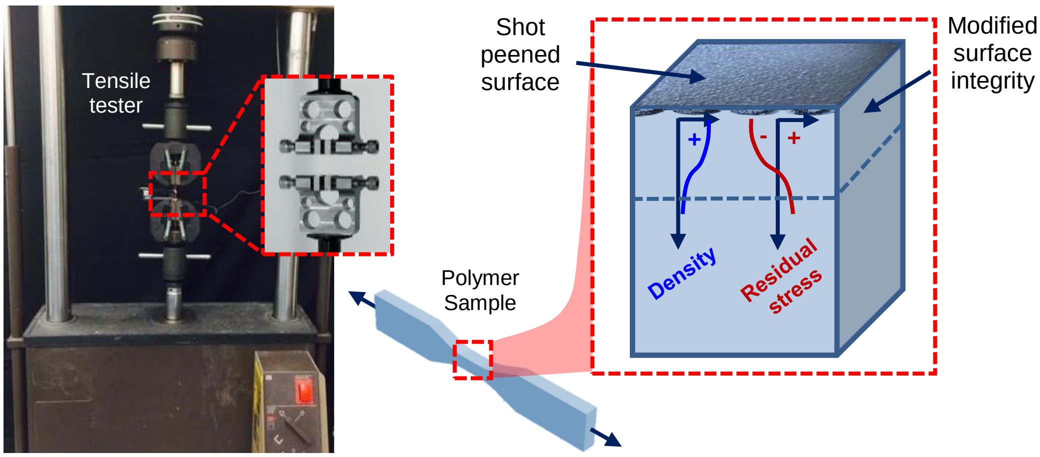

Fig. 1 Shot peening the surface of an MIP-SLA polymer tensile specimen to determine the effect on mechanical behavior.

2. Stereolithography

Stereolithography (SLA) is based on the process of photopolymerization, which makes use of curable resins that react to ultraviolet (UV) radiation. A part's build time in SLA depends on the size, complexity, and layer thickness. SLA polymer parts need to be post-cured under UV light to have increased stiffness. However, this process imposes an unexpected shrinkage and affects the dimensional accuracy. Wang *et al.* found that this error can be accounted for by manipulating process parameters [5]. Using the least squares method, a strong correlation existed between shrinkage and the process parameters such that a regression model was developed to predict distortion from nominal conditions. Other parameters like layer thickness also influence the mechanical properties of SLA parts [6]. Typically, smaller layer thickness results in a higher strength.

In order to achieve the high precision required by some industries, the stereolithography process must be optimized to achieve better quality builds. To this aim, Campanelli *et al.* performed a statistical analysis to specify the optimal parameter settings resulting in the best dimensional accuracy of printed parts [7]. Considering the two printing resolutions, they found that by setting the proper layer thickness, hatch over cure (HO), and border over cure (BO), the post processing requirement such as post curing can be neglected as the whole resin will be cured using the optimal printing parameters.

Irradiation parameters are also critical in obtaining homogeneous polymerization. Chartier *et al*. investigated the influence of different process parameters, including laser power, scanning speed, and number of irradiations on the degree of polymerization to reach the lowest internal stresses and risk of deformation [8]. They showed that a low scanning speed along with a limited laser power lead to the more homogeneous polymer but it increases the build time. They also revealed that based on the layer thickness, the number of affected layers by irradiation of the upper layers will be changed.

3. Shot Peening

Shot peening is a mechanical surface treatment where a stochastic stream of particles impinges the surface to impart favorable compressive residual stresses by severe plastic deformation (**Fig. 2**). The particles, also referred to as peening media, can be composed of metal, glass, or ceramic beads that are on the range of a few hundred microns to several millimeters in diameter. Shot peening is a low cost and quick process to enhance a large surface area component. The shot acts like a hammer, dimpling the surface and causing compressive stresses under the dimple. As shots continue to strike the surface, multiple dimples form as compressive stresses continue to build in the workpiece. These stresses decrease the risk of static and fatigue failures. The use of shot peening on polymers is poorly understood since this process is typically reserved for metals and sometimes ceramics. This work investigates the use of shot peening to modify the mechanical behavior of SLA tensile test specimens.

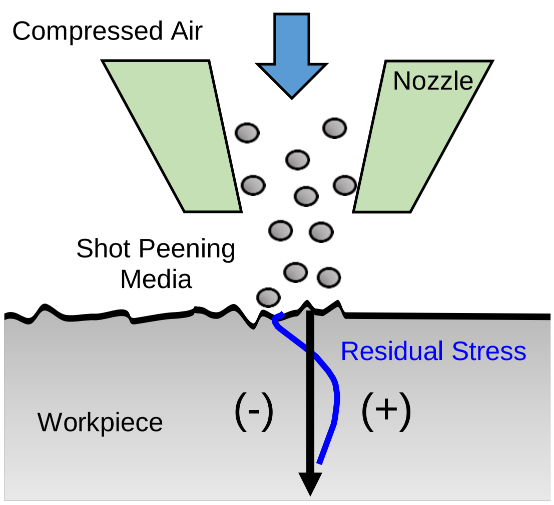

Fig. 2 Shot peening process schematic.

Fig. 3 B9 Creator mask image projection stereolithography (MIP-SLA) printer.

4. Experimental Procedure

4.1 Mask Image Projection Stereolithography (MIP-SLA)

The SLA machine used for printing parts (pseudo-Almen strips and ASTM tensile samples) was a B9 Creator (**Fig. 3**) with a printing resolution of 30 µm to 100 µm. Given the flexibility of the printed parts, several resins were tested to determine which one provide the stiffest part. As a result, the Monocure 3D Blue Resin provided the most accurate and stiff parts.

In order to evaluate the effect of process parameters on the printed parts' quality, layer thickness and UV sensitivity were studied. From the literature review above, layer thickness highly influences build quality and mechanical properties of SLA polymers. UV sensitivity determines the length of time each layer is exposed to the UV light, which can affect how much each layer is going to be cured.

Using a central composite design, cross sectional area (related to the middle part) and tensile strength were measured for ASTM D638 Type 5 samples. The sample geometry is provided in **Fig. 4**. The statistical parameters used for the experiment are shown in **Table 1**. It should be mentioned that with regard to the effective post curing time (less than 10 minutes) related to the printed parts in this experiment (low scale objects), the fixed post curing time of 5 minutes was applied for all parts.

Table 1 MIP-SLA Process Parameters based on a Central Composite Design

Key process input variable	Layer Thickness (µm)	UV sensitivity
Negative alpha (-α)	30	0.320
Low	45	0.370
Center	65	0.435
High	85	0.500
Positive alpha (+α)	100	0.550

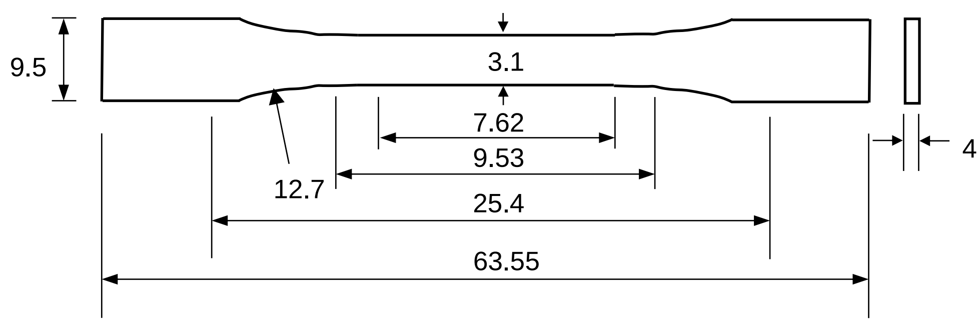

Fig. 4 ASTM D638 Type 5 samples used for tensile test (Units: mm).

4.2 Shot peening

Shot peening is a surface treatment process widely used to improve fatigue strength of metal parts by inducing compressive residual stresses in surface layers. In order to have control of shot peening in metals, industry depends on the use of an "Almen gauge" introduced by J.O. Almen. Rectangular steel strips of controlled composition and thermal history are peened while being held flat. Deflection on release from the sample holder is measured. This deviation is the "Almen arc height" and is indicative of the amount of residual stresses in the subsurface. This arc height is used to plot a saturation curve. The saturation curve is plotted with the Almen strip deflection as a function of peening time. This curve indicates the point at which deflection in the material does not change by more than 10%, even if the peening time/peening pressure is increased. Since Almen strips pertain strictly to metals, the term pseudo-Almen strip was used to describe MIP-SLA printed polymer strips used to determine saturation. The geometry of the pseudo-Almen strip is presented in **Fig. 5** and is geometrically based on a standard Almen strip from Electronics Inc.

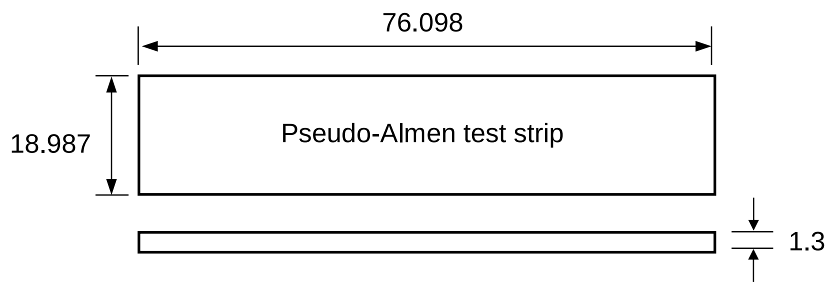

Fig. 5 Pseudo-Almen strip geometry used to determine saturation by shot peening an MIP-SLA polymer (all dimensions are in mm).

There exist a standard procedure for finding the saturation point for metals. In the case of polymers, there is no standard defined for shot peening. Without a standard procedure, a methodology similar to metals was implemented to find the saturation curve for polymers. Pseudo-Almen strips were printed on the B9 creator and shot peened. The deflection of the pseudo-Almen strips was measured using images taken with a Nikon D3200 DSLR camera and analyzed using image processing techniques in AutoCad software. Pseudo-Almen strips were shot peened with glass beads from 10 to 25 passes in increments of 5 passes at a constant maximum air pressure of 85 psi with the gun nozzle one inch from surface.

At these shot peening parameters, there was no visual deflection observed in the pseudo-Almen strips. Since deflection is required to plot a saturation curve, the shot peening media was changed to steel since steel beads provide greater impact energy to impart compressive stresses. Coverage was also increased to 60 passes using the same shot peening parameters described previously. Even with increased coverage and steel beads, there was no visual deflection in the pseudo-Almen strips (**Fig. 6**). In order to determine if the material had any ability to plastically deflect, a strip was shot peened for a set time of 5 minutes with steel beads at maximum pressure with the nozzle directly on the material's surface. Still, there was no deflection observed in workpiece. The material was too flexible. The hyper elastic nature of the material prevented permanent plastic deformation.

Fig. 6 Pseudo-Almen strips before and after shot peening. No deflection was observed.

As there was no deflection observed under any shot peening parameters for this photopolymer, a saturation curve obtained for ABS material was used. Using this saturation curve, the ASTM samples were shot peened on both sides for 20 passes using steel beads with one pass defined as full coverage; the shot peening nozzle was kept 0.5 inch from the sample.

4.3 Tensile Testing

Ultimate strengths of shot peened ASTM D638 Type 5 samples were measured using an MTS 810 tensile tester (see **Fig. 1**). The grips of tensile tester were tightened and aligned between the two grips of unit. A computerized load cell located in the grips of the tensile tester measured applied force to the gauge section of the samples. To calculate strain, the distance between the grips was measured for each sample, and elongation was obtained from computer software. Engineering stress was calculated by dividing the force applied on the sample with the cross-sectional area. The cross-section for each sample was measured using digital vernier calipers. Each measurement was repeated three times and the average value was reported.

5. Results

5.1 Effect of Process Parameters on Build Quality

An analysis of variance (ANOVA) was performed on the tensile strength of the ASTM D638 Type 5 samples. **Fig. 7** represents the interaction plot for ultimate tensile strength (UTS). Based on the interaction plot, the best print settings that provided the highest UTS were using a 45-micron layer height along with a UV sensitivity factor of 0.370. It can be concluded that by increasing the UV sensitivity, the UTS generally decreased.

As per the ANOVA results in **Table 2**, layer thickness was the only parameter that had a statically significant effect on cross-sectional area with a *P*-value less than 0.05. The *P*-value for both layer thickness and UV sensitivity were greater than 0.05 indicating the two parameters did not have any combined effect on UTS of polymer parts. That is, no factor significantly affects the UTS with 5% significance level.

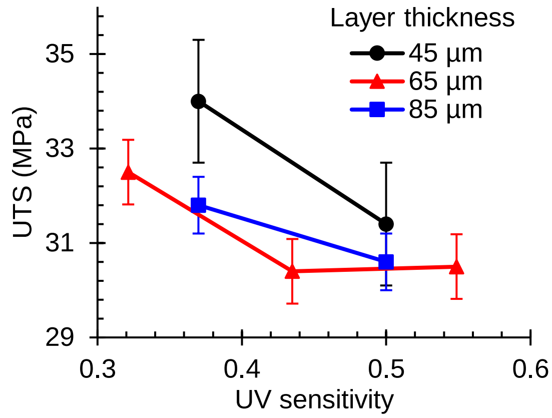

Fig. 7 Interaction plot for ultimate tensile strength of ASTM D638 Type 5.

Table 2 ANOVA Results Evaluating the Effect of Layer Height and UV sensitivity on Cross-Sectional Area and Ultimate Tensile Strength

	Cross sectional area					Ultimate tensile strength					
Source	DF	Seq SS	Adj SS	Adj MS	F	P	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	2	0.415	0.415	0.207	11.22	0.005	2	5.500	5.500	2.750	1.86	0.218
Linear	2	0.415	0.415	0.207	11.22	0.005	2	5.500	5.500	2.750	1.86	0.218
Layer thickness	1	0.414	0.414	0.414	22.36	0.001	1	0.117	0.117	0.117	0.08	0.785
UV sensitivity	1	0.001	0.001	0.001	0.08	0.785	1	0.117	0.117	0.117	0.08	0.093
Residual error	8	0.148	0.148	0.018			8	11.85	11.85	1.481		

5.2 Effect of Shot Peening on Mechanical Properties

The ultimate tensile strength (UTS) of shot peened ASTM D638 Type 5 samples were measured using an MTS 810 tensile tester. The surface was shot peened according to the procedure identified in Section 4.2. From the design of experiments mentioned above, eleven different ASTM D638 samples were printed on the B9 creator using Monocure blue resin. Each sample was repeated three times and the average results were reported.

Fig. 8a shows a comparison of the UTS for shot peened and non-shot peened samples with respect to layer height. From this figure, it can be observed that for most of the samples (except at a layer height of 30 µm), shot peening reduced the UTS as compared to the non-shot peened case. The dashed lines indicate the grand means. The difference between shot peened and non-shot peened samples was dependent on layer thickness. At lower layer thicknesses, this difference was greater compared to the 85 µm and 100 µm layer thicknesses.

Similarly, the variation of ultimate tensile strength with UV sensitivity is shown in **Fig. 8b**. Here also, shot peened samples exhibited a decrease in tensile strength for most of the samples. Generally, the difference between shot peened and non-shot peened samples decreased as the UV sensitivity increased. The exception where shot peening improved the UTS was at a UV sensitivity of 0.5.

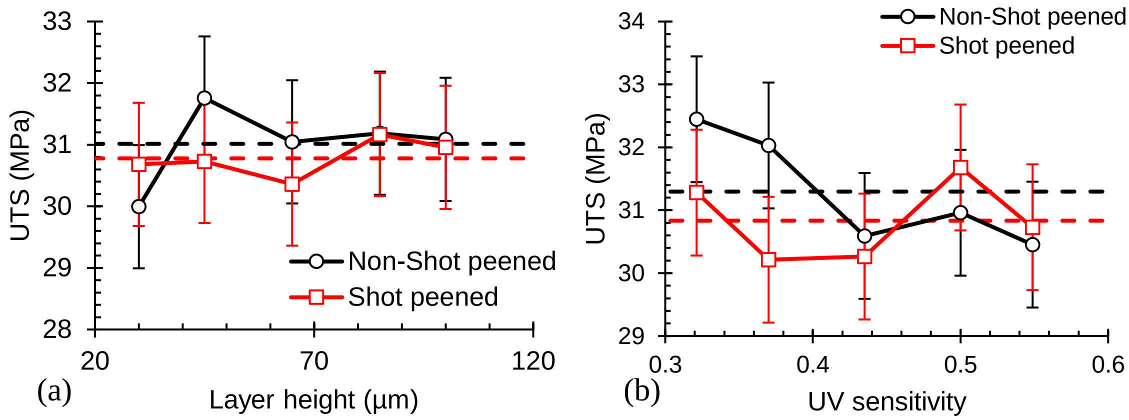

Fig. 8 Ultimate tensile strength *vs*. (a) layer height and (b) UV sensitivity for shot peened and non-shot peened MIP-SLA printed samples.

With respect to both layer height and UV sensitivity, the average tensile strengths of samples decreased compared to non-shot peened samples. This may be due to damage introduced to the samples by shot peening. Beads travelling at high velocities may have caused damage in the form of micro-cracks on the surface of the material rather than inducing favorable compressive residual stresses. Furthermore, it was interesting that some printing parameters were able to see improvements to strength after shot peening. The mixed results indicate that further investigation is needed on multiple polymer systems in order to draw wider conclusions related to the effect of shot peening on 3D printed polymers.

So to find the effect of shot peening on polymer parts, ANOVA was performed on all printing conditions of both shot peened and non-shot peened samples. **Table 3** below represents the ANOVA test on these two groups. Per the large *P*-value (0.074), which is greater than the accepted rate of 0.05, application of shot peening did not significantly improve or deteriorate the UTS of MIP-SLA parts. More data or a wider confidence level is needed to draw solid conclusions regarding the effects of shot peening on additive polymer parts.

Table 3 One-way ANOVA Comparing UTS of Shot Peened and Non-shot Peened Samples

Source	DF	SS	MS	F	P
Factor	1	6.22	6.22	3.29	0.074
Error	60	113.28	1.89		
Total	61	119.5			

6. Summary & Conclusions

Shot peening of pseudo-Almen strips made of a photopolymer using mask image projection stereolithography (MIP-SLA) did not cause any measurable deflection. This may be because shot peening did not induce any residual stresses because the work piece to hyper elastic. Instead, the saturation point of an alternative polymer (ABS) from a parallel project was used to determine the preferred shot peening condition on Monocure blue resin ASTM D638 Type 5 tensile test samples. ANOVA analysis was done to find effect of layer thickness and UV sensitivity. From the analysis, layer thickness affected the cross section of the material. At a lower layer thickness, the layer bonded to previous layers more effectively thus improving dimensional accuracy of parts. ANOVA analysis was also performed on tensile test data of non-shot peened samples. The *P*-value was not less than 0.05 for both process parameters, which indicated that layer height and UV sensitivity did not have a statistically significant effect on tensile strength. This is in contradiction to what was found literature. This contradiction may due to the fewer number of replications used for the experiments that will affect the accuracy of the statistical analysis.

Tensile tests were performed on shot peened samples, and results indicated that the average ultimate tensile strength (UTS) of shot peened samples was less than the non-shot peened samples. An ANOVA analysis compared all the non-shot peened samples with all shot peened samples. From the analysis, it was found that the *P*-value was not less than 0.05 implying that shot peening did not have a statistically significant effect on the UTS. Based on the results, the effect of shot peening on the strength is inconclusive, but generally it will decrease. More studies using a wider variety of materials and printers as well as an investigation in to damage mechanisms on polymers from shot peening is needed.

7. Acknowledgments

Undergraduate and graduate students conducted this research as a course project in MECH 498/898: Additive Manufacturing at the University of Nebraska-Lincoln (UNL). The authors would like to acknowledge the support of the Department Chair in Mechanical and Materials Engineering at UNL, Dr. Jeffrey Shield, for enabling Drs. Rao and Sealy to develop a research-based course in additive manufacturing in order to spur more undergraduate involvement in research.

8. References

[1] Saleh, N., Hopkinson, N., R.J.M. Hague, Wise, S., 2004. Effects of electroplating on the mechanical properties of stereolithography and laser sintered parts, Rapid Prototyping Journal, 105, pp. 305-315.

[2] Zarringhalam, H., Hopkinson, N., 2003. Post-Processing of Duroform Parts for Rapid Manufacture, Solid free form fabrication symposium, University of Texas-Austin, pp. 596-606.

[3] Fuentes, F., Gallardo Jr, A., Martinez, J., Bulman, J., Foyos, J., Mendelson, M., Noorani, R., Fritz, B., 2002. Effects of Cryogenic Aging on a Rapid Protoyped polymer, International Solid Freeform Fabrication Symposium, Austin, Texas, pp. 115-123.

[4] Jackson, J., Chapple, G., Do, J., Zhuang, X., Bulman, J., Foyos, J., Mendelson, M., Noorani, R., Fritz, B., 2003. Effects of Cryogenic Processing on Rapid Prototyping Materials, International Solid Freeform Fabrication Symposium, Austin, Texas, pp. 607-615.

[5] Wang, W.L., Cheah, C.M., Fuh, J.Y.H., Lu, L., 1996. Influence of process parameters on stereolithography part shrinkage, Materials & Design, 174, pp. 205-213.
[6] Chockalingam, K., Jawahar, N., Chandrasekhar, U., 2006. Influence of layer thickness on mechanical properties in stereolithography, Rapid Prototyping Journal, 122, pp. 106-113.
[7] Campanelli, S.L., Cardano, G., Giannoccaro, R., Ludovico, A.D., Bohez, E.L.J., 2007. Statistical analysis of the stereolithographic process to improve the accuracy, Computer-Aided Design, 391, pp. 80-86.
[8] Chartier, T., Dupas, C., Geffroy, P., Pateloup, V., Colas, M., Cornette, J., Guillemet-Fritsch, S., 2017. Influence of irradiation parameters on the polymerization of ceramic reactive suspensions for stereolithography, Journal of the European Ceramic Society, pp. 1-6.