TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 68, Issue Special I, May, 2025

SIZE AND BUILD ORIENTATION EFFECT ON THE TENSILE PROPERTIES OF POLYMERS MANUFACTURED THROUGH STEREOLITHOGRAPHY

Alexandru COȘA, Alexandra USUSAN, Cristian COSMA, Dan ȘERBAN

Abstract: *This study aims to investigate the geometry scale effect and printing orientation on the tensile properties of common photosensitive resins produced via stereolithography (SLA). Through tensile tests, the research evaluates how variations in part size and orientation on the build-platform influence mechanical performance, with a particular focus on challenges in scaling SLA technology for practical applications. By analyzing the interaction between printing parameters relative to tensile forces and resulting mechanical properties, this study provides insights into optimizing SLA processes for enhanced tensile strength and stiffness. The results contribute to understanding how SLA can evolve from prototyping to reliable production of functional parts, offering supplementary insights in additive manufacturing.*
Keywords: *Stereolithography, 3D printing, Size Effect, UV curing, Tensile tests*

1. INTRODUCTION

Additive manufacturing is broadly known as a process suitable for transforming digital models into parts by depositing and solidifying material layer by layer [1]. It still revolutionizes industries such as automotive [2], aerospace [3], healthcare [4] and education [5], with convenient advantages such as reduced production time, more design freedom compared to conventional methods and great representations of different details or critical sections of the very complex parts [6]. From a wide range of 3D printing technologies, stereolithography (SLA) stands out for its capability to achieve high-resolution parts by curing photosensitive resin with a light source, obtaining precise components with smooth finishes and intricate geometries [7].

Stereolithography is widely used for the great surface quality and a broad range of possible materials to choose from, combined with a very lucrative and low defect rate for the prints. The first step in prototyping is to create a digital model, sliced into thin cross-sections that guide the laser's path, in this case, a software called PreForm$^{@}$ is used and it very intuitive and user-friendly so all the steps that take a 3D element and create the ready to print part are in concise order [8]. As a layer is cured, the build platform moves incrementally until the object is fully formed. SLA is particularly favored for applications requiring high-resolution prototypes and more compact volume.

Most common parts and samples investigated are on a small scale as the technology is limited in dimensions and bigger manufacturing equipment also comes with an exponential increase in costs, thus the question remains if the findings can be extrapolated for larger counterparts and if there is something affecting the process scalability. The main reason for this is that there are not so many studies on the size effect on resin samples manufactured through stereolithography technology [9].

Important aspects when designing 3D-printed parts are orientation on the build platform and the size effect, which describes how mechanical properties vary with the dimensions of the printed specimen [10]. More commonly, the trends in the industries are to shift from small prototype components to larger parts, thus understanding size-dependent behaviors becomes essential for ensuring reliable performance in different areas of use [11], with smaller specimens exhibiting higher strength due to a narrower area that is cured on each layer and reduced chances of flaws, with a more controlled manufacturing process, including reduced exposure time to photopolymerization rays and better stability of the specimen on the build platform, along with a lower number of support elements needed for creation, whereas larger samples can have more defects that alter load-bearing capacity [12]. Although the layer thickness is lower than 0.1mm, and normally SLA manufacturing cures one layer simultaneously, there can be observed some irregularities and defects in larger parts. Due to uneven distribution of stresses during curing, warping or shrinkage can be observed in unsupported regions or in very thin areas [13]. These behaviors highlight the importance of considering specimen dimensions during testing and product development to optimize both the manufacturing process and part quality, along with the optimal orientation of the parts to achieve the best performance for the desired mode of use.

An important consideration in additive manufacturing is the orientation of the specimens on the build platform, along with the parameters used for the printing [14]. Research has shown that specimen dimensions can significantly influence material behavior, such as tensile strength and deformation characteristics, and in particular case of SLA technology, there is also the after-processing factor of curing that has a considerable influence on the final properties (both as temperature and time of cure) [5, 15]. This phenomenon may arise from factors like surface-to-volume ratio, distributions of micro-porous areas and defects and various uncompleted cure areas between layers because of micro-defects on lenses or hardened particles in the resin tank. Understanding how size of specimens impacts tensile properties is critical for ensuring scalability and reliability for practical applications [16]. However, studies on this topic remain limited, particularly for SLA-fabricated resins.

In this study, an in-depth analysis is undertaken, considering the behavior of SLA printed specimens and the influence of the orientation on the platform, along with the influence of the size of the sample. Considering the variation of the properties with the sample dimension, the goal is to determine the variation that can be used in future research and can compensate for the size differences between prototyped parts. For this study, only one curing setting was used as post-processing for all the batches of samples: a 10 min cure at ambient temperature (23°C).

2. MATERIALS AND METHODS

Figure 1 represents an SLA printer (Formlabs Form 3+[@]) that consists of a resin tank that can hold various types of liquid photopolymer resin, specially designed for different applications. The printing process involves a build platform, situated above the resin tank that gradually moves vertically while lifting the printed object out of the resin tank as each layer is cured.

The Form3+ uses a 250mW laser as light source, with 405nm wavelength (UV) to cure liquid photopolymer resins objects layer by layer. The laser is a very important part of the system of mirrors and lenses which are part of the light processing unit (LPU) of the printer. With a very efficient laser, prototyped parts attain a high resolution of the surface as the laser spot can be on the order of microns [17]. Another particularity of Formlabs printers is that, unlike traditional SLA systems where lasers are fixed, the LPU in them moves beneath the flexible resin tank. The LPU physically moves along a rail system under the resin tank, sweeping the laser beam across the print area in a linear path. This movement reduces peel forces during layer separation, which is critical for maintaining part accuracy and minimizing defects [18].

Fig. 1. Form 3+ SLA printer (formlabs.com)

The photosensitive resin used to manufacture the specimens (White V4[@]) has the chemical composition defined by the manufacturer as: Urethane Dimethacrylate (55-75%), Methacrylate Monomer(s) (15-25%), Ethyl phenyl (2,4,6-trimethylbenzoyl) phosphinate (<1%), and Table 1 presents the properties from the material datasheet [19, 20]. The resin manufacturer recommends it for general-purpose applications, such as household applications, functional prototypes, various housings and holders and other end-user parts. The literature survey of recent advances in additive manufacturing field showed variations in mechanical properties (in the range of 20-40%, depending on the parameters used [21]) thus further analysis is reasonable to have a better overview on possible causes.

Table 1

Material properties from the datasheet

	Green	**Post-Cured**
Tensile Properties		
Ultimate Tensile Strength	38MPa	65MPa
Tensile Modulus	1.6GPa	2.8GPa
Elongation at Break	12%	6%
Flexural Properties		
Flexural Modulus	1.3GPa	2.2GPa
Impact Properties		
Notched Izod	16J/m	25J/m
Thermal Properties		
Heat Deflection Temp. @ 1.8 MPa	43°C	58°C
Heat Deflection Temp. @ 0.45 MPa	50°C	73°C

* "Data was obtained from parts printed using Form 2, 100 µm, Clear settings and post-cured with 1.25 mW/cm² of 405 nm LED light for 60 minutes at 60 °C [20]".

Before the curing was performed in the Form Cure machine, the specimens were cleaned in isopropyl alcohol (IPA) for 5 minutes to remove the excess resin and soften the areas of contact where the supports are joined to the part. The cleaning process was done in a Form Wash machine where the specimens were immersed in IPA and an integrated impeller agitated and thoroughly cleaned them inside the tank. The curing process was performed under UV light (405nm) for 10minutes, as for this study the focus was the orientation and the size effect, not the post processing parameters.

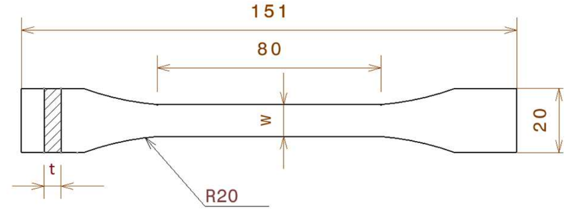


Fig. 2. Tensile specimen dimension for nominal scale, mm

The Formlabs White V4 resin specimens were manufactured according to the standard for plastics ISO 527-2 [22] with the nominal dimensions presented in Figure 2. The specimens were arranged in 3 different positions on the build platform (each corresponding to a different coordinate axis) and noted as "x", "y", "z" according to the direction (Figure 3a).

In Table 2, the different dimensions of the calibrated region cross section of the investigated specimens are presented.

Table 2

Dimensions of specimens in the calibrated region

Specimen	**Thickness t [mm]**	**Width w [mm]**
V1	4	12
V2	4	10
V3	4	8
V4	2	6
V5	2	5
V6	2	4

An important aspect to consider when curing SLA specimens is the arrangement inside the curing machine (see Figure 3b) as all the specimens need to be evenly spaced and well arranged to get enough exposure and to avoid shadowing effects from adjacent samples.

a b

Fig. 3. Arrangement: a. on the build-platform, b. inside curing machine and representation of different scaling dimensions

In the PreForm@ software, an alignment was created for all the specimens on the build platform. As the platform is restricted to a volume of 145x145x185 mm, several prints were needed to manufacture all 90 specimens (5 pairs of each one of the 6 different sizes, all on 3 orientations). In Figure 4, support parameters are presented, along with the layer thickness and a visualization of one print with 1865 layers and a printing time of more than 10hours.

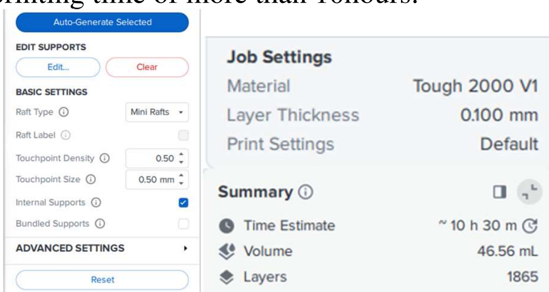


Fig. 4. Settings of slicer software

3. EXPERIMENTAL PROCEDURES

The tensile tests were performed on a Zwick Roell Z005 testing machine (Figure 4a), with an integrated 5kN load cell. An incremental extensometer (Figure 4b) with an initial gauge length of 30mm was used to measure the strain of the specimens as the crosshead moved with 5 mm/min at room temperature (23°C).

a b

Fig. 5. Zwick Roell Z005

The evaluation is focused on the influence of the principal axis alignment on the platform and the influence of the size of the specimen on the final properties. Although there are more parameters that will affect the results, these are the first ones that are affecting the parts in terms of manufacturing process.

As the cross-section of the calibrated region was scaled (Table 2), there is a critical difference between the V1…V3 and V4…V6 specimen preparation, the larger ones being prepared according to 1A dimensions and the smaller specimens according to 1BA dimensions of the ISO-527-2:1996 standard.

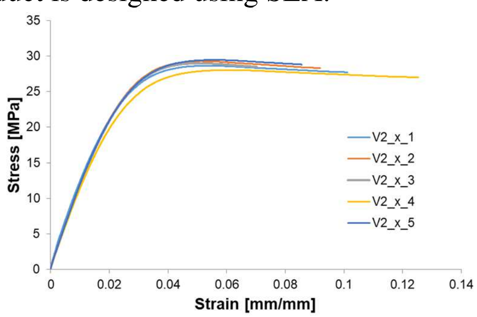
Regarding dimensional stability, there were some aspects that need to be mentioned, as the dimensions for V4…V6 specimens were at a thickness of 2.35mm when placed on the build platform, and 2mm when the orientation was along “z” direction (in height). This variation was caused by the auxiliary “supports” needed on the platform.

Figure 5 depicts the specimens after the test was performed. Most of the specimens have exhibited similar behavior under load and the failure occurred between the extensometer’s blades.

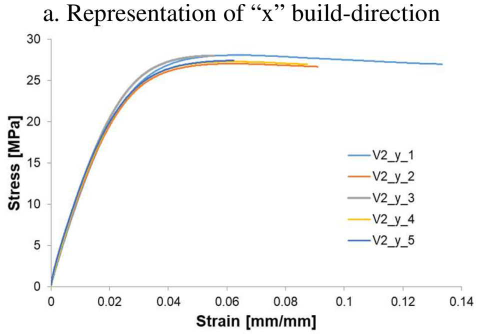
Fig. 6. Specimens after tensile test for size “2”

4. RESULTS AND DISCUSSIONS

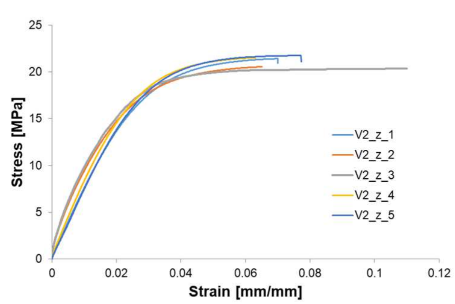
In Figure 6, the stress-strain curves of the investigated specimens are represented: along the x-direction (a), y-direction (b) and z-direction (c). The variation is similar between Figure 6a and 6b, as the specimens were created with the arranged parallel to the build platform, and perpendicular to each other, with an average difference of 1.3MPa or 4,7%. Although the results for this sample present a small difference when compared to the values of the material datasheet, the results are still valid because of the vatiations of the post-process parameters, this is why the curing time and temperature are important and need to be considered if a specific product is designed using SLA.



a. Representation of “x” build-direction



b. Representation of “y” build-direction

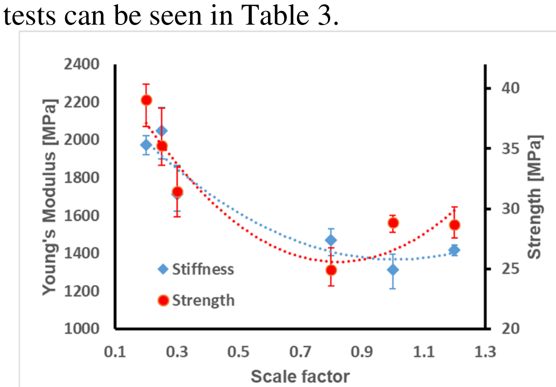


c. Representation of “z”build-direction

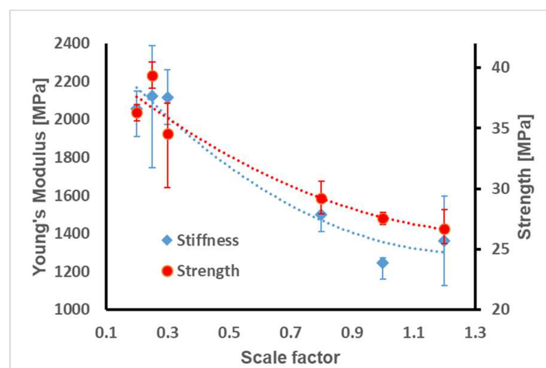
Fig. 7. Stress-strain curves for different orientation on the build-platform for the same size of specimen

Another observation, in regards to the orientation perpendicular to the build-platform (or along “z”axis), with lower results in strength (Figure 6c). The maximum strength and stiffness for each direction are represented in Figure 7 a, b, c, with a visible dependency on the size of the specimen.

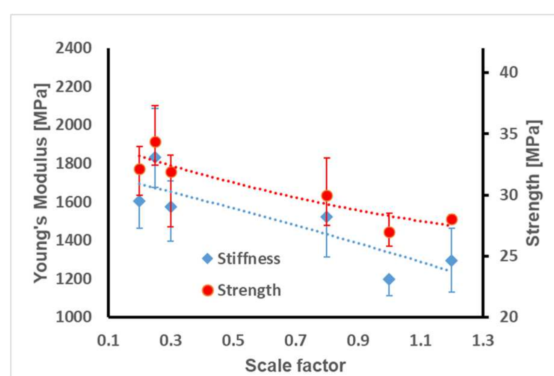
Increasing the size of the specimens leads to a decrease in their properties, with a similar trend for each orientation. The difference between strength and stiffness obtained for the tests can be seen in Table 3.



a. Variation for “x” build-direction



b. Variation of “y” build-direction



c. Variation of “z”build-direction

Fig. 8. Strength and Stiffness representation for various geometry of specimens

The elongation at break was somehow similar between "x" and "y" build orientations, but the results showcased a decreased elongation for the specimens that were built on "z" direction, highlighting the fact that for this specific application, the ductility decreases with different orientations. This behavior was also observed in other research [23] and one of the most common causes is the layer thickness that creates a weaker interlayer adhesion, as each layer was cured after the previous one, thus the bigger the layer is, the lower is the number of interfaces and the results can decrease the ductility and the parts are more prone to brittle failure. Also, the anisotropic behavior was observed and is in sync with current research in the field of additive manufacturing [24] as the specimens had different properties when the orientation was changed, this is also a reason of the lower ductility along "z" axis, along with lower elongation at break. These findings have an important role in developing the ideal orientation and size ratio of a product, considering the specificity of the application it is designed to and there are more parameters to be considered if a product manufactured through 3D printing is used.

Table 3

Experimental values of specimens

Nr.	Stiffness [MPa]	Strength [MPa]	% in variation of the values	
			Stiff.	Strength
V1_x	1416.74	28.66	3.7	4.5
V2_x	1315.51	28.87	6.8	2.4
V3_x	1469.01	24.92	4.5	6.2
V4_x	1713.45	31.41	6.9	6.6
V5_x	2048.5	35.25	6.5	6.7
V6_x	1973.92	39.08	2.5	4.5
V1_y	1362.17	26.71	17	5.2
V2_y	1247.62	27.55	4.4	1.8
V3_y	1499.46	29.24	5.5	4.6
V4_y	2115.06	34.53	6.7	9.5
V5_y	2124.49	39.33	14.5	2.7
V6_y	2057.75	36.29	5.6	1.8
V1_z	1296.59	28.05	9.1	0.9
V2_z	1197.56	27.01	3.5	4.8
V3_z	1523.69	30.05	9.6	9.5
V4_z	1575.43	31.88	9.8	8.1
V5_z	1831.38	34.34	10.1	6.9
V6_z	1605.41	32.12	8.8	6.2

5. CONCLUSIONS

This researched focused on the impact of orientation of the specimens, combined with the size effect on the mechanical properties of Formlabs White V4 resin, with a specific emphasis on tensile strength and stiffness. Systematic experiments were conducted to evaluate how variations in size and orientation affected the material properties of SLA-prototyped specimens.

The experimental results revealed that both strength and stiffness decreased with the size of the specimens, up to a certain point. Beyond this point, an increase in mechanical properties was observed and it concludes that more detailed investigations are needed, but with a wider choice of parameters, combining these findings with different curing times at different temperatures and creating a decisional matrix on the influence of all the parameters involved, thus making this domain worth researching in the future. The difference in the properties was also observed between different orientations, likely due to different interactions between photopolymerized layers.

To conclude, this study highlights the importance of optimization of sample geometry and orientation, combined with a good understanding of curing parameters, to reach the optimal mechanical properties of SLA specific photosensitive resins. By choosing the right dimensions and the optimal orientation on the platform, the mechanical performance of the manufactured parts and serviceability of SLA technology could be significantly improved, obtaining more reliable and scalable 3D printed physical models.

6. ACKNOWLEDGEMENT

This work was partially funded by the Research Grant PN-III-P2-2.1-PED-2021-1134, contract number 586PED/2022.

7. REFERENCES

[1] Gibson, I., Rosen, D., Stucker, B. *Introduction and basic principles in Additive Manufacturing Technologies*, pp

1-18, ISBN 978-1-4939-2113-3_1, Springer Nature Link., Boston, 2010

[2] Dalpadulo, E., Petruccioli, A., Gherardini, F., Leali, F., *A Review of Automotive Spare-Part Reconstruction Based on Additive Manufacturing*, J. Manuf. Mater. Process. , vol. 6, no. 133, 2022.

[3] Getachew, M. T., Shiferaw, M. Z., Ayele, B. S., *The Current State of the Art and Advancements, Challenges, and Future of Additive Manufacturing in Aerospace Applications*, Advances in Materials Science and Engineering, vol. 8817006, p. 13, 2023.

[4] Ling, L., Lai, T., Malyala, R., *Mechanical Properties and Degree of Conversion of a Novel 3D-Printing Model Resin*, Polymers , vol. 16, no. 24, p. 3562, 2024.

[5] Coșa, A.V., Șerban, D.A., Baban, M.V., *Influence of curing time and temperature on the mechanical properties of resins manufactured through stereolithography,* IOP Conference Series: Materials Science and Engineering, vol. 1319, no. 012020, 2024.

[6] D. Șerban, R. Negru, S. Sărăndan, G. Belgiu and L. Marșavina, "Numerical and experimental investigations on the mechanical properties of cellular structures with open Kelvin cells," Mechanics of Advanced Materials and Structures, vol. 28, no. 13, p. 1367–1376, 2021.

[7] Șerban, D., Negru, R., Sărăndan, S., Belgiu, G., Marșavina, L., *Numerical and experimental investigations on the mechanical properties of cellular structures with open Kelvin cells*, Mechanics of Advanced Materials and Structures, vol. 28, no. 13, p. 1367–1376, 2021.

[8] Khoo, H., Allen, H., Arroyo-Currás, W.S., et al., *Rapid prototyping of thermoplastic microfluidic devices via SLA 3D printing*, Scientific Reports, vol. 14, p. 17646, 2024.

[9] Ghosh, M., D'Souza, N., Xu, Y., Nartu, M., Pagadalu, V., Rastegarzadeh, S., Huang, J., *Scalability in SLA lattice through lattice orientation and hybrid frame and plate architectures*, Journal of Materials Research and Technology, vol. 35, no. 2238-7854, pp. 645-659, 2025.

[10] Sadaghian, H., Dadmand, D., Pourbaba, M., Jabbari, S., Yeon, J., *The Effect of Size on the Mechanical Properties of 3D-Printed Polymers,* Sustainability, vol. 16, no. 356, 2024.

[11] Bezzini, R., Bassani, G., Avizzano, C., Filippeschi, A., *Design and Experimental Evaluation of Multiple 3D-Printed Reduction Gearboxes for Wearable Exoskeletons*, Robotics , vol. 13, no. 168, 2024.

[12] Park, W., Kim, M., Lee, H., Cho, H., Leu, M., *In-process layer surface inspection of SLA products*, in Intelligent Systems in Design and Manufacturing, Boston, 1998.

[13] Chouhan, G., Bidare, P., Doodi, R., Murali, G.B. *Identification of Surface Defects on an SLA-Printed Gyroid Lattice Structure*, Design in the Era of Industry 4.0, pp. 978-981-99-0263-7, 300 07 2023.

[14] Miller, Z., Stidham, B., Fairbanks, T., Maldonado, C., *The Use of Stereolithography (SLA) Additive Manufacturing in Space-Based Instrumentation,* IEEE Aerospace Conference, 2023, Big Sky.

[15] Riccio, C., Civera, M., Grimaldo Ruiz, O., Pedulla, P., Rodriguez Reinoso, M., Tommasi, M., Vollaro, M., Burgio, V., Surace, C., *Effects of Curing on Photosensitive Resins in SLA Additive Manufacturing,* Appl. Mech., vol. 2, pp. 942-955, 2021.

[16] Martín-Montal, J., Pernas-Sánchez, J., Varas, D., *Experimental Characterization Framework for SLA Additive Manufacturing Materials*, Polymers , vol. 13, no. 1147, 2021.

[17] Patmonoaji, A., Mahardika, M., Nasir, M., She, Y., Wang, W., Muflikhun, M., Suekane, T., *Stereolithography 3D Printer for Micromodel Fabrications with Comprehensive Accuracy Evaluation by Using Microtomography*, Geosciences , vol. 12, no. 183, 2022.

[18] Formlabs, "Formlabs," 15 10 2024. [Online].Available:https://support.formlabs.com/s/article/Understanding-Light-Processing-Unit-lifetime-Form-4-generation?language=en_US. [Accessed 11 02 2025].

[19] Formlabs, "Safety Data Sheet of White V4 resin," Formlabs, Berlin, 2024.

[20] Formlabs, "Datasheet of White Resin Material," Formlabs, Berlin, 2024.

[21] Valls-Esteve, A., Lustig-Gainza, P., Adell-Gomez N., e. al., *A state-of-the-art guide about the effects of sterilization processes on 3D-printed materials for surgical planning and medical applications: A comparative study,* International Journal of Bioprinting, vol. 9, no. 5, pp. 145-165, 2023.

[22] ISO 527-1, Plastics-Determination of Tensile Properties-part 1: General Principles. International Organization for Standardization; ISO: Geneva, Switzerland, 23, 2012.

[23] Chockalingam, K., Jawahar, N. Chandrasekhar, U. *Influence of layer thickness on mechanical properties in stereolithography*, Rapid Prototyping Journal, vol. 12, no. 2, pp. 106-113, 2006.

[24] Jirků, P., Urban, J., Müller, M., Kolář, V. Chandan, V., Svobodová, J., Mishra, R., Jamshaid, H., *Evaluation of Mechanical Properties and Filler Interaction in the Field of SLA Polymeric Additive Manufacturing*, Materials , vol. 16, p. 4955, 2023.

Efectul dimensiunii și orientării asupra proprietăților mecanice ale pieselor realizate prin stereolitografie

Rezumat: Acest studiu își propune să investigheze efectul dimensional și orientarea epruvetelor în timpul fabricației asupra proprietăților mecanice ale rășinilor fotosensibile produse prin stereolitografie (SLA). Prin teste de tracțiune, cercetarea evaluează modul în care variațiile dimensionale ale pieselor și orientarea acestora influențează performanța mecanică, cu un accent deosebit pe provocările legate de scalarea tehnologiei SLA pentru aplicații practice. Analizând interacțiunea dintre parametrii de fabricație în raport cu forțele de tracțiune și proprietățile mecanice rezultate, acest studiu oferă perspective asupra optimizării proceselor de fabricație aditivă prin SLA pentru îmbunătățirea rezistenței la tracțiune și a rigidității. Rezultatele contribuie la înțelegerea modului în care tehnologia SLA poate evolua de la prototipare la producția fiabilă a pieselor funcționale, oferind perspective suplimentare în domeniul fabricației aditive.

Alexandru-Viorel COȘA, PhD student, Politehnica University of Timisoara, Materials and Manufacturing Engineering, alexandru.cosa@student.upt.ro, +40761249347, B-dul Mihai Viteazu nr. 2, 300222 Timisoara, Romania.

Alexandra-Florina USUSAN, Eng., Politehnica University of Timisoara, ususan.alexandra @yahoo.com, Bdul Mihai Viteazu nr. 2, 300222 Timisoara, Romania.

Cristian COSMA, Assoc. Professor, Politehnica University of Timisoara, Materials and Manufacturing Engineering, cristian.cosma@upt.ro, Bdul Mihai Viteazu nr. 2, 300222 Timisoara, Romania.

Dan-Andrei ȘERBAN, Professor, Politehnica University of Timisoara, Department of Mechatronics, dan.serban@upt.ro, Bdul Mihai Viteazu nr. 2, 300222 Timisoara, Romania.