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EXPERIMENTAL MECHANICAL CHARACTERIZATION OF PARTS MANUFACTURED BY SLA AND DLP TECHNOLOGIES

EKSPERIMENTALNA MEHANIČKA KARAKTERIZACIJA DELOVA PROIZVEDENIH SLA I DLP TEHNOLOGIJAMA

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Ključne reči
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- SLA
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- ABS smola
- mehaničke osobine

Abstract

Since the beginnings of additive manufacturing (AM) in the 1980s, vat polymerization was the first and most intensively developing technology that enabled the production of very precise parts from photosensitive polymer resins. One of the most studied polymer materials is acrylonitrile butadiene styrene (ABS), but mostly in the form of filaments for the FDM (Fused Deposition Modelling) process. The objective of this research was to investigate in detail the mechanical properties of ABS resin specimens fabricated by stereolithography (SLA) and digital light processing (DLP). Specimen geometries were based on standards for tensile, three-point bending, and compression tests. By combining deformation and mechanical tests with optical microscopic analyses of the morphology and fracture surface structures, as well as Shore A hardness measurements, a deeper insight into the behaviour of commercially available ABS resins was gained.

Izvod

Od početaka razvoja aditivne proizvodnje (AM) osamdesetih godina prošlog veka, polimerizacija u kadi je bila prva i najintenzivnije razvijana tehnologija koja je omogućila proizvodnju veoma preciznih delova od fotoosetljivih polimernih smola. Jedan od najviše proučavanih polimernih materijala je akrilonitril butadien stiren (ABS), ali uglavnom u obliku filamenata za FDM (Fused Deposition Modelling) proces. Cilj ovog istraživanja je detaljno ispitivanje mehaničkih svojstava uzoraka ABS smole proizvedenih stereolitografijom (SLA) i digitalnom obradom svetla (DLP). Geometrije uzoraka su zasnovane na standardima za ispitivanje na zatezanje, savijanje u tri tačke i na pritisak. Kombinovanjem deformacionih i mehaničkih ispitivanja sa optičkim mikroskopskim analizama morfologije i strukture površine loma, kao i merenjem tvrdoće po Šoru A, stečen je dublji uvid u ponašanje komercijalno dostupnih ABS smola.

INTRODUCTION

The history of additive manufacturing (AM), also known as rapid prototyping, 3D printing (3DP), or layered manufacturing, began in the 1980s with the introduction of a new concept for the production of customized and complex parts /1/. The first commercialised AM technology was stereolithography (SLA), a vat photopolymerization process enabling the fabrication of very accurate parts from photosensitive polymer resins, /2/. Although six other types of AM technologies have been developed over the years, each using different materials (metals, ceramics, composites, etc.), processes addressing polymer printing have made significant progress. In particular, processes are being investigated and improved, in which liquid starting monomer resins are solidified by a light-induced polymerization reaction, resulting in elements with high resolution and different sizes and thicknesses, /3, 4/. In vat photopolymerization, the liquid monomer solutions or photocurable resins are exposed to radiation - UV light or laser - in a controlled manner, resulting in a chemical-physical reaction that cures the layers and produces a three-dimensional solid polymer material. Vat photopolymerization processes are divided into different categories depending on the light source and the corresponding polymerization mechanism. In addition to SLA, there is also digital light processing (DLP), continuous liquid interface (CLIP), and two-photon polymerization (2PP), which can be used to produce parts with controllable mechanical, chemical, dimensional, and optical properties, /5, 6/.

SLA is a process in which the laser is used as an initiator of polymerization in the layering of photocurable resin. There is a strong correlation between the printing speed on one side, and the depth and light penetration on the other, depending on the material used /7/. In the DLP process, the resin is selectively cured layer by layer, where the part to be printed is projected through a small projector/mirror that displays a single image at a time, unlike SLA, where the exposure is dot by dot /8/. The resolution of the printed part is directly related to the number of projectors/mirrors that printers have.

Mechanical testing of polymeric materials is challenging for certain materials due to their amorphous nature /9/. The properties of the raw materials are not the only factor affecting the mechanical properties of AM parts. Much research has been conducted to improve and establish mechanical performance in terms of AM process properties as well, /10/. Manufacturers have developed standard polymer resins with unique formulations depending on the desired application, and in this way, special light-curable formulations of already well-known polycarbonate, polyester, and polyether polymers have emerged, /11/. Acrylonitrile butadiene styrene (ABS) is one of the most studied and important rubber-curing thermoplastics, used primarily in applications requiring high toughness and surface gloss, /12/. It is most commonly used in the form of filaments in the fabrication of parts using the fused deposition modelling (FDM) process. Research on ABS in the form of resins was conducted in the 1990s, but unfortunately there is a lack of recent literature and research on the mechanical behaviour of this material. ABS is composed of three monomers: acrylonitrile, butadiene, and styrene, and each of these monomers is an important component of these resins that affect the various properties of the material and the parts made from it. Therefore, ABS resins are part of the large family of thermoplastic polymers, /13/. Research on fracture, deformation and flow behaviour has mainly focused on the analysis of the chemically different ABS resins, and on the influence of the different particle size distribution and inter-particle spacing on the properties, /14/.

The present investigations were carried out on specimens made of ABS resin produced on SLA and SLP 3D printers. The objective was to perform tensile, three-point bending and compression tests to obtain detailed mechanical properties of the ABS-like resin material. Optical microscopy provided information on the microstructure of the material and visual differences between the two printing processes. Finally, Shore A hardness testing was performed to compare the properties of the material with its hardness grade.

ADDITIVELY MANUFACTURED SPECIMENS

Two batches of ABS resin material (Creality, Shenzhen, China) are produced, each containing five specimens. The fabrication of the specimens started with 3D modelling in the corresponding software CAD (SolidWorks, Dassault Systèmes SE, Vélizy-Villacoublay, France), after converting the model to STL file format, which is further sliced in the corresponding software (Simplify3D, Cincinnati, OH, USA). The specimens are modelled according to the standards for mechanical testing: ISO 527-2 for tensile testing, ISO 604: 2002 for compression testing, ISO 178:2019 for three-point bending testing. The 3D printers used for fabrication were SLA (Kings 600 Pro, Shenzhen, China) and DLP (Creality LD-002R, Shenzhen, China). Since the specimens were printed on an industrial SLA printer and on desktop DLP printer, the parameters can also be compared in this sense. The infill density of all specimens was 100 %, the infill pattern was grid, and print orientation was 45°. All specimens were printed, stored, and tested at room temperature of 23℃ and humidity of 55 % RH.

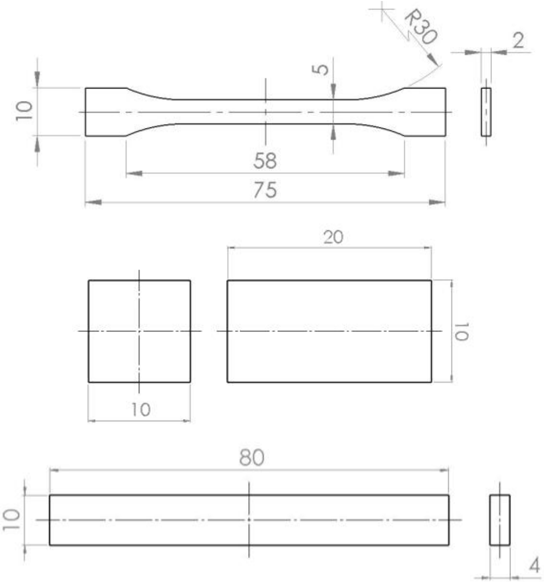


Figure 1. Specimens for mechanical tests: ISO 527-2 tensile test; ISO 604:2002 compression test; ISO 178:2019 three point bending test.

Mechanical testing was performed on the Shimadzu AGS-X universal testing machine (Shimadzu Corp., Kyoto, Japan) equipped with a load cell with a capacity of 100 kN. According to the standards, the testing speed was 1 mm/min.

Optical microscopy was performed to evaluate the structure of the material at the cracked site after the mechanical tests. The microscopic images were taken with a Mustool G600 Digital Portable Microscope (Shenzhen, China).

Measuring the hardness of a particular material provides information about the material’s ability to recover after a force indentation, /15/. The hardness tests were carried out per ASTM D2240 to determine the Shore D magnitude and the measurements were taken 5 times from each surface.

Shore A hardness tests were performed on a commercial hardness measurement device (SAUTER HDA100-1; Conrad, Berlin, Germany) with five indentations in each resin specimen, according to ASTM D2240.

MECHANICAL TESTING AND RESULTS

Vat polymerization printing technology plays an important role in the engineering manufacturing process for plastic parts that are printed for final use. Therefore, it is important to understand how the most inclined build orientation (45°) ensures the longevity of the part, depending on the specific use of the part. This paper focuses on the mechanical properties of the resin material ABS and two 3D printing processes - SLA and DLP.

The analysis of the results is done using Matlab® to process the tables of mechanical properties, originally created by Shimadzu software. The differences in the behaviour of the same material printed by two similar technologies are shown in the stress-strain curves in Fig. 2. Obviously, SLA printed ABS shows a dominant flexural strength in contrast to DLP printed ABS, which shows a dominant compressive strength. Regardless of the type of 3D printing process, tensile strength is not the advantage of ABS resin. The reason for the differences in mechanical properties of ABS resin depending on the printing technology is due to the curing process of the resin. In the case of SLA, the ABS resin is periodically irradiated with UV laser light to build up a dense structure, unlike the DLP process, where the layers are flashed all at once to cure the resin in the resin container.

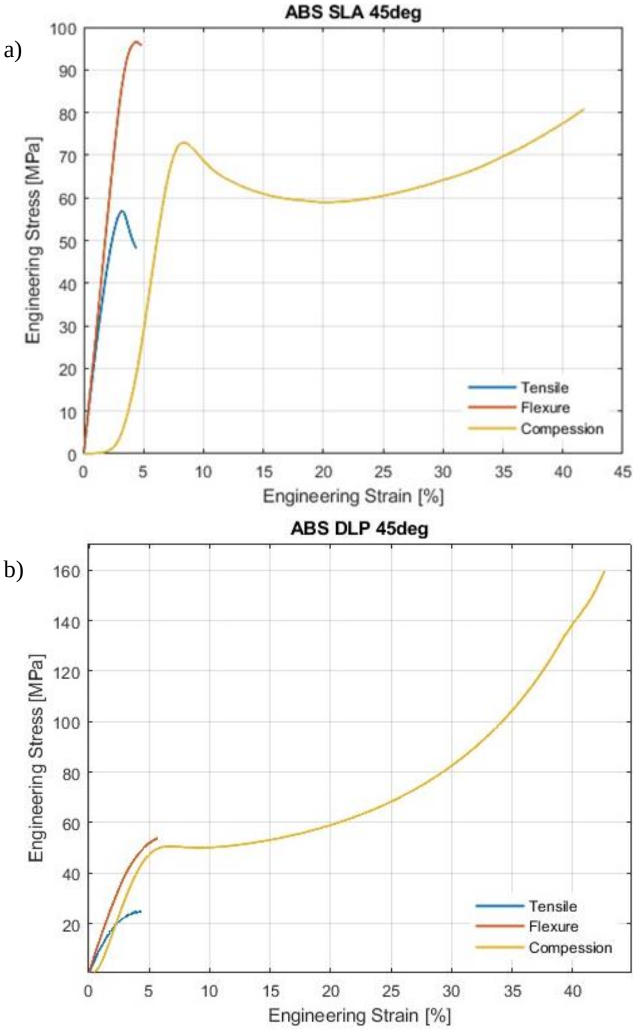
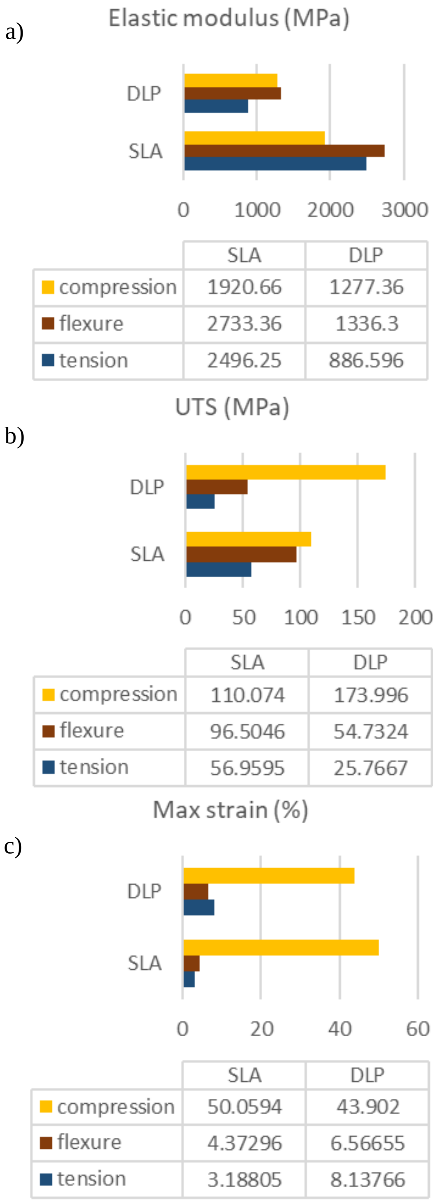


Figure 2. Stress-strain curves for tensile, three-point bending, and compression tests for ABS resin's standard specimens build using: a) SLA; and b) DLP technology.

The mechanical properties of 3D-printed ABS resin on SLA and DLP printers are compared in the graphs in Fig. 3. SLA printed ABS resin shows similarities in elastic modulus values (Fig. 3a), and regardless of the type of testing, SLA produces specimens with higher elastic modulus values compared to DLP specimens. The highest elastic modulus was the flexural modulus, 2733 MPa, in the case of SLA.

A compressive strength of 174 MPa, a flexural strength of 110 MPa, and a tensile strength of 57 MPa are the highest values in their respective categories (Fig. 3b). The tensile and flexural strength are higher for SLA printed ABS resin, and compressive strength is higher for DLP printed ABS resin. Looking at the elongation at yield (Fig. 3c), the highest elongation of 50 % occurred in SLA compression tests. Since the DLP elongation is 44 %, it is obvious that vat photopolymerization can produce 3D printed ABS parts with good compressive toughness. Although the SLA part has higher elongation in compression, the other DLP method is the better choice when parts with tensile and flexural toughness ABS are required.



	SLA	DLP
■ compression	1920.66	1277.36
■ flexure	2733.36	1336.3
■ tension	2496.25	886.596

	SLA	DLP
■ compression	110.074	173.996
■ flexure	96.5046	54.7324
■ tension	56.9595	25.7667

	SLA	DLP
■ compression	50.0594	43.902
■ flexure	4.37296	6.56655
■ tension	3.18805	8.13766

Figure 3. Mechanical properties for ABS resins specimens: a) elastic modulus; b) strength; and c) elongation at yield.

It can be concluded that the respective technology - SLA or DLP - and the performance of the 3D printer - industrial or desktop, appear to play a large factor in the tensile, flexural, and compressive properties of ABS resin material. The significant difference in strength, stiffness, and toughness of the specimens is evident from stress-strain curves in Fig. 2, and mechanical properties in Fig. 3. SLA printed specimens exhibit higher stiffness than DLP specimens in all three tests. In other words, a part made from ABS withstands deformation better when made with SLA technology. DLP technology prints weaker specimens from ABS resin material than SLA technology, especially when subjected to tensile and flexure stresses. Unlike the previous, compression leads to densification of specimens printed with DLP. The ability of the ABS material to absorb energy before failing in tension, three-point bending, and compression is better in SLA printed specimens. The toughness of the ABS resin in changing 3D printing technologies is evident.

Fractured SLA and DLP-printed specimens are shown in Fig. 4 (left), and Fig. 5 (left), respectively. After tensile testing, both batches of specimens exhibit a similar looking brittle fracture in the narrow part of the geometry. Each curved SLA printed specimen loses a piece of itself during snapping and exhibits two levelled fracture surfaces. Each DLP-printed specimen exhibits a clean, cut-like fracture. SLA and DLP-printed specimens do not compress in the same way. SLA retains the outer shell in flakes and fractures inward, exhibiting more ductile behaviour. DLP specimens shatter into sharp splinters and exhibit more brittle behaviour.

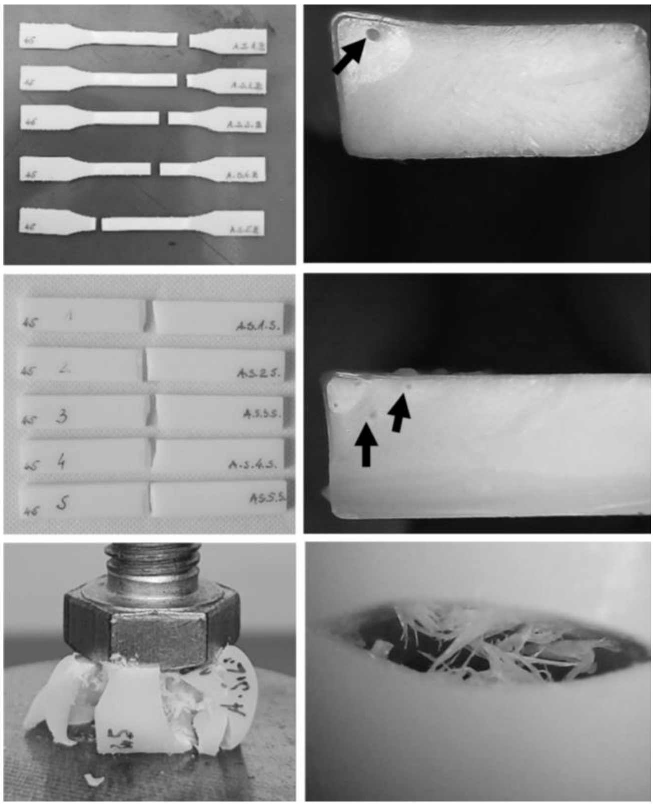


Figure 4. Left: fractured SLA printed specimens; right: fractured surfaces after tensile (first row), three point bending (second row), and compression (third row) testing.

2D images were acquired using digital microscopy and show the fractured surfaces of SLA and DLP-printed specimens in Fig. 4 (right) and Fig. 5 (right), respectively. SLA fractured surfaces have irregularities in the form of bubbles (indicated by arrows in Fig. 4 (right)). During the SLA printing process, some of the two-dimensional bubbles are mixed with the resin and apparently remain inside the vat and are trapped in the cured resin. It can be concluded that such irregularities in broken surfaces prove that the bubbles cause weak spots and initiate cracks. The outer layers also differ in cross-section and show different behaviour, which is particularly noticeable in compression tests.

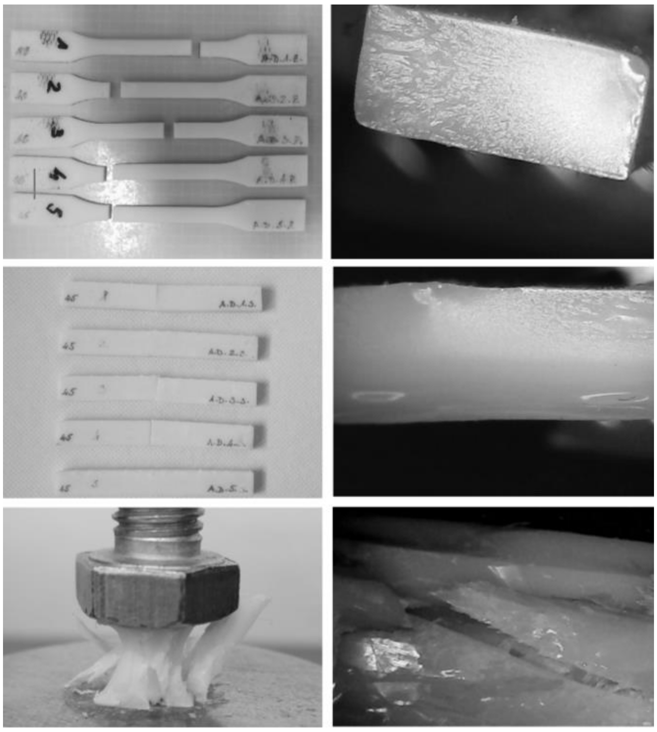


Figure 5. Left: broken DLP printed specimens; right: fractured surfaces after tensile (first row), three point bending (second row), and compression (third row) testing.

In Fig. 5 (right), the striation on the left side transitions to a brittle fracture surface in the centre, which ends by tearing off on the right side of the surface fractured during the tensile tests. After the bending tests, the image of the fractured surface shows the initiation of fracture as a ductile mode and then the transition to brittle mode as a result of initial fretting order, and finally the fracture.

The hardness of ABS specimens for compression tests varies in the range of 85.1 to 87.6 Shore A. The obtained results prove that ABS resin material falls into the hard polymer resin category.

CONCLUSIONS

By combining deformation and mechanical examination, with optical microscopy analyses of morphology and fracture surface structures, as well as Shore A hardness measurements, a deeper insight into the behaviour of commercially available ABS resins is gained.

Overall, the ABS resin processed with SLA technology is stiffer, stronger, tougher, and harder than the ABS resin processed with DLP. The differences in the mechanical properties of the ABS resin in relation to the printing technology are in favour of SLA printing technology in terms of the curing process of the resin, which is periodically exposed to UV laser light, thereby building up a more isotropic structure, compared to DLP technology, which flashes entire layers at a time to cure the resin in the resin tank. It can be concluded that the printing technology has a significant influence on the mechanical properties of the ABS resin material.

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