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A COMPARATIVE STUDY ON THE TENSILE PROPERTIES OF 3D PRINTED ABS FILAMENT AND RESIN: EFFECTS OF AGING

KOMPARATIVNA ISTRAŽIVANJA ZATEZNIH SVOJSTAVA 3D ŠTAMPANOG ABS FILAMENTA I SMOLE: EFEKTI STARENJA

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Keywords
- acrylonitrile butadiene styrene (ABS)
- fused deposition modelling (FDM)
- stereolitography (SLA)
- digital light processing (DLP)
- statistical analysis

Abstract

This study investigates the effects of environmental aging on the tensile properties of 3D printed specimens using Fused Deposition Modelling (FDM), Stereolithography (SLA) and Digital Light Processing (DLP) technologies. Specimens are printed from Acrylonitrile Butadiene Styrene (ABS) filament and ABS-based resin. Tensile testing is conducted on samples directly after printing and then following aging periods of one month and two months in a controlled environment (23 °C, 55 % RH). Statistical analysis is performed using ANOVA to evaluate the influence of the printing method, material type, and aging time on tensile strength, Young's modulus, and elongation at break. The tensile performance of FDM-printed specimens generally decreases over time, which is evident from the comparative analysis. Specimens aged for two months exhibit significantly reduced tensile strength compared to both unaged and one-month aged SLA specimens. Interestingly, one-month aged specimens show a slight improvement in tensile performance compared to unaged samples which is an unexpected outcome. On the other hand, DLP specimens display a clear sensitivity to the aging process, with a marked degradation in performance when subjected to tensile load over time. This highlights a lack of tolerance to aging in DLP 3D printed materials under mechanical stress.

Ključne reči
- akrilonitril butadien stiren (ABS)
- tehnika deponovanja istopljenog filamenta (FDM)
- stereolitografija (SLA)
- digitalno procesiranje svetlosti (DLP)
- statistička analiza

Izvod

U radu se istražuje uticaj starenja u kontrolisanim uslovima na zatezna svojstva uzoraka izrađenih 3D štampom, uključujući tehnikom deponovanja istopljenog filamenta (FDM), stereolitografijom (SLA) i digitalnom obradom svetlosti (DLP). Uzorci su izrađeni od filamenta akrilonitril butadien stirena (ABS) i smole na bazi ABS. Zatezno ispitivanje je sprovedeno na uzorcima neposredno nakon štampe, kao i nakon perioda starenja od jednog i dva meseca u kontrolisanim uslovima (23 °C, 55 % relativne vlažnosti). Statistička analiza je izvršena korišćenjem ANOVA metode radi procene uticaja metode štampe, vrste materijala i trajanja starenja na zateznu čvrstoću, modul elastičnosti i istezanje do loma. Zatezna svojstva uzoraka izrađenih FDM tehnologijom uglavnom opadaju tokom vremena, što je evidentno iz uporedne analize. Uzorci stari dva meseca pokazuju značajno smanjenu zateznu čvrstoću u poređenju sa neostarelim uzorcima i uzorcima starim 30 dana izrađenim SLA tehnologijom. Zanimljivo je da uzorci stari jedan mesec beleže blago poboljšanje zateznih svojstava u poređenju sa neostarelim uzorcima, što je neočekivani rezultat. S druge strane, uzorci izrađeni DLP tehnologijom pokazuju izraženu osetljivost na proces starenja, sa značajnim pogoršanjem svojstava prilikom opterećenja zatezanjem tokom vremena. Ovo ukazuje na nedostatak otpornosti DLP materijala na starenje u uslovima mehaničkih naprezanja.

INTRODUCTION

The growing adoption of additive manufacturing, i.e., 3D printing for both educational purposes and the production of functional end-use components has created a demand for a deeper understanding of the mechanical behaviour of 3D-printed parts. This need highlights the importance of developing advanced analytical tools and design guidelines to support engineers in their work. These methods are perfect for creating unique models, intricately designed parts, or small-batch production. Over time, 3D printing has become widely popular due to its simplicity and the excellent value it offers in terms of cost and performance /1/. 3D printing technology evolves and has a great impact on industrial innovation, highlighting advancements in manufacture, education, research, art, fashion, food and nutrition, healthcare, housing, automotive and aeronautics industry, and biomedicine /2-4/.

This study involves tensile testing of 3D-printed specimens created using FDM, SLA, and DLP processes, using ABS filament and ABS resin. Specimens are tested immediately after printing, and one and two months post-printing. FDM is 3D a printing process where a thermoplastic filament is heated and extruded in layer by layer manner, creating the 3D object. It is popular due to its affordability, using a continuous filament fed into the extruder which melts the material and deposits it precisely onto the build platform. The printed object is constructed from outer walls and internal structures, with varying infill patterns and densities tailored to the design /5/. SLA is a method that uses light-sensitive resin, which is cured layer by layer using a laser beam. The resin-filled container submerges the print bed, and the laser traces the object's shape, curing each layer before the bed moves up for the next. While SLA offers high precision, it is limited by a smaller print area, though it remains relatively unaffected by external environmental factors /6/. DLP, is a technique similar to SLA, involving the curing of light-sensitive materials using light emitted by a projector. The difference is that DLP creates models by curing the whole layer at a time, and in SLA, the laser beam moves from point to point, tracing the geometry /7/.

3D printing is used not only for prototyping, but also to fabricate functional, end-use components. This is achieved through a range of materials, including polymers, metals, composites and ceramics, and various printing techniques suited to each material type /8/. Polymers are among the most frequently utilised materials in 3D printing processes. Utilised in long-term industrial applications polymers are susceptible to aging which can significantly degrade their material properties and overall performance, /9/.

ABS is a thermoplastic characterised by a low glass transition temperature (approximately 105 °C), enabling rapid solidification. It offers moderate strength and performance, making it an economical choice for a wide range of applications, /10/.

Regarding mechanical examination, tensile testing is an important method for evaluating the mechanical behaviour and reliability of printed components, particularly for engineering and industrial applications. The tensile strength, Young's modulus, and strain at fracture can vary significantly based on factors such as print orientation, infill density, and the presence of internal voids. Zhang et al. have shown that print orientation affects mechanical properties, i.e., specimens printed in the 0° orientation demonstrate higher tensile strength compared to 45° and 90° orientations due to better layer-to-layer adhesion in the loading direction /11/. Riffugiato et al. demonstrated that tensile strength in 3D-printed ABS parts is affected by internal voids and underscores the importance of porosity analysis in predicting potential failure points /8/. Another study shows that internal voids and porosity significantly reduce the tensile strength of ABS parts /12/. However, in this research tensile testing is done on aged specimens in order to evaluate the time passing on the mechanical properties of ABS filament and resin materials.

Photodegradation of ABS is investigated under UVB radiation and oxygen at 45 °C. ATR-FTIR analysis reveals that degradation is spatially homogenous /13/. Gawali and Jain investigate how natural aging affects the mechanical properties of 3D-printed ABS tensile specimens exposed to outdoor conditions (sunlight, moisture, and temperature) for 12 months and compares them to unexposed control specimens. They find that aging leads to a slight reduction in tensile strength (up to 4 %) for X-build orientation and a significant reduction (up to 18 %) for Z-build orientation. Surface analyses reveal microstructural changes and increased surface roughness due to aging /14/. A study by Amza et al. investigates how accelerated aging affects the mechanical properties, including tensile strength. The conclusion is that accelerated aging significantly reduces the tensile strength of 3D-printed ABS specimens, with UV-B exposure causing notable degradation. The findings emphasise the need for protective measures and material selection when 3D printing parts intended for long-term outdoor use /15/.

The aim of this research is to provide a comparative analysis of the mechanical performance of ABS materials printed via FDM, SLA and DLP 3D printing processes. Tensile testing is used to evaluate changes in mechanical properties immediately after printing, and at subsequent intervals of one and two months. No specific aging or degradation conditions are imposed, reflecting practical scenarios where components are stored at ambient temperature, and washed daily. Statistical analysis through ANOVA and Tukey's HSD post-hoc test is conducted to determine significant differences across groups. Mechanical testing and statistical analysis enable the examination of how these parameters influence material performance over time, which is crucial for applications requiring material longevity.

METHODOLOGY

Specimen - material and preparation

In this study, two commercially available materials are employed: ABS filament from Creality (Shenzhen, China) and ABS-like resin from eSUN (Shenzhen, China). Specimen geometry is designed using CAD software (SolidWorks), ensuring compliance with ISO 527-2 standard for tensile testing.

Once specimen design is finalised, it is converted into an STL file format. This file is then sliced using Simplify3D (Cincinnati, OH, USA) for the FDM process, Lychee for SLA process and ChiTuBox (Shenzhen, China) for the DLP-LCD process.

The FDM printer used in this study is the Creality CR-10 Smart Pro FDM (Creality, China). DLP printer used is LD-002R (Creality, China), while the SLA printer employed is the industrial Kings 600 Pro (Shenzhen, China). The DLP printer used is the Creality LD-002R.

FDM printing parameters included a nozzle temperature of 250 °C, a build platform temperature of 90 °C, and layer height of 0.24 mm. For the SLA process, specimens are printed using 355 nm wavelength light and a layer thickness of 0.005 mm (Fig. 1). For the DLP-LCD process, specimens are printed using a 405 nm LCD projector with layer thickness of 0.005 mm. Both SLA and DLP specimens are subsequently post-cured under UV light to complete the material's structure. The infill density for all specimens is set to 100 %, with a grid infill pattern and print orientation of 90 %.

Figure 1. 3D printed and mechanically tested specimens.

Mechanical testing

Mechanical testing of all 45 specimens is carried out using the Shimadzu AGS-X universal testing machine (Shimadzu Corp., Kyoto, Japan), equipped with a 100 kN load cell. The testing speed is set to 1 mm/min, complying to the ISO 527-2 standard. Engineering stress-strain curves are generated by averaging the results from the specimens, with data analysis performed using Matlab R2022b software (MathWorks, Natick, MA, USA).

Aging

The specimens underwent daily cleaning and were kept in a natural environment for a period of two months. This aging procedure aimed to replicate typical indoor conditions in a resting state, in order to observe any property changes. Specimens are stored in an open plastic container, shielded from direct sunlight but exposed to both natural daylight and artificial lighting at night. During the study, the temperature varied between 17 and 25 °C, reflecting seasonal changes. To maintain cleanliness, specimens were washed daily in water at 37 °C using Frosch gel.

Statistical analysis

The observation of material properties over three time periods (immediate, 1 month, and 2 months) justified the use of statistical analysis through Analysis of Variance (ANOVA). Experimental results are processed using IBM SPSS 26 software (IBM, Armonk, NY, USA). A key assumption for using ANOVA is the homogeneity of variance, which was tested using Levene's test. Although this assumption was not satisfied (Sig. < 0.05), the Welch and Brown-Forsythe tests, which are more robust to assumption violations, were applied to analyse the data.

RESULTS

Mechanical testing

Tensile mechanical tests are performed at group of five specimens per each testing session. Overall, 45 specimens gathered in three groups are tested and are precisely fifteen per each AM technology (FDM, SLA DLP-LCD). Using Matlab the average values for stress and strain are calculated. Stress-strain curves for same AM technology and different maturing period are compared and presented in Figs. 2-4. Mechanical tests are repeated, and the first trial (denoted as 0m) is performed on specimens immediately after 3D printing; the second trial (denoted as 1m) is conducted on specimens after month of aging; and the third trial (denoted as 2m) is directed on two-month old specimens.

Stress-strain curves for FDM in Fig. 2 reveal that the elasticity modulus of aged specimens increases by 12.1 % and 2.3 % for 1-month and 2-month aging periods, respectively. Elongation at yield decreases with aging, showing reductions of 14.8 % after 1 month and 3.5 % after 2 months. This indicates that the thermoplastic polymer undergoes a form of maturation, likely influenced by exposure to warm water, making the material more resistant.

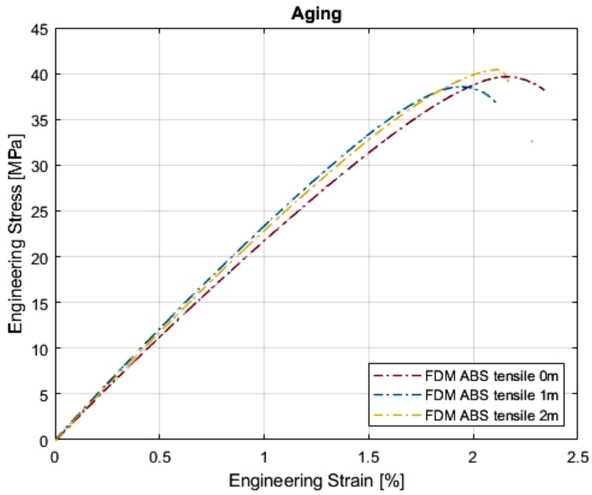

Figure 2. Tensile testing of FDM specimens.

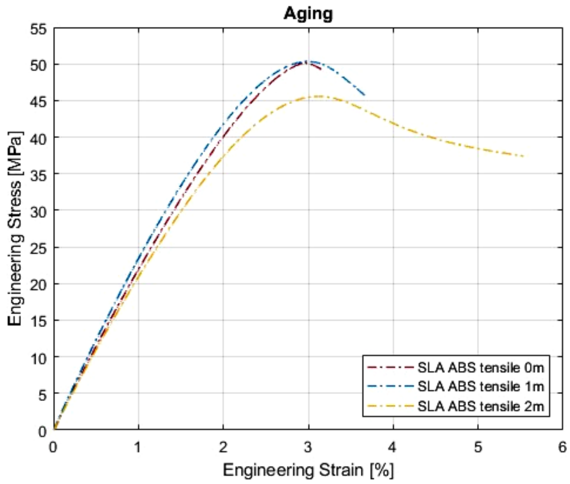

Figure 3. Tensile testing of SLA specimens.

In Fig. 3, it can be observed that after the first month, the tensile curve shows improved performance across all three mechanical properties, with slight increases in their values. However, after the second month, this trend reverses, and aged specimens exhibit poorer tensile performance compared to both unaged and 1-month aged SLA specimens. Specifically, the specimens aged for 2 months show a 9.8 % decrease in elasticity modulus and a 9.7 % decrease in ultimate tensile stress, while elongation at yield increases by 72.8 % compared to the unaged group.

During the first month, aging slightly enhances the tensile performance of SLA-printed specimens, indicating relatively stable behaviour after this period. However, after two months, both elasticity and toughness decrease by approximately 10 %, while elongation at yield increases significantly by around 70 %. Therefore, aging in SLA-printed specimens leads to an increase in strain to break, accompanied by a reduction in tensile strength.

The comparison of mechanical properties for DLP tensile specimens is shown in Fig. 4, highlighting significant changes in aged specimens. The ultimate tensile stress exhibits a downward trend, decreasing by 66.1 % after one month and by 75.4 % after two months of the aging process. The elasticity modulus also shows a substantial decline, decreasing by 59.6 % after one month and by 75.5 % after two months compared to unaged specimens.

The elongation at yield for aged specimens is reduced by approximately 50 %, and the durability is more than two times worse compared to initial (unaged) specimens. Overall, aged DLP specimens perform significantly worse in tensile tests than nonaged specimens across all measured mechanical properties. Therefore, DLP-printed specimens are not recommended for long-term use due to their rapid degradation under aging conditions.

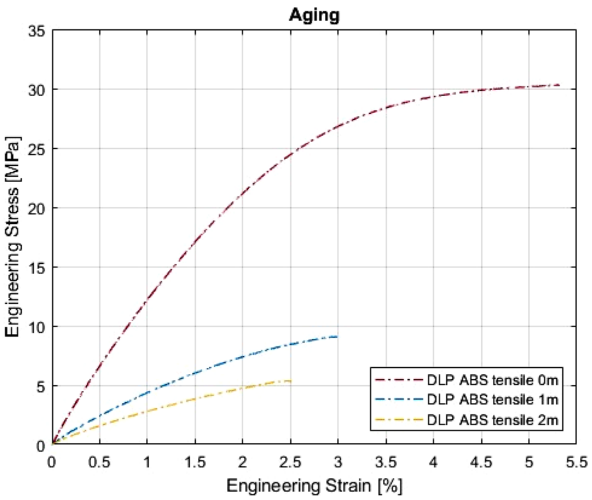

Figure 4. 3D printed and mechanically tested specimens.

Statistical analysis

Univariate Analysis of Variance (a two-way analysis of variance ANOVA) is conducted to assess differences in the mean values of dependent variables - elasticity modulus (MPa), ultimate stress (MPa), and strain at break (%) - across groups defined by the independent variables, printing type (FDM, SLA and DLP) and aging (immediately, after 1 month and after 2 months), Tables 1, 2 and 3.

In ANOVA partial eta squared measures the proportion of variance explained by an effect, controlling for other variables in the model. Partial eta squared tends to yield higher values because it only accounts for the variance specific to the effect, not the entire variance of the model. Partial eta squared values provide insight into not just whether there is an effect but also how strong that effect is, helping researchers understand the practical significance of their findings. Partial eta squared values range from 0 to 1. Higher values indicate a stronger effect of the independent variable on the dependent variable.

A two-way ANOVA reveals a significant main effect of printing type on elasticity modulus, $F(2,36) = 925.415$, Sig. < 0.001, partial Eta squared = 0.981, indicating that 98.1 % of the variance in elasticity modulus is explained by printing type, controlling for aging process, Table 1, Fig. 5. Statistically significant main effect of aging is also found ($F(2,36) = 34.271$, Sig. < 0.001), with a partial eta squared of 0.656, indicating that 65.6 % of the variance of elastic modulus is explained by aging when the printing type is held constant.

The interaction effect between printing type and aging for elasticity modulus parameter is statistically significant, $F(4,36) = 29.843$, Sig < 0.001 with a partial eta squared of 0.768 indicating that 76.8 % of the variance in elasticity modulus is explained by interaction between printing type and aging.

The obtained values of the elastic modulus parameter are significantly higher for FDM and SLA printing types compared to the DLP printing type. Homogeneous subsets are displayed in Table 1 and Fig. 5.

Table 1. Homogeneous subsets for elasticity modulus, Tukey HSD[a,b].

		Subset 1	Subset 2
DLP	15	595.3703	
SLA	15		2260.6393
FDM	15		2301.2727
Sig.		1.000	.637

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square(Error) = 14922.268.
[a] Uses harmonic mean sample size = 15.000.
[b] Alpha = .05.

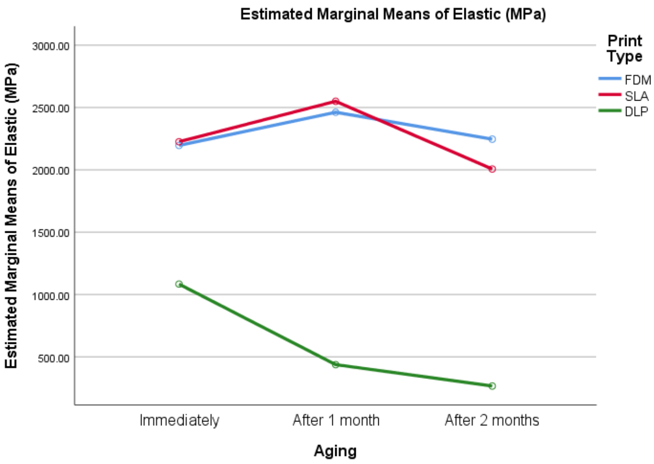

Figure 5. Impact of aging and printing type on elasticity modulus.

The obtained values of the ultimate stress parameter are significantly higher for FDM and SLA printing types compared to the DLP printing type. Homogeneous subsets are displayed in Table 2 and in Fig. 6.

The interaction effect between printing type and aging for strain at break parameter is statistically significant, $F(4,36) = 7.368$, Sig. < 0.001 with a partial eta squared of 0.450 indicating that 45 % of the variance in strain at break parameter is explained by interaction between printing type and aging, Table 3.

Table 2. Homogeneous subsets ultimate stress, Tukey HSD[a,b].

		Subset 1	Subset 2
After 2 months	15	31.282955	
After 1 month	15	33.224853	
Immediately	15		40.453073
Sig.		.073	1.000

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square(Error) = 5.470.
[a] Uses harmonic mean sample size = 15.000.
[b] Alpha = .05.

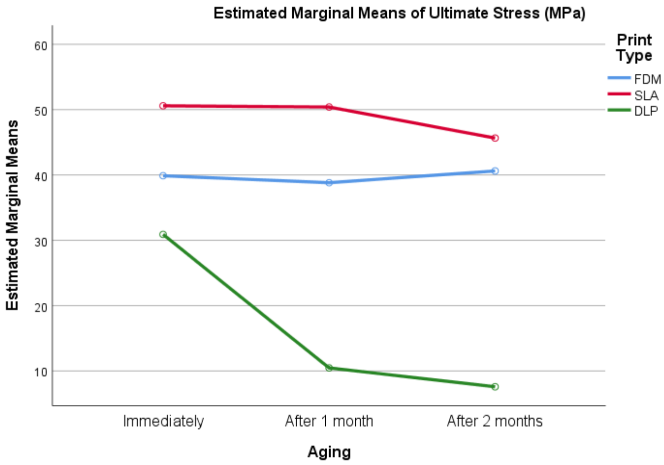

Figure 6. Impact of aging and printing type on ultimate stress.

Table 3. Homogeneous subsets strain at break, Tukey HSD[a,b].

		Subset 1	Subset 2
FDM	15	2.6281100	
SLA	15		4.6628193
DLP	15		5.4064740
Sig.		1.000	.221

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square(Error) = 1.443.
[a] Uses harmonic mean sample size = 15.000.
[b] Alpha = .05.

Statistically significant main effects of print type ($F(2,36) = 21.498$, Sig. < 0.001, partial eta squared = 0.544) and aging ($F(2,36) = 3.365$, Sig. $< 0.046 < 0.05$, partial eta squared = 0.157), are also found.

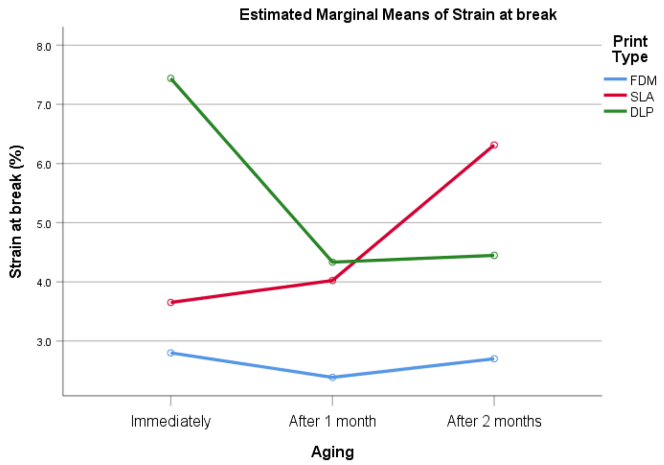

Figure 7. Impact of aging and printing type on strain at break.

A partial eta squared value of 0.544 for the variable printing type in ANOVA indicates a very large effect size. Specifically, this means that 54.4 % of the variance in the strain in break (%) can be explained by the differences in printing type. This is well above typical thresholds for a large effect (generally 0.14 or higher), so printing type plays a critical role in influencing the outcome. The interaction between the type of printing and aging is also significant (partial eta squared = 0.45), as is the effect of material aging itself (partial eta squared = 0.157).

The obtained values of the strain at break parameter are significantly higher for DLP and SLA printing types compared to the FDM printing type. Homogeneous subsets are displayed in Table 3 and Fig. 7.

DISCUSSION AND CONCLUSION

3D printing technologies are widely used because they are easily accessible and can be applied across various industries. The ability to quickly create customised products that meet specific needs has made these technologies popular. However, the components made using 3D printing processes are often exposed to various environmental factors, and the effects of these factors on the materials are not always fully understood. The printing method and material selection also play a crucial role in determining the final properties and performance of the parts, influencing how they behave over time and under different conditions.

The mechanical properties of 3D-printed ABS components depend on the printing method and evolve over time due to environmental exposure. This study provided insight into how FDM, SLA, and DLP-printed ABS materials perform under real-world conditions, which is insightful for applications requiring prolonged use of printed parts. Statistical analysis using ANOVA and Tukey's HSD identify key factors contributing to material degradation and performance differences, guiding future work in optimising 3D-printed parts for long-term durability.

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