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Research Article

The effect of build direction on component strength in SLA-based additive manufacturing

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ABSTRACT

Nowadays additive manufacturing is frequently used, especially in industrial applications such as aerospace and biomedical. In the additive manufacturing method, thanks to the layered manufacturing technique, it enables the production of components with all kinds of complex geometries and accelerates the production process. As it is known, the orientation of the layers in the additive manufacturing technique affects the mechanical properties of the components. Among the parameters affecting strength, layer thickness, production direction and layer geometry are of great importance. In this study, the effect of layer orientation on component strength in SLA-based additive manufacturing was experimentally investigated. Consequently, standard tensile samples were produced at four different production orientation using the UV Stereolithography method. Tests of the tensile samples were carried out at constant tensile speed and tensile curves were obtained. According to the results, it was determined that the layer joints parallel to the shear plane exhibited the lowest strength. Therefore, samples produced at the parallel to the shear plane fractures at lower loads and showed low strength. Considering the experimental results obtained, it has been determined that the structure orientation affects the mechanical properties of the component by ~20%.

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1. Introduction

Additive manufacturing is a production process in which the material is added layer by layer using sliced three-dimensional data. It is utilized in various fields such as the automotive industry, defense sector, biomedical field, and consumer sector, helping to overcome limitations often encountered in traditional production techniques (Chong et al. 2018; Mohanavel et al. 2021; Wang et al. 2021). Additive manufacturing technology is highly popular, particularly in the production of parts with complex geometries.

There are many 3D printing technologies available to better respond to industry applications. Among these, fused deposition modelling (FDM), stereolithography (SLA), selective laser sintering (SLS) technologies have been developed by commercial companies and are widely used today (Sürmen et al. 2019). In addition to obtaining the desired geometric properties of the parts with the additive manufacturing technology, the mechanical performance in the field of use is also very important (Tymrak et al. 2014; Chacón et al. 2017). Many parameters such as continuity in layer geometries, layer thickness, layer adhesion performance, position of layers according to part load balance, production surface quality affect the mechanical effect of these parts (Sheoran et al. 2020). Wang et al. performed experimental and numerical analyzes to determine the effects of layer thickness and printing angle for the elastoplastic structure. Based on the data acquired from the study, it was observed that the elastic modulus and tensile strength decrease as the layer thickness increases (Wang et al. 2020). Matos et al. proposed multi-objective approximation functions to assist in determining the optimal build orientation for part production. These objective functions were developed based on parameters such

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as the requirement for support structures, production time, surface roughness, and overall surface quality (Matos et al. 2021). Shim et al. (2020) examined the effect of printing orientation in additive manufacturing on surface characteristics and microbial adhesion, as well as mechanical properties. They have experimentally proven that they get the best results from the researched findings with 0 degree production orientation according to positioning. Hada et al. (2020) produced the maxillary prosthesis models with different angles (0°, 45°, and 90°) to assess the impact of production direction on the accuracy of model. They found that the printing direction set at 45° yielded the highest production accuracy. Al - Dulaijan et al. (2023) experimentally confirmed that for production orientations grouped as 0.45 and 90 degrees, the highest bending strength values were obtained from production parts with 0 degrees. In addition, they stated that high energy was required for crack propagation and that these properties increased significantly as the curing time increased. Li and Teng (2024), emphasized that tensile strength is affected by printing orientation, explained that the strength decreases with increasing orientation angle with a linear correlation.

Additive manufacturing is very often preferred for the production of complex geometries with its development in the design configuration in the field. Complex geometries have internal structures with angle values that differ according to the direction of manufacturing. The aim of this study is to experimentally investigate the changes in the mechanical differences that the build orientation will create in the structure. Standard tensile samples are produced with SLA method at different build orientations (0°, 30°, 45°, and 90°) and subjected to mechanical tests. A stress-strain curve is generated for each individual sample.

2. Materials and Method

Standard tensile samples were taken as reference in the study. Tensile samples were modeled in accordance with ASTM D638 (Fig. 1).

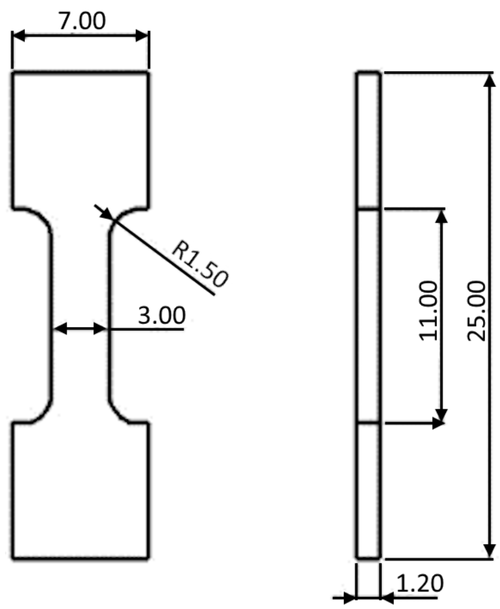


Fig. 1. The tensile test samples dimensions.

Tensile samples were positioned on the build platform at 0°, 30°, 45°, and 90° angle values according to the build direction (Fig. 2). Fig. 2 was showed the visualization that the layers will have the same layer spacing and different layer numbers according to the placements at different angles.

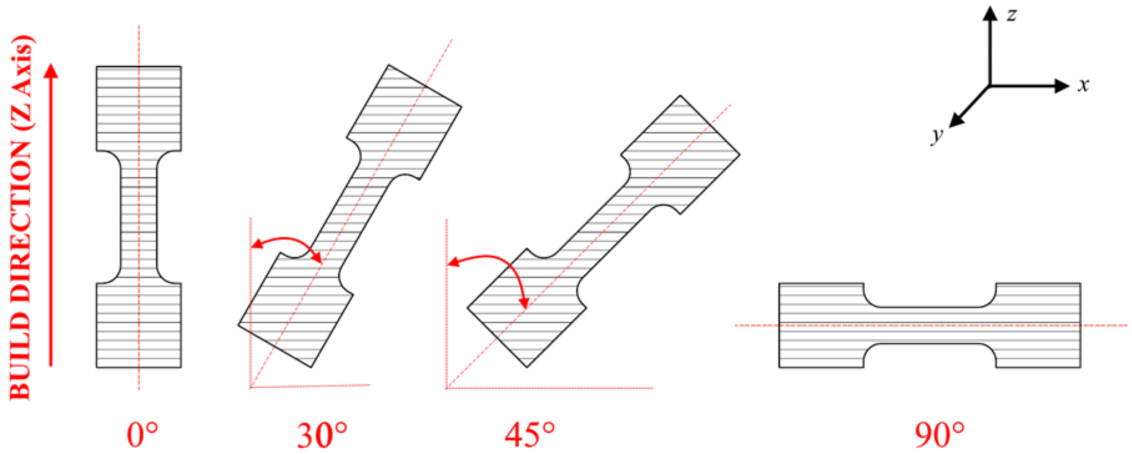


Fig. 2. The build orientation of tensile samples production.

Stereolithography (SLA) technology, one of the additive manufacturing methods, was preferred for production (Fig. 3). With this technology, the build platform is immersed in the liquid resin tank for each production layer, and solidification is carried out with the ultraviolet rays. It provides solidification of parts in desired geometries in a short time with ultraviolet rays.

The production device used was the Anycubic Photon M3 3D printer model (Fig. 4a). A gray liquid resin from the SLA printer's brand was utilized. Five samples were generated for each build orientation. The layer thickness was set to 0.05 mm and the normal exposure time was set to 2 s. After the production period of approximately 1 hour and 45 minutes, the samples were washed with ethanol alcohol together with the build platform (Fig. 4b). Afterwards, the samples were separated from the build platform and placed in the curing device of the same brand for curing. The curing process was carried out in 10 minutes (Fig. 4c).

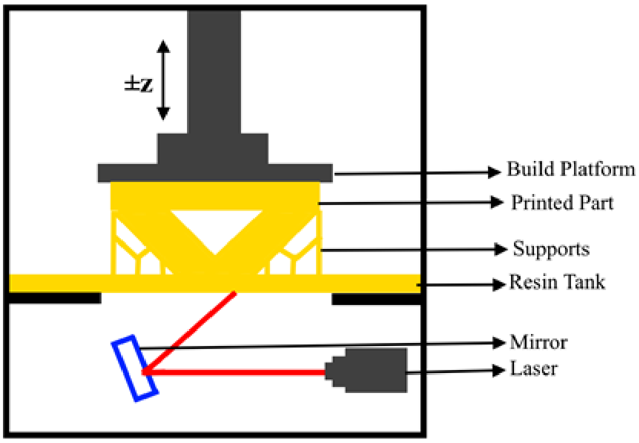


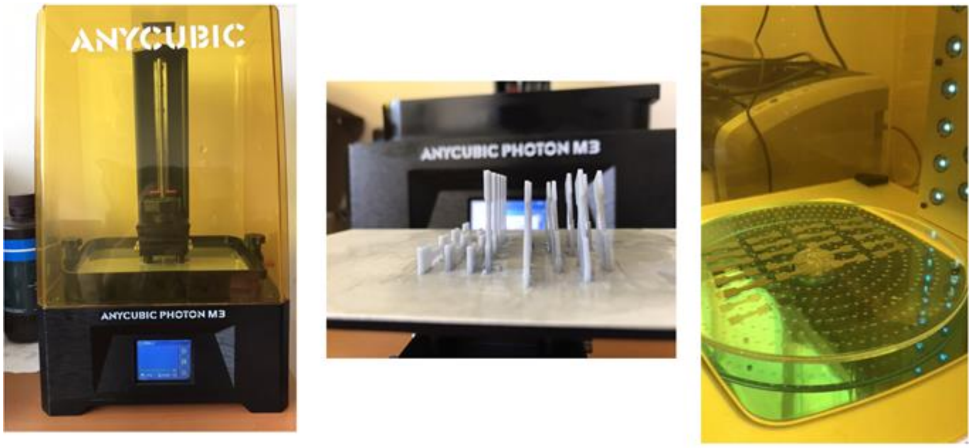
Fig. 3. UV Stereolithography method, one of the additive manufacturing technologies.

The mechanical performances of the samples were evaluated by tensile tests. Tensile tests were performed using the INSTRON 3382 brand (Fig. 5). Three samples at each angle value were tested. Strain at a rate of 0.5 mm/min was applied until fracture was observed in the samples. Metal plates were attached to both grip section of the samples. This prevented the compression of the polyethylene materials in the tensile samples between the grips of the tensile machine.

3. Results and Discussion

Tensile samples produced using SLA were visualized using light microscopy (Fig. 6). The layer orientation of samples with different build orientations was described. The enlarged layer lines depicted in Fig. 1 were obtained in consistent directions during production. The green lines indicated the layer direction, serving as indicators of the desired build orientations.

Three tensile tests were performed for each orientation. Data for each angle was created by taking the average of repeated tests. As a result of the tensile tests, the stress-strain curves of the samples in different build orientations were added as Fig. 7. Tensile samples had a typical curve like ductile materials.



(a) (b) (c)

Fig. 4. (a) Anycubic Photon M3 model printer used for production; (b) Post-production sample images; (c) The curing process applied to the samples.

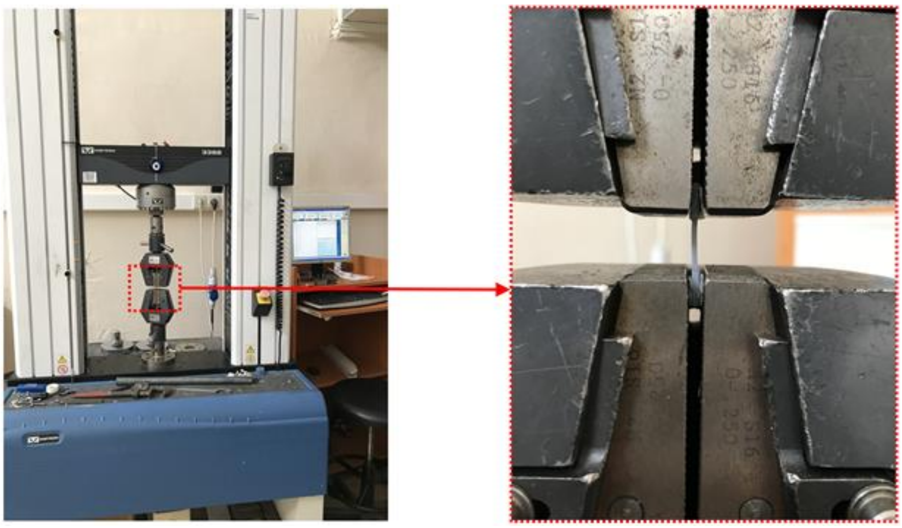


Fig. 5. The tensile testing machine and the specimens being tested.

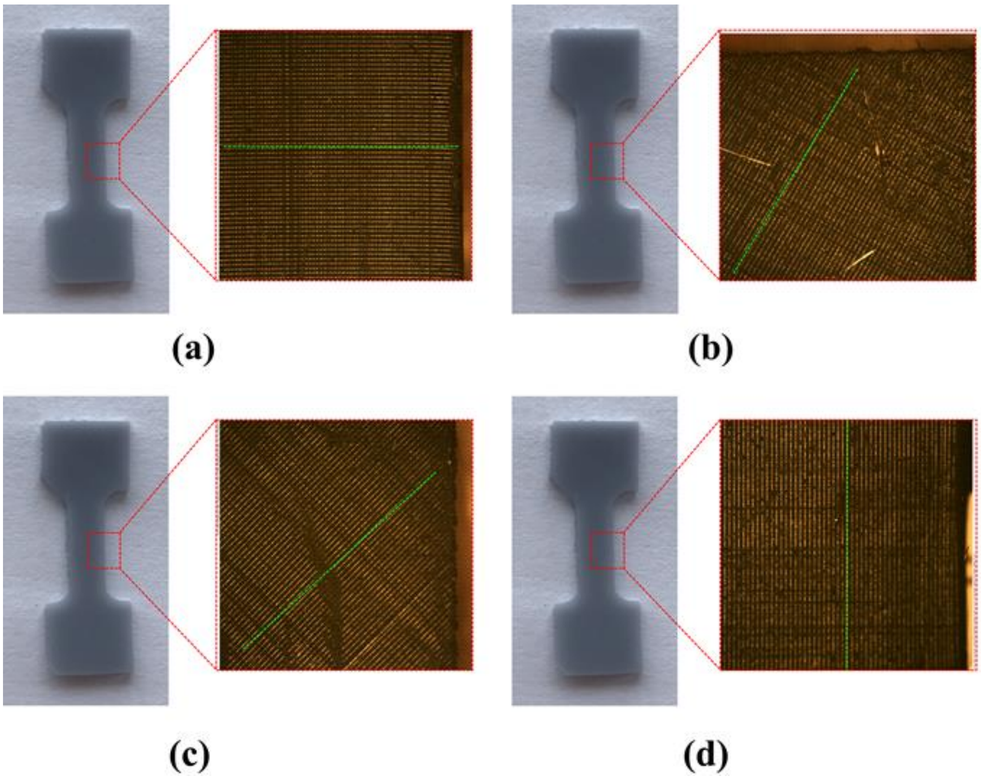


Fig. 6. Post-production images: (a) 0°; (b) 30°; (c) 45°; and (d) 90° samples.

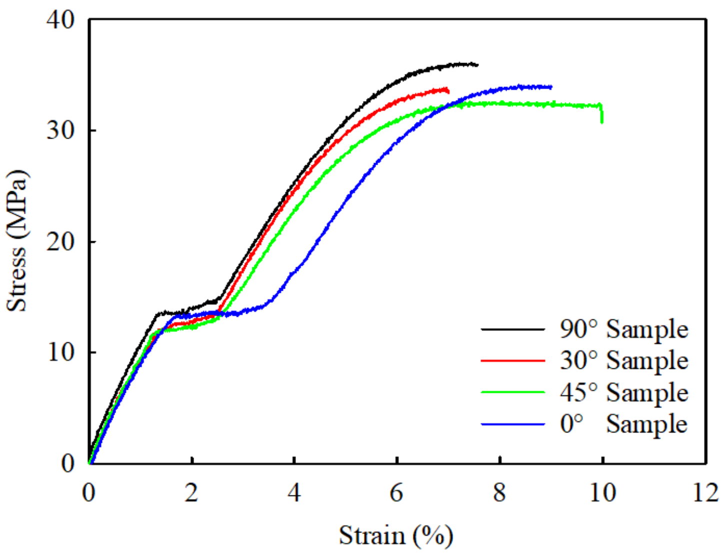


Fig. 7. Stress–strain curve: (a) 0°; (b) 30°; (c) 45°; and (d) 90° samples.

The samples with the same cross-sectional area fractured at different strain and stress values relative to each other. While 90° samples had the highest ultimate strength, 45° samples had the lowest. However, the 45° samples had the highest strain rate. The experimental results of the samples were added to Table 1.

Table 1. Average tensile test data and standard deviation for each manufacturing orientation.

Sample	Yield strength (MPa)	Strain (%)	Ultimate strength (MPa)
0°	13.1805 ± 0.46	9.0103 ± 1.17	33.9613 ± 2.13
30°	11.1325 ± 0.98	6.9934 ± 0.49	33.3697 ± 1.5
45°	12.0127 ± 0.99	9.9815 ± 0.41	33.44993 ± 1.31
90°	13.0798 ± 1.6	7.5654 ± 0.27	35.9398 ± 4.36

According to the yield strength in Table 1, the 30° samples had the lowest strength. 0° showed the highest yield strength. When the yield strength is listed quantitatively, the yield strength increases respectively: 30°, 45°, 90°, and 0°. There is approximately a 1% difference between the yield strength of 0° and 90° samples.

The strain rate value increases between 30°, 90°, 0° and 45° samples, respectively. Ultimate strength was also a precursor to the mechanical difference in build orientation. Also, the 45° sample with the highest strain value had the lowest ultimate strength. The 90° sample had the highest ultimate strength. Fracture images of tensile samples with different build orientations were in Fig. 8.

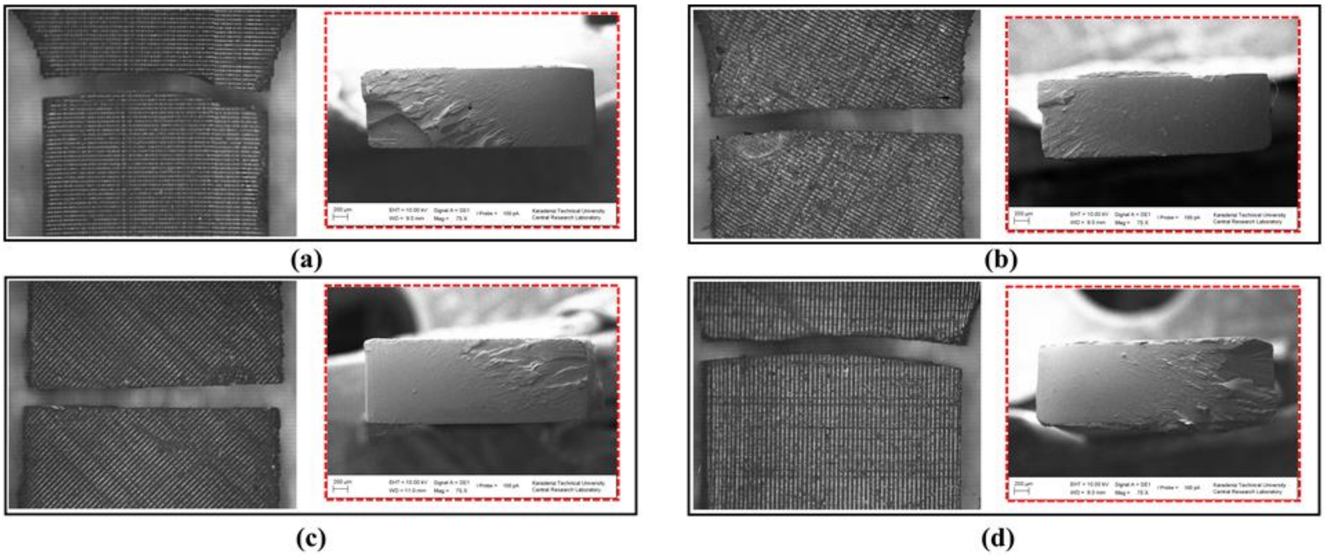


Fig. 8. The fractures samples surface after tensile test: (a) 0°; (b) 30°; (c) 45°; (d) 90°.

The fracture mechanism in the 0° samples was shear failure type (Fig. 7a) (Pelleg et al. 2021). This fracture, which is considered to be very ductile, originates from the layer merge planes. The plastic behavior in the interlayer adhesion regions produced parallel to the x-plane is higher than the layer structure (Aliheidari et al. 2018). The difference in ductile behavior caused the fractures to occur in the fracture plane close to 45°. In 30° samples, the fracture plane was perpendicular to the loading direction (Fig. 7b). This fracture mechanism type shows that the structure exhibits less ductile behavior. The fact that it had the lowest strain rate (Table 1) was proof of that. The fracture plane of the 45° samples was also parallel to the x plane, but the strain rate of the structure was the highest compared to the other structures (Fig. 7c). As it is known, the maximum shear stress in structures occurs at 45° (Goh et al. 2021). Maximum shear stresses occurring in tensile specimens with 45° build orientation are in the same plane with the layer merges. Farkas et al. (2023) noted in their experimental study that the fracture plane was "V" shaped. They stated the reason for this is the eccentric tensile load according to the layer combinations. It is also encountered in these samples that the plastic behavior between the layers is more than the layer. This is proof that it has the highest ductility despite the lowest ultimate strength. A fully ductile fracture type was observed as the fracture mechanism in the 90° specimens (Fig. 6d). However, the data in Table 1 indicate that the ductile behavior of the structure is lower compared to the 0° and 45° samples. The main reason for the occurrence of this type of fracture is the ductile behavior difference between the layer interior structure and the interlayer points (Aliheidari et al. 2018). Layers that are less ductile have higher tensile strength but lower deformation. The tensile strength of the layer junction planes after a layer has broken is low, but the ductility is partially higher.

It was evident from the experimental results that the build orientation affected the mechanical properties of the tensile specimens. The same situation is observed in samples produced with different additive manufacturing technologies (Wang et al. 2021; Patadiya et al. 2018). In various studies, it has been experimentally stated that production accuracy, surface roughness and especially mechanical properties vary depending on the angle of the layers with the production platform (Naik and Kiran 2018; Coppola et al. 2022). This will assist in evaluating the mechanical properties of porous structures popular with additive manufacturing technology (Günther et al. 2022), considering especially its lightness superiority (Ghahramanzadeh Asl and Karaman 2024). Complex geometry surfaces of porous structures have different angles with respect to the production plane. Different effects can be observed on the surfaces as a result of mechanical loading in the porous structures produced. This situation may be related to build orientation and this effect is proven once again by this study.

4. Conclusions

In this study, the effects of build orientation on the mechanical performance of structures in additive manufacturing technologies were investigated. Tensile specimens with 0°, 30°, 45°, and 90° build orientations were produced with SLA. Stress-strain curves of the samples were obtained by tensile tests performed with a constant strain rate. In terms of ultimate strength, 90° samples had the highest ultimate strength, while 45° samples had the lowest ultimate strength. 30° samples had higher ultimate strength than 0° and 45° samples. However, rupture occurred at the lowest strain rate of the four samples. It has been proved by the experimental results that the build orientation is directly effective in structural mechanics.

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Conflict of Interest

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Author Contributions

All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

REFERENCES

AlDulaijan YA, Alsulaimi L, Alotaibi R, Alboainain A, Akhtar S, Khan SQ, Gad MM (2023). Effect of printing orientation and postcuring time on the flexural strength of 3D-printed resins. *Journal of Prosthodontics,* 32(S1), 45-52.

Aliheidari N, Christ J, Tripuraneni R, Nadimpalli S, Ameli A (2018). Interlayer adhesion and fracture resistance of polymers printed through melt extrusion additive manufacturing process. *Materials & Design*, 156, 351-361.

Chacón JM, Caminero MA, García-Plaza E, Núnez PJ (2017). Additive manufacturing of PLA structures using fused deposition modelling: Effect of process parameters on mechanical properties and their optimal selection. *Materials & Design*, 124, 143-157.

Chong L, Ramakrishna S, Singh S (2018). A review of digital manufacturing-based hybrid additive manufacturing processes. *The International Journal of Advanced Manufacturing Technology*, 95, 2281-2300.

Coppola B, Schmitt J, Lacondemine T, Tardivat C, Montanaro L, Palmero P (2022). Digital light processing stereolithography of zirconia ceramics: Slurry elaboration and orientation-reliant mechanical properties. *Journal of the European Ceramic Society*, 42(6), 2974-2982.

Farkas AZ, Galatanu SV, Nagib R (2023). The influence of printing layer thickness and orientation on the mechanical properties of DLP 3D-printed dental resin. *Polymers*, 15(5), 1113.

Ghahramanzadeh Asl H, Karaman D (2024). The novelty design method in lightweight structures with low effective elastic modulus. *Challenge Journal of Structural Mechanics*, 10(2), 47-57.

Goh GD, Toh W, Yap YL, Ng TY, Yeong WY (2021). Additively manufactured continuous carbon fiber-reinforced thermoplastic for topology optimized unmanned aerial vehicle structures. *Composites Part B: Engineering*, 216, 108840.

Günther F, Hirsch F, Pilz S, Wagner M, Gebert A, Kästner M, Zimmermann M (2022). Structure-property relationships of imperfect additively manufactured lattices based on triply periodic minimal surfaces. *Materials & Design*, 222, 111036.

Hada T, Suzuki T, Minakuchi S, Takahashi H (2020). Reduction in maxillary complete denture deformation using framework material made by computer-aided design and manufacturing systems. *Journal of the Mechanical Behavior of Biomedical Materials,* 103, 103514.

Li Y, Teng Z (2024). Effect of printing orientation on mechanical properties of SLA 3D-printed photopolymer. *Fatigue & Fracture of Engineering Materials & Structures*, 47(5), 1531-1545.

Matos MA, Rocha AMA, Costa LA (2021). Many-objective optimization of build part orientation in additive manufacturing. *The International Journal of Advanced Manufacturing Technology*, 112, 747-762.

Mohanavel V, Ali KA, Ranganathan K, Jeffrey JA, Ravikumar MM, Rajkumar S (2021). The roles and applications of additive manufacturing in the aerospace and automobile sector. *Materials Today: Proceedings*, 47, 405-409.

Naik DL, Kiran R (2018). On anisotropy, strain rate and size effects in vat photopolymerization based specimens. *Additive Manufacturing*, 23, 181-196.

Patadiya N H, Dave H K, Rajpurohit S R (2020). Effect of build orientation on mechanical strength of FDM Printed PLA. *Advances in Additive Manufacturing and Joining: Proceedings of AIMTDR 2018 Springer Singapore,* 301-307.

Pelleg J (2021). Fracture in nano-structures. *In: Mechanical Properties of Nanomaterials: Engineering Materials*. Springer, Cham.

Sheoran AJ, Kumar H (2020). Fused deposition modeling process parameters optimization and effect on mechanical properties and part quality: Review and reflection on present research. *Materials Today: Proceedings*, 21, 1659-1672.

Shim JS, Kim JE, Jeong SH, Choi YJ, Ryu JJ (2020). Printing accuracy, mechanical properties, surface characteristics, and microbial adhesion of 3D-printed resins with various printing orientations. *The Journal of Prosthetic Dentistry*, 124(4), 468-475.

Sürmen HK (2019). Eklemeli İmalat (3B Baskı): Teknolojiler ve Uygulamalar. *Uludağ University Journal of the Faculty of Engineering*, 24(2), 373-392. (in Turkish)

Tymrak BM, Kreiger M, Pearce JM (2014). Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions. *Materials & Design*, 58, 242-246.

Wang Y, Li X, Chen Y, Zhang C (2021). Strain rate dependent mechanical properties of 3D printed polymer materials using the DLP technique. *Additive Manufacturing*, 47, 102368.