



FROM GEOMETRY TO STRENGTH: THE ROLE OF INTERFACE DESIGN IN MULTI-MATERIAL FDM STRUCTURES

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Abstract: Fused deposition modeling (FDM), also known as or filament freeform Fabrication Fused filament (FFF), is a 3D printing process that uses a continuous filament of a thermoplastic material and is one of the most used 3D printing technology. This study investigated the effect of interface geometry on the tensile performance of multi-material FDM specimens manufactured from UltraFuse PLA Blue and PLA/PHA Shining Silver filaments. Experimental results showed that interface design significantly influences load transfer, mechanical interlocking, tensile strength, and strain at break. Among the tested configurations, the 2U-shaped interface achieved the highest tensile strength (≈ 37 MPa), while the double semicircular geometry exhibited the greatest deformation capability ($\approx 6\%$ strain at break). The findings demonstrate that both interface geometry and printing parameters contribute to the mechanical performance of multi-material components, highlighting interface optimization as an effective strategy for enhancing the structural integrity of FDM-printed parts.

Keywords: interface geometry, tensile strength, mechanical interlocking, additive manufacturing.

1. INTRODUCTION

Additive manufacturing (AM) has experienced remarkable development over the last decade due to its ability to fabricate complex geometries, reduce material waste, and enable highly customized component production. Among AM technologies, Fused Deposition Modeling (FDM) has become one of the most widely adopted techniques for polymer processing because of its low cost, process flexibility, and compatibility with a broad range of thermoplastic materials. In recent years, increasing attention has been directed toward multi-material and bicomponent FDM printing, where two or more materials are combined within a single structure to obtain enhanced mechanical, thermal, or functional properties [1–3].

Wang et al. [1] performed a systematic review on multi-material additive manufacturing by FDM and highlighted that interfacial bonding remains one of the major challenges limiting the structural integrity of multimaterial components. The authors reported that material feeding systems and switching mechanisms may generate discontinuities and local porosity in the interface region, directly influencing the mechanical behavior of the printed structures.

Bandyopadhyay et al. [2] reviewed the recent advances in multi-material additive manufacturing and demonstrated that the design of the interface geometry significantly affects load transfer between materials. Their study emphasized the importance of nondestructive characterization methods, especially X-ray micro-computed tomography (micro-CT), for identifying internal defects and porosity distributions in additively manufactured structures. However, the authors also pointed out that correlations between interfacial morphology and mechanical performance are still insufficiently investigated.

Guessasma et al. [3] investigated different interface geometries in FDM multimaterial structures, including T-shaped and dovetail interfaces. Their results demonstrated that mechanical interlocking geometries improve interfacial strength compared with planar interfaces due to enhanced stress distribution. Nevertheless, the study revealed that void formation and poor material continuity at the interface remain significant limitations.

Frasccio et al. [4] analyzed enhanced interfacial adhesion in multi-material filament printing using T-type and modified “Mickey Mouse” interface geometries. The authors reported improved tensile performance for mechanically interlocked interfaces and demonstrated that geometric optimization can reduce stress concentrations. Despite these improvements, local defects and incompatibility between materials continued to affect the overall mechanical response.

Delia et al. [5] studied the factors affecting interface bonding in multimaterial additive manufacturing using combinations of polymeric materials. The researchers concluded that deposition order, interfacial contact area,

and thermal compatibility strongly influence adhesion quality. They also observed that process-induced porosity and local geometric inconsistencies negatively impact structural reliability.

Brown et al. [6] presented a comprehensive analysis of multimaterial extrusion printheads and discussed their influence on interface formation in FDM printing. Their study showed that advanced extrusion systems can generate complex interfacial geometries and graded transitions between materials. However, challenges related to flow instability, nozzle contamination, and imperfect layer deposition were identified as major sources of internal voids and weak bonding regions.

Li et al. [7] reviewed the modeling and manufacturing of heterogeneous and multimaterial structures fabricated by additive manufacturing. The authors emphasized that multimaterial systems allow localized tailoring of material properties, but the characterization of interface integrity and internal defects remains insufficiently explored. They highlighted the need for advanced three-dimensional characterization techniques capable of correlating internal morphology with mechanical properties.

Ettayan et al. [8] reviewed the influence of processing parameters on the mechanical behavior of multimaterial FDM structures. The study demonstrated that nozzle temperature, raster orientation, layer thickness, and interfacial geometry substantially affect bonding quality and tensile performance. The authors also underlined the limited number of studies simultaneously investigating surface topography, porosity, and interfacial morphology. Several researchers have focused specifically on porosity characterization in FDM structures using micro-CT analysis. Moini et al. [9] used X-ray micro-computed tomography to investigate the internal architecture of additively manufactured materials and demonstrated that micro-CT enables accurate visualization of pores, interlayer gaps, and interfacial discontinuities. Their findings showed that printing orientation and deposition strategy significantly influence pore distribution.

Similarly, Prause et al. [10] employed micro-CT and scanning electron microscopy for microstructural investigations of additively manufactured hybrid materials. They identified spherical pores and irregular material distributions associated with the printing process and concluded that nondestructive imaging techniques are essential for understanding structure–property relationships.

Zhang et al. [11] investigated porosity formation in FDM-printed polymer structures and demonstrated that air gaps between deposited filaments represent one of the main causes of mechanical degradation. The authors observed that pore size and morphology are strongly dependent on extrusion temperature and printing speed. However, the study was limited to single-material systems.

Ahn et al. [12] analyzed the anisotropic properties of FDM structures and reported that interlayer bonding defects and void formation are directly responsible for reduced tensile strength and fatigue resistance. Their results established an important relationship between processing parameters and microstructural discontinuities.

Spoerk et al. [13] investigated the influence of raster arrangement and layer adhesion on FDM components and demonstrated that internal voids can significantly reduce stiffness and structural reliability. The authors emphasized the need for improved interfacial characterization techniques capable of evaluating local defects in multimaterial systems.

In addition to internal characterization, the analysis of surface quality has become increasingly important for understanding the performance of additively manufactured components. Optical profilometry and interferometric methods have emerged as valuable techniques for three-dimensional surface characterization. Zuo et al. [14] demonstrated that high-resolution optical profilometry enables accurate three-dimensional measurement of complex surfaces and defect regions. Although their study was not focused specifically on FDM multimaterial structures, the authors highlighted the applicability of these methods for evaluating microscale surface irregularities.

Leach [15] reviewed the application of optical metrology techniques for advanced surface characterization and emphasized that coherence scanning interferometry (CSI) provides nanometric vertical resolution suitable for the evaluation of roughness and local surface discontinuities in additively manufactured components.

Thompson et al. [16] analyzed the role of surface quality in additive manufacturing and concluded that roughness and local topographical defects significantly influence mechanical behavior, fatigue performance, and interfacial adhesion. Their study highlighted the necessity of combining surface characterization with internal structural analysis.

Yadav et al. [17] studied the influence of process parameters on the surface morphology of FDM-printed PLA structures. The authors demonstrated that layer thickness and deposition temperature strongly affect surface roughness and dimensional accuracy. However, the study focused only on monomaterial samples and did not investigate internal porosity.

Rajpurohit and Dave [18] investigated the effects of process parameters on porosity and surface finish in FDM printing and showed that lower layer heights and optimized extrusion temperatures improve surface quality while reducing internal void formation. Nevertheless, the study did not include multimaterial interfaces.

Farahani et al. [19] reviewed the role of surface metrology in additive manufacturing and reported that advanced profilometry methods provide important information regarding layer morphology, defect distribution, and printing consistency. The authors emphasized that combining surface analysis with volumetric characterization techniques such as micro-CT could provide a more complete understanding of structure–property relationships.

Ngo et al. [20] reviewed the current challenges and applications of additive manufacturing technologies and identified interfacial bonding and porosity as critical issues in multimaterial FDM structures. The authors noted that despite significant progress in process optimization, there remains a lack of studies addressing complex interface geometries and biodegradable polymer combinations.

Although substantial progress has been achieved in multimaterial FDM manufacturing, several limitations remain. Most studies focus either on mechanical testing or on isolated microstructural characterization, without establishing a direct correlation between surface topography, internal porosity, and interface geometry. Furthermore, only a limited number of investigations have addressed biodegradable polymer combinations such as UltraFuse PLA and PLA/PHA, particularly for complex interface geometries, including T, dovetail, U-shape, and semicircular configurations.

Therefore, the present study aims to characterize bicomponent FDM-printed structures manufactured from UltraFuse PLA and PLA/PHA using complementary nondestructive techniques, namely 3D topography and X-ray micro-computed tomography (micro-CT). Surface topography measurements were performed using coherence scanning interferometry (CSI) in order to evaluate the texture and discontinuities in the vicinity of the multimaterial interfaces, while micro-CT analysis was employed to investigate the internal porosity distribution and its correlation with the mechanical behavior of the printed samples.

The novelty of the present work consists in the combined investigation of complex interface geometries (T, dovetail, U-shape, and semicircle) in biodegradable bicomponent FDM structures fabricated from UltraFuse PLA and PLA/PHA, through the simultaneous use of high-resolution 3D topography and micro-CT analysis. Unlike previous studies that investigated either surface quality or internal defects separately, the present research establishes a direct correlation between interfacial morphology, surface texture, internal porosity, and the resulting structural performance of multimaterial printed parts.

2. MATERIALS AND METHODS

The materials selected for the experimental investigation were UltraFuse PLA Blue and PLA/PHA Shining Silver. UltraFuse PLA is commonly employed in fused deposition modeling (FDM) because of its ease of processing and consistent mechanical performance [21, 22]. Tensile test specimens were manufactured in accordance with the requirements of the ISO 527 standard.

All specimens were fabricated using an Ultimaker 3 Extended FDM printer featuring a dual-extrusion setup. The printing conditions were maintained at 100% infill density, a flat printing orientation, a build plate temperature of 60°C, a printing speed of 60 mm/s, and a nozzle temperature of 215°C. The investigated process parameters included layer height (0.1 mm and 0.3 mm), number of deposited layers (2 and 4), and interface design (T-shape, double T-shape, dovetail, double dovetail, U-shape, double U-shape, semicircular, and double semicircular geometries). For each parameter combination, three specimens were produced.

Uniaxial tensile tests were carried out using an Instron 3382 universal testing machine. The tests were performed at a constant crosshead speed of 5 mm/min, following the recommendations of ISO 527-3:2003. The grip separation was set to 115 mm, while data acquisition was conducted at a frequency of 10 Hz. All measurements were performed under ambient laboratory conditions at a temperature of 23°C.

3. RESULTS AND DISCUSSION

3.1 Tensile test

The tensile test results highlight the significant influence of interface geometry on the mechanical response of the multi-material samples manufactured by fused deposition modeling (FDM). Since the investigated structures were produced through bi-component printing, the overall mechanical performance is governed by the combined effect of interfacial adhesion, filament continuity across the interface, and the mechanical interlocking generated by the interface design. In addition, the selected process parameters, namely the layer height (0.1 mm and 0.3 mm) and the number of deposited layers (2 and 4), contribute to the quality of bonding developed between the two materials and therefore affect the tensile response.

T-shape interface and 2T-shape interface

A comparison between the T-shaped and 2T-shaped interfaces reveals a moderate improvement in both tensile strength and elongation at break when the additional locking feature is introduced. The highest tensile strength

recorded for the T-shaped interface was approximately 33 MPa, Figure 1(a), whereas the 2T-shaped configuration reached approximately 34 MPa (Figure 1(b)). A similar tendency was observed for strain at break, where the maximum value increased from about 4.3% for the T-shaped specimens to nearly 4.8% for the 2T-shaped specimens, Figure 2. This behavior suggests that the addition of a second transverse anchoring region enhances the load transfer capability between the two materials. Under tensile loading, the 2T-shaped geometry promotes a more uniform stress distribution along the interface and reduces the likelihood of localized stress concentrations that may initiate premature failure. Furthermore, the enlarged contact region created by the additional geometric feature increases the effectiveness of the interfacial bonding developed during the deposition process. The experimental results also indicate that the influence of the interface geometry cannot be separated from the effect of the printing parameters. Within the experimental plan, odd-numbered experiments were associated with a layer height of 0.1 mm and two deposited layers, whereas even-numbered experiments were manufactured using a layer height of 0.3 mm and four deposited layers. The highest mechanical responses were not observed for all parameter combinations, indicating that the quality of the bond formed between the deposited materials depends on the interaction between the geometric configuration and the deposition conditions. Variations in layer height modify the contact area between adjacent filaments and influence the thermal history of the deposited material, while the number of deposited layers affects the continuity of the interface region and the ability of the materials to develop a cohesive bond.

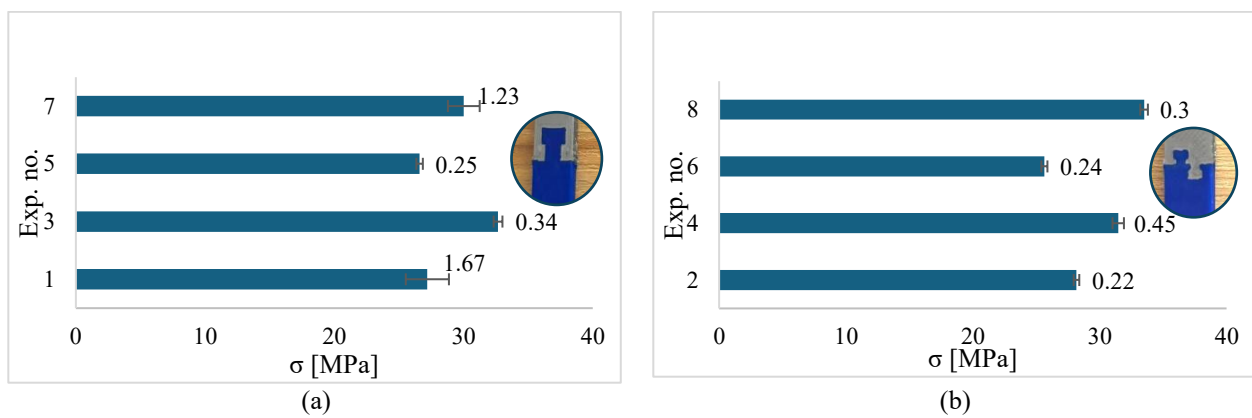


Fig. 1. Tensile strength: (a) T-shape interface (b) 2T-shape interface

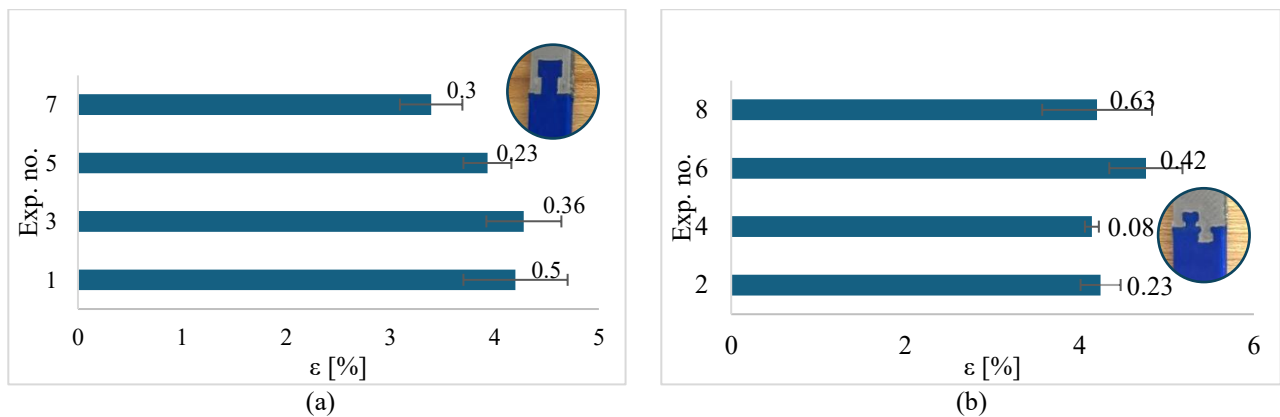


Fig. 2. Strain at break: (a) T-shape interface (b) 2T-shape interface

Dovetail and double dovetail interfaces

A similar trend can be observed when comparing the dovetail and double dovetail interfaces. The dovetail geometry exhibited the highest tensile strength among the investigated configurations, reaching approximately 35 MPa, while the double dovetail interface achieved a maximum value close to 34 MPa, Figure 3. Although the difference in strength is relatively small, a more pronounced distinction was observed in terms of elongation at break. The maximum strain obtained for the dovetail interface was approximately 4.5%, whereas the double dovetail samples reached values slightly above 5%, Figure 4. These results indicate that the introduction of a second dovetail feature increases the deformation capability of the interface before failure occurs.

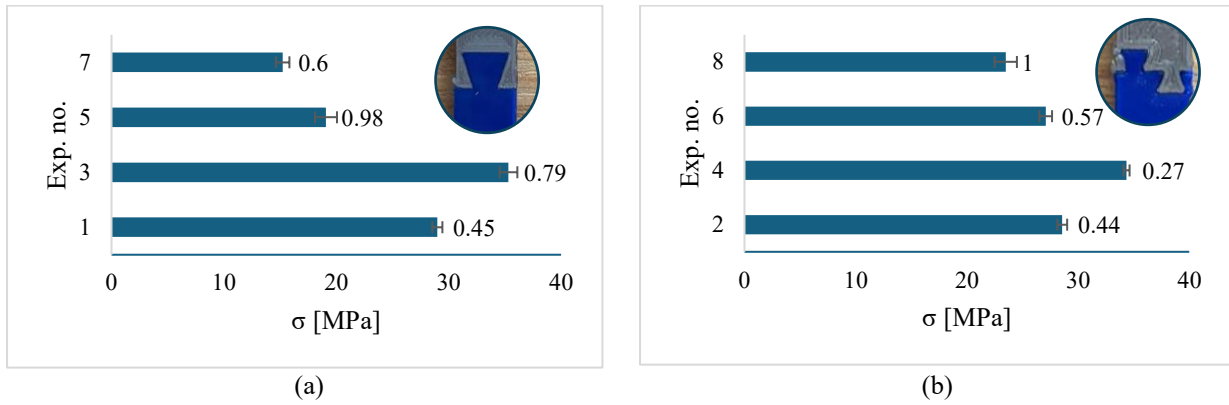


Fig. 3. Tensile strength: (a) dovetail interface (b) double dovetail interface

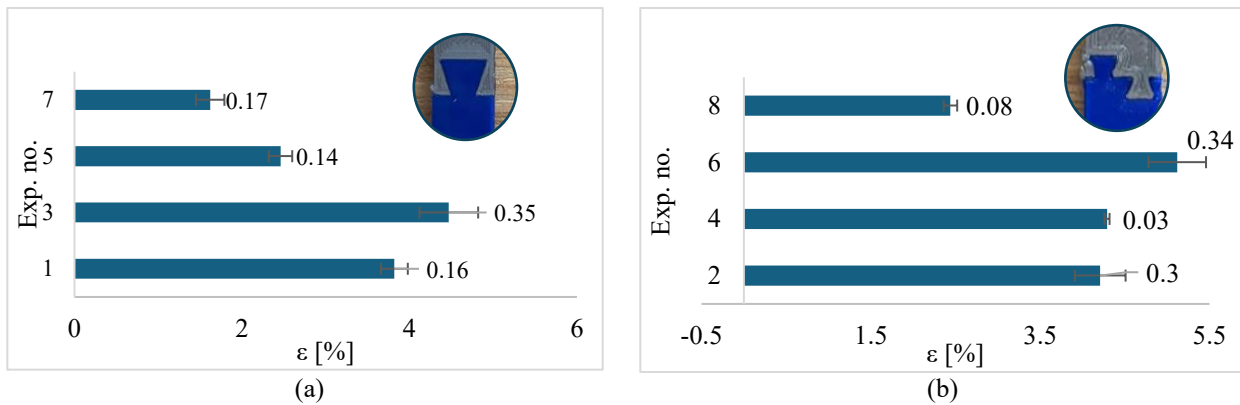


Fig. 4. Strain at break: (a) dovetail interface (b) double dovetail interface

The superior mechanical behavior of the dovetail-based geometries can be attributed to their ability to generate a strong mechanical interlocking effect. Unlike the T-shape configurations, where a larger portion of the applied load is sustained through adhesion between the two materials, the dovetail geometry creates a geometric constraint that directly opposes relative displacement at the interface. Consequently, part of the applied tensile load is transferred through the interface shape itself, reducing the dependence on adhesive bonding alone. The double Dovetail configuration further enhances this mechanism by creating multiple load-transfer paths, which promotes a more gradual redistribution of stresses during deformation and delay the onset of crack propagation.

Overall, the comparison between the paired geometries demonstrates that increasing the complexity of the interface design generally leads to improved mechanical performance. For both interface families, the double configurations exhibited either higher tensile strength, higher elongation at break, or a combination of both. These findings suggest that the optimization of interface geometry represents an effective strategy for improving the structural integrity of multi-material FDM components, particularly when combined with appropriate deposition parameters that facilitate strong interfacial bonding and efficient load transfer between the constituent materials.

U-shape and 2U-shape interfaces

The tensile behavior of the U-shape and 2U-shape interfaces demonstrates that modifications of the interface geometry significantly influence both strength and deformation capability in multi-material FDM structures. The highest tensile strength obtained for the U-shape interface was approximately 36 MPa, whereas the 2U-shape specimens reached a maximum value of about 37 MPa, Figure 5. Although the difference is relatively small, it suggests that introducing a second anchoring region positively contributes to the load-bearing capacity of the interface. A more pronounced effect was observed in terms of strain at break. The maximum elongation recorded for the U-shape configuration was approximately 5.3%, while the 2U-shaped samples exhibited values approaching 5.8%, Figure 6.

The improved performance of the 2U-shaped interface can be associated with the increased mechanical interconnection generated by the additional geometric feature. During tensile loading, the double configuration creates multiple regions capable of transferring stresses between the two materials, thereby reducing the concentration of stresses within a limited area of the interface. As a result, the onset of interfacial damage is delayed, allowing the sample to sustain larger deformations before failure. Furthermore, the increased contact

area between the deposited materials promotes the development of a more extensive bonding zone, which contributes to the observed enhancement in mechanical performance.

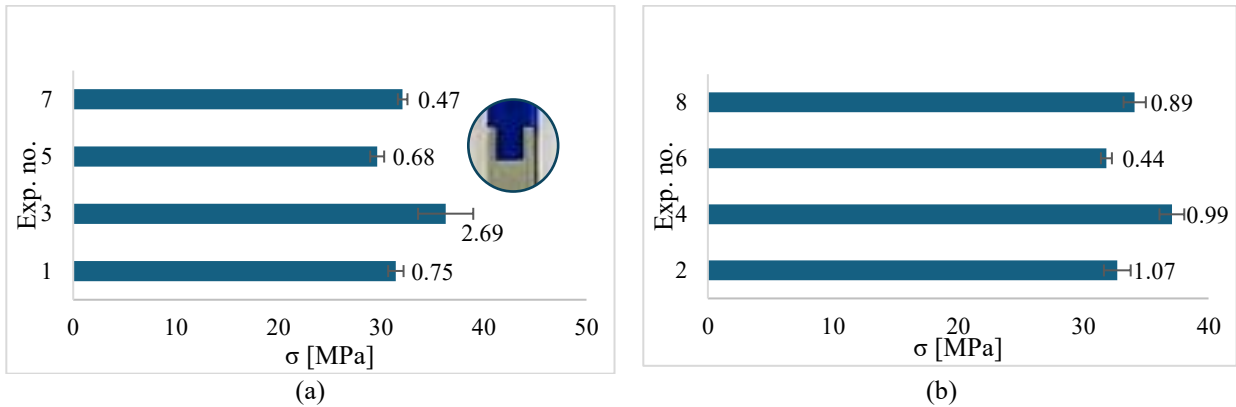


Fig. 5. Tensile strength: (a) U-shape interface (b) 2U-shape interface

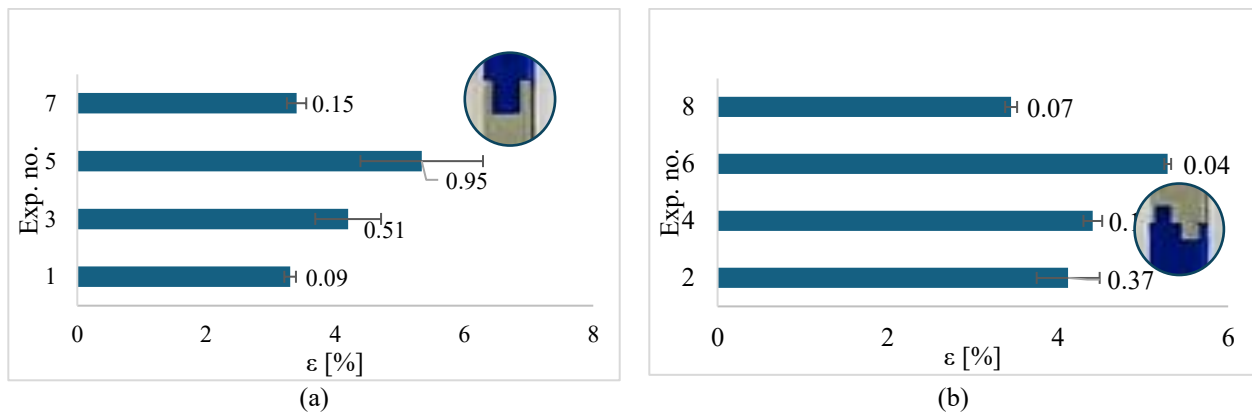


Fig. 6. Strain at break: (a) U-shape interface (b) 2U-shape interface

The experimental results also suggest that the interaction between interface geometry and processing parameters plays an important role in determining the final mechanical response. Since the specimens were manufactured using different combinations of layer height and number of deposited layers, variations in thermal history and filament arrangement are expected to affect the bonding quality developed at the material junction. In particular, the ability of the deposited roads to conform to the interface geometry becomes increasingly important for complex shapes, where the continuity of the deposited material can significantly influence stress transfer efficiency.

Semicircular and double semicircular interfaces

A similar tendency was observed for the semicircular and double Semicircular interfaces. The semicircular geometry exhibited a maximum tensile strength of approximately 34 MPa, while the double semicircular configuration reached values close to 33 MPa. Figure 7. Although the difference in strength is modest, the deformation behavior revealed a noticeable advantage for the Double Semicircular interface. The highest strain at break recorded for the semicircular specimens was approximately 5.6%, whereas the double semicircular geometry achieved values close to 6%, Figure 8.

The mechanical response of these interfaces can be explained by the smooth curvature of the contact region. Unlike geometries containing sharp corners or abrupt transitions, semicircular interfaces promote a gradual redistribution of stresses along the bonded area. This characteristic reduces the likelihood of localized stress concentrations and contributes to a more stable deformation process. The introduction of a second semicircular feature further enhances this effect by increasing the number of load-transfer paths available within the interface region. Consequently, the Double Semicircular configuration exhibits an improved capacity to accommodate deformation before failure, even though the increase in tensile strength remains limited.

Another aspect that may contribute to the observed behavior is the manner in which the deposited filaments conform to curved geometries during the FDM process. Rounded interfaces generally facilitate a smoother deposition path and may reduce the occurrence of localized discontinuities or voids that could act as crack initiation sites. As a consequence, failure is less likely to originate from isolated defects, leading to a more

progressive damage evolution and higher elongation values. This effect becomes particularly evident in the Double Semicircular specimens, where the combined influence of geometric interlocking and improved stress redistribution results in the highest deformation capacity among the investigated configurations.

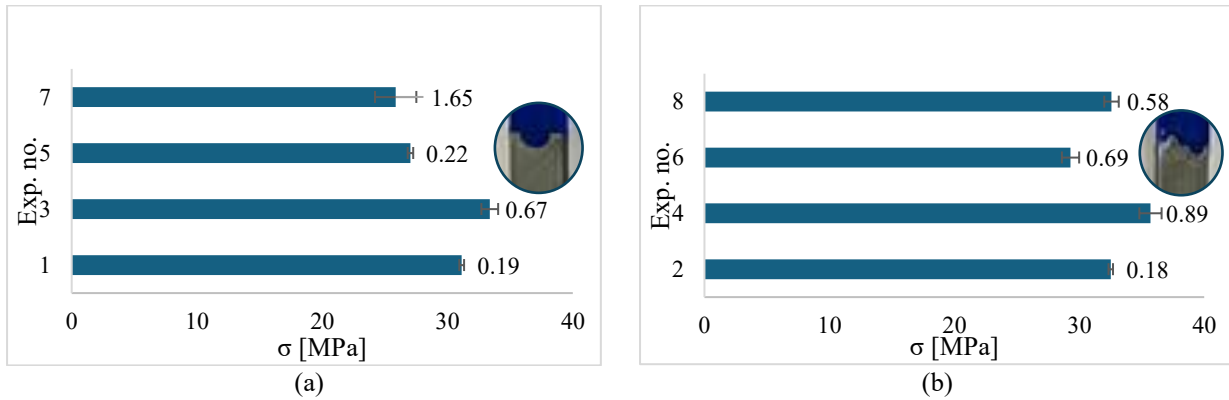


Fig. 7. Tensile strength: (a) semicircular interface (b) double semicircular interface

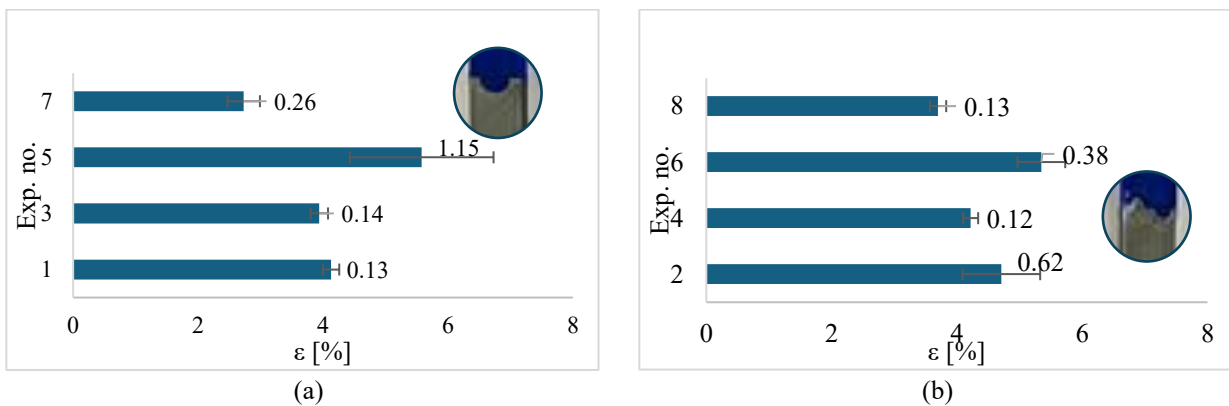


Fig. 8. Strain at break: (a) semicircular interface (b) double semicircular interface

Overall, the comparison between the U-shape and 2U-shape interfaces, as well as between the semicircular and double semicircular geometries, indicates that the introduction of additional interlocking regions generally improves the ability of the interface to transfer loads and accommodate deformation. While the increase in tensile strength is not always substantial, the enhancement of strain at break suggests that more complex interface architectures can contribute to a more gradual failure process and a more efficient utilization of the bonding mechanisms developed during multi-material FDM fabrication.

Thus, the results show that geometries with curved surfaces (U and semicircular) exhibit a different behavior compared to geometries with pronounced edges (T and dovetail). Curved interfaces distribute stresses more uniformly and reduce the occurrence of local stress concentrations, which explains their high strain-at-break values. In addition, the filament path deposited by the FDM process follows a curved geometry more naturally, reducing the likelihood of void formation or discontinuities in the contact region between the materials.

In contrast, the dovetail geometry develops a pronounced mechanical interlocking effect, leading to high tensile strength values. However, the presence of abrupt cross-sectional changes may generate regions of elevated local stresses, limiting the deformation capability compared to curved geometries.

From a practical application perspective, if the primary objective is to achieve maximum strength, the 2U interface appears to be the most advantageous solution, followed by the U geometry and the dovetail configuration. However, if the application requires high energy absorption capacity, deformation tolerance, and a less abrupt failure mode, the Double Semicircular interface represents the most suitable choice.

Overall, among all the investigated configurations, the 2U interface can be considered the most balanced solution, as it provides both the highest tensile strength and one of the highest strain-at-break values. This behavior indicates a favorable combination of interfacial adhesion, mechanical anchoring effects, and uniform stress distribution during tensile loading.

4. CONCLUSIONS

The experimental results demonstrated that interface geometry plays a critical role in determining the mechanical performance of bi-component FDM structures. Both tensile strength and strain at break were strongly affected by the ability of the interface design to promote efficient load transfer and mechanical interlocking between the joined materials. Among the investigated configurations, the double U-shape interface exhibited the highest tensile strength, reaching approximately 37 MPa, while the double semicircular geometry provided the highest deformation capability, with strain at break values approaching 6%. Compared with their single counterparts, most double-interface configurations showed improved mechanical performance, indicating that the introduction of additional anchoring regions enhances the bonding efficiency and delays the initiation of interfacial failure. The results also highlighted the combined influence of interface geometry and process parameters. Variations in layer height and number of deposited layers affected the quality of the bond formed between adjacent materials, demonstrating that mechanical performance cannot be attributed solely to geometric design. Instead, an appropriate combination of interface architecture and printing conditions is required to maximize the structural integrity of multi-material components. From an engineering perspective, the 2U-shape interface can be considered the most balanced solution, as it combines high tensile strength with a significant deformation capacity before failure. Consequently, this geometry is recommended for applications requiring both load-bearing capability and structural reliability. Potential applications include lightweight structural elements, customized fixtures, functional prototypes, automotive interior components, consumer products, and multi-material assemblies subjected to moderate mechanical loads. On the other hand, the double semicircular interface may be more suitable for applications where energy absorption, flexibility, and damage tolerance are of primary importance. Examples include protective elements, vibration-damping components, wearable products, soft mechanical systems, and non-critical joints exposed to repeated deformation. The findings of this work confirm that optimizing the interface geometry represents an effective strategy for improving the mechanical performance of multi-material FDM parts. Future research should focus on a more detailed investigation of failure mechanisms through fractographic analysis, as well as on the development of numerical models capable of predicting stress distribution and damage evolution at complex multi-material interfaces.

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5. REFERENCES

- [1]. Wang Z., Wang L., Tang F., Chen J., (2025), *Multi-material additive manufacturing via fused deposition modeling 3D printing: A systematic review on the material feeding mechanism*, Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 239(6), DOI: 10.1177/09544089231223316.
- [2]. Bandyopadhyay A., Heer B., et al., (2023), *Multi-material additive manufacturing: A systematic review of design, properties, applications, challenges, and 3D printing of materials and cellular metamaterials*, Materials & Design, 226, art. 111661, DOI: 10.1016/j.matdes.2023.111661.
- [3]. Guessasma S., Belhabib S., Nouri H., (2019), *Interface geometries in 3D multi-material prints by fused filament fabrication*, Rapid Prototyping Journal, 25(1), 38–46, DOI: 10.1108/RPJ-05-2017-0107.
- [4]. Frascio M., Zafferani A., Monti M., Avalle M., (2024), *Investigating enhanced interfacial adhesion in multi-material filament 3D printing: A comparative study of T and Mickey Mouse geometries*, Progress in Additive Manufacturing, 9, 2113–2122, DOI: 10.1007/s40964-024-00570-8.
- [5]. Delia S., Rochman A., Curmi A., (2024), *Factors affecting interface bonding in multi-material additive manufacturing*, Progress in Additive Manufacturing, 9, pp. 1365–1379, DOI: 10.1007/s40964-024-00617-w.
- [6]. Brown N.C., Ames D.C., Mueller J., (2025), *Multimaterial extrusion 3D printing printheads*, Nature Reviews Materials, 10, 807–825, DOI: 10.1038/s41578-025-00809-y.
- [7]. Li B., Fu J., Feng J., Shang C., Lin Z., (2020), *Review of heterogeneous material objects modeling in additive manufacturing*, Visual Computing for Industry, Biomedicine, and Art, 3(6), DOI: 10.1186/s42492-020-0041-6.

- [8]. Ettayan H., Abdous I., Ouballouch A., Boutahar L., (2024), *Review on multi-material 3D printing via FDM: Insights into mechanical performance and printing parameters*, Journal of Machine Construction and Maintenance, DOI: 10.5604/01.3001.0055.4326.
- [9]. Moïni M., Olek J., Magee B., Zavattieri P., Youngblood J., (2019), *Additive Manufacturing and Characterization of Architected Cement-based Materials via X-ray Micro-Computed Tomography*, Materials Characterization, 150, 168–180.
- [10]. Prause E., Hey J., Beuer F., Yassine J., Hesse B., Gerber J., Schmidt F., (2024), *Microstructural investigation of hybrid CAD/CAM restorative dental materials by micro-CT and SEM*, Dental Materials, 40(1), 58–69, DOI: 10.1016/j.dental.2023.10.012.
- [11]. Zhang Y., Chou K., (2008), *Three-dimensional finite element analysis simulations of the fused deposition modelling process*, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 222(8), 959–967, DOI: 10.1243/09544054JEM858.
- [12]. Ahn S.H., Montero M., Odell D., Roundy S., Wright P.K., (2002), *Anisotropic material properties of fused deposition modeling ABS*, Rapid Prototyping Journal, 8(4), 248–257, DOI: 10.1108/13552540210441166.
- [13]. Spoerk M., Arbeiter F., Raguž I., Weingrill G., Fischinger T., Traxler G., Schuschnigg S., Cardon L., Holzer C., (2018), *Polypropylene filled with glass spheres in extrusion-based additive manufacturing: Effect of filler size and printing parameters*, Macromolecular Materials and Engineering, 303(4), DOI: 10.1002/mame.201700326.
- [14]. Zuo C., Tao T., Feng S., Huang L., Asundi A., Chen Q., (2018), *Micro Fourier Transform Profilometry (μ FTP): 3D shape measurement at 10,000 frames per second*, Optics and Lasers in Engineering, 102, 70–91, DOI: 10.1016/j.optlaseng.2017.10.019.
- [15]. Leach R., (2011), *Optical Measurement of Surface Topography*, Springer, Berlin, DOI: 10.1007/978-3-642-12012-1.
- [16]. Thompson M.K., Moroni G., Vaneker T., et al., (2016), *Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints*, CIRP Annals, 65(2), 737–760, DOI: 10.1016/j.cirp.2016.05.004.
- [17]. Yadav D., Chhabra D., Garg R.K., Ahlawat A., Phogat A., (2020), *Optimization of FDM 3D printing process parameters for multi-material using artificial neural network*, Materials Today: Proceedings, 21, 1583–1591, DOI: 10.1016/j.matpr.2019.11.286.
- [18]. Rajpurohit S.R., Dave H.K., (2018), *Effect of process parameters on tensile strength of FDM printed PLA part*, Rapid Prototyping Journal, 24(8), 1317–1324, DOI: 10.1108/RPJ-06-2017-0134.
- [19]. Farahani R.D., Dubé M., Therriault D., (2016), *Three-dimensional printing of multifunctional nanocomposites: Manufacturing techniques and applications*, Advanced Materials, 28(28), 5794–5821, DOI: 10.1002/adma.201506215.
- [20]. Ngo T.D., Kashani A., Imbalzano G., Nguyen K.T.Q., Hui D., (2018), *Additive manufacturing (3D printing): A review of materials, methods, applications and challenges*, Composites Part B: Engineering, 143, 172–196, DOI: 10.1016/j.compositesb.2018.02.012.
- [21]. Fico D., Rizzo D., Casciaro R., Esposito Corcione C., (2022), *A Review of Polymer-Based Materials for Fused Filament Fabrication (FFF): Focus on Sustainability and Recycled Materials*, Polymers, 14, art. 465, DOI: 10.3390/polym14030465.
- [22]. Cojocar V., et al., (2022), *The Influence of the Process Parameters on the Mechanical Properties of 3D Printed Parts*, Polymers, 14, art. 886, DOI: 10.3390/polym14050886.