BEAD-WEAVED LAYERED PRINTS FOR IMPROVED INTERLAYER ADHESION IN ADDITIVE MANUFACTURING

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Abstract

Additive manufacturing (AM) with polymer materials has seen widespread adoption across industries due to its numerous benefits: rapid prototyping, material variety, cost efficiency, manufacturing complexity, on-demand production, and sustainability. AM enables fast prototyping, diverse material choices, and cost savings by eliminating tooling and reducing waste. It excels at producing intricate, lightweight designs while on-demand production leads to a reduction of inventory and lead time. Polymer AM contributes to sustainability by minimizing material waste. These advantages make polymer AM popular in aerospace, automotive, healthcare, and consumer products industries. Despite these advantages, interlayer adhesion has been a reoccurring issue with additive manufacturing of polymer materials. With polymer printing, there has been a decline in mechanical properties because of poor interlayer adhesion. Due to this issue, there has been a rise in research related to the improvement of interlayer bonding with Fused Deposition Modeling (FDM), giving rise to the idea of bead-weaved layered prints. **The goal of this work is to leverage anisotropic mechanical properties, which currently limit the application of AM parts, such that deposited material is preferentially orientated to expected strain fields by using multi-axis 3D printing.** To achieve these goals, the following hypothesis statements were tested. Hypothesis Statement 1: The weaving of beads, as opposed to planar layers whose interaction with upper/lower material is solely dependent on interlayer bonding, will fundamentally change the shear and tensile stresses experienced by AM parts. Hypothesis Statement 2: The deposition of transversal beads will reduce stress concentrations at layer interfaces yielding isometric mechanical properties - a desirable characteristic not currently associated with material extrusion AM. Hypothesis Statement 3: Multi-planar deposition will improve part complexities by enabling the manufacturing of complex geometries without the need for support material.

Background

Fused Deposition Modeling (FDM), a prominent 3D printing technology, has revolutionized the manufacturing landscape, enabling rapid prototyping, customized production, and complex geometries that traditional methods cannot achieve. The significance of FDM lies in its versatility and accessibility, making it an indispensable tool in fields ranging from aerospace to biomedical engineering. However, as the technology advances, it encounters a spectrum of challenges. Among these, ensuring structural integrity and mechanical performance of printed objects remains a paramount concern. This is particularly crucial in applications where failure due to material weaknesses can have serious implications, such as in load-bearing components or medical implants.

Printing with polymer materials presents several challenges that engineers and manufacturers need to address. One significant challenge is the issue of material compatibility. Polymer 3D printing relies on the specific properties of the chosen polymer, and ensuring that the material is suitable for complex printing processes. Factors such as viscosity, temperature sensitivity, and adherence to build surfaces must be carefully considered to achieve optimal print quality. Additionally, polymer materials can be prone to warping during the printing process, leading to deformities in the final product [1]. This challenge necessitates the development of precise printing conditions and support structures to mitigate warping and maintain the integrity of the printed object.

Another notable challenge in polymer 3D printing is the limited range of materials available compared to traditional manufacturing processes. While the variety of polymer materials for 3D printing has expanded in recent years, it still lags behind the extensive range of materials available for conventional manufacturing methods. This limitation hinders the versatility of polymer 3D printing in producing functional and durable components for various applications. Researchers and industry professionals are actively working on expanding the repertoire of printable polymer materials, addressing challenges related to strength, flexibility, and other material properties to enhance the overall capabilities of polymer 3D printing technology. For example, the efforts made by Neiko Levenhagen at The University of Tennessee, who investigated the use of low molecular weight surface segregating additives to improve the interlayer adhesion and reduce the anisotropy in the mechanical properties of 3D printed parts made by fused deposition modeling [2]. Other research contributing to the advancement of interlayer adhesion demonstrates that when using polylactic acid (PLA) as the material, cold plasma treatment significantly enhances the interlayer bonding strength of FDM printed parts by over 100% with 30 seconds of treatment and over 50% with 300 seconds of treatment [3].

Introduction

The core challenge of polymer AM lies in the aspect of interlayer adhesion. In FDM, objects are constructed layer by layer, and the strength of these layers' bonds directly impacts the overall structural integrity of the final product. Poor adhesion can lead to delamination, reduced strength, and ultimately, failure of the component under stress. Orienting the material in alignment with anticipated strain directions is a critical strategy in overcoming these limitations. This approach has shown promise in two-dimensional applications, but its extension to three-dimensional printing presents a complex challenge, requiring a deep understanding of material properties, print settings, and stress distribution. The contribution from Yutong Fu, explores the design strategies and mechanical properties of 3D printed continuous fiber reinforced thermoplastic fabric composites, finding that fiber volume fraction and bead aspect ratio are crucial for strength and space utilization, with performance enhancements achievable through optimized printing methods compared to traditional resin transfer molding [4]. In a similar way that the fabric composites were produced to optimize the strength, the bead-weaved prints were also created centered around the same approach. Previous research in this area has laid a foundation, but there remains a significant gap in applying these principles effectively in FDM.

Since interlayer adhesion plays a crucial role in determining the overall strength and integrity of the printed object, research studies often focus on optimizing printing parameters, such as temperature, layer height, and printing speed, to enhance interlayer adhesion and eliminate potential weaknesses or delamination issues between layers. An example of this is Alberto Andreu's effort to increase the mechanical properties in FDM by using a heated roller to compress each printed layer, resulting in increased interlayer adhesion, tensile strength, flexural strength, and reduced porosity in the produced components [5].

Additionally, in traditional 2D manufacturing processes, interlayer adhesion is a fundamental consideration in the fabrication of materials like composites and laminates. The bonding between layers in materials such as plywood, composite materials, and adhesive-bonded structures is essential for achieving the desired mechanical properties and structural stability. Numerous research papers delve into the mechanics of interlayer adhesion in these materials, investigating factors such as adhesive properties, surface preparation, and curing conditions. For instance, the significant progress in developing high-performance polymer nanocomposites for AM, emphasizes the potential to enhance performance and multifunctionality across techniques like FDM, Selective Laser Sintering, Multi Jet Fusion, and Stereolithography, thereby expanding the materials portfolio and enabling the production of complex multifunctional parts [6].

The primary aim of this research is to address the critical challenge of layer adhesion in FFF of polymer materials. By leveraging insights from two-dimensional applications and advancing them into the realm of three-dimensional printing, this study seeks to develop strategies that enhance interlayer bonding without compromising the material's integrity or the printing process's efficiency. The research will explore various aspects, including material composition, print settings, post-processing techniques, and the orientation of filament deposition. The ultimate goal is to establish guidelines that can be universally applied to improve the reliability and performance of FDM-printed objects, thereby expanding the potential applications of this transformative technology in various industries.

Methodology

A. Bead-weaved Pattern with Modified Transition

Due to the challenge of interlayer adhesion presented in Material Extrusion, bead-weaved layered prints were fabricated to not only promote better interlayer adhesion, but also to see if the introduction of angles increases the print properties with respect to polymer chain orientation.

Bead-weaved prints, shown in Figure 1, are alternating orthogonal and planar prints at 90° and 0° and aligned with the x and y - axis. This has been researched to see if the method of bead-weaving the deposited polymer will not only promote better interlayer adhesion, but also to see if the introduction of angles increases the print properties with respect to polymer chain orientation.

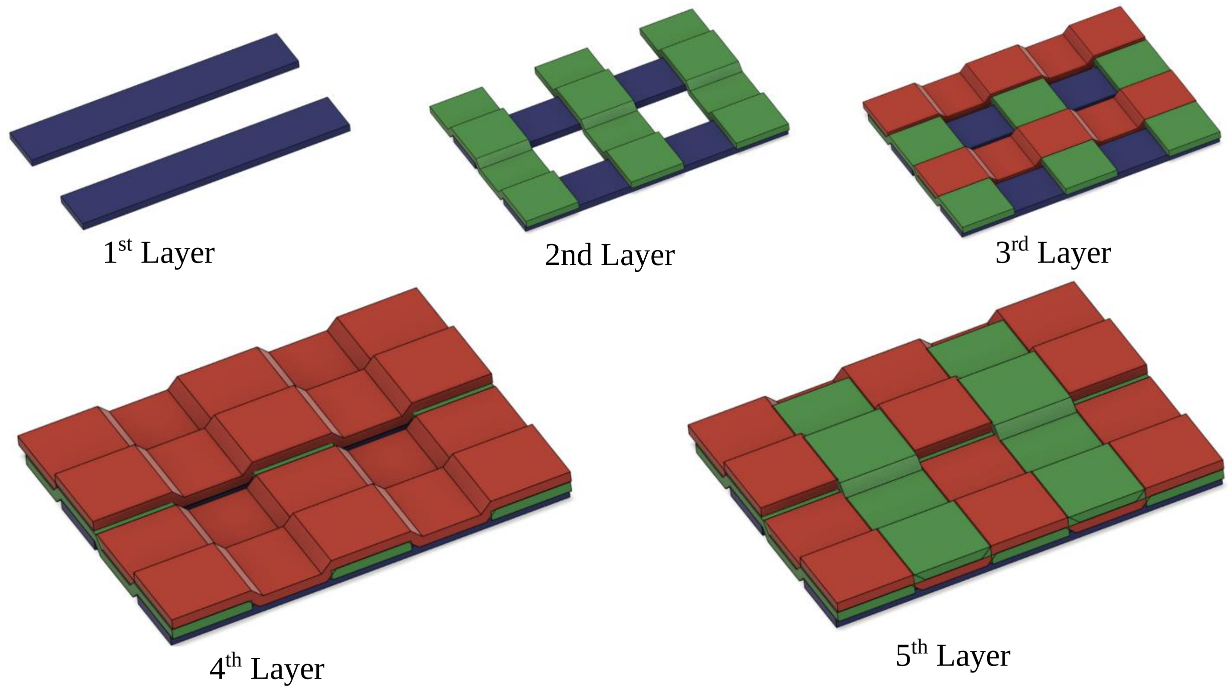

Figure 1 Bead-weaved structure

The innovative bead-weaved infill pattern employed in this study represents a unique and intricate methodology in polymer 3D printing. The process involves the strategic placement of small clusters of beads that are extruded along the x and y-axis of the print bed during the layer-by-layer printing of objects, creating a distinctive bead-weaved effect reminiscent of woven textiles. This infill pattern was created at every layer of the print.

In the context of FDM 3D printing, replicating traditional bead-weaved patterns poses unique challenges. Unlike traditional methods, where materials are not fused together, FDM printing involves the layer-by-layer deposition of melted polymer strands, limiting accessibility to the underside of the material once it has been deposited. This restriction impedes the execution of the same types of weaves seen in traditional applications.

While the direct translation of traditional bead-weaved patterns may be challenging in FDM printing, the technology offers a distinctive advantage in its ability to vary the dimensions of the strand within 3D space. In this approach, the strand can be manipulated in terms of thickness and direction, providing flexibility in creating complex and innovative bead-weaved structures. The strand is not confined to linear travel but can vary in directions within the 3D space, allowing for the creation of intricate patterns that go beyond the constraints of traditional weaving techniques.

In the experimental setup, a gcode was created to deposit additional material in the gaps formed during the Z-axis transition of the extruded bead. This supplementary material was precisely placed to fill the voids, ensuring a continuous and solid structure throughout the 3D printed object, shown in Figure 2. Various combinations of deposition rates and transition distances were systematically tested to determine the optimal parameters for enhancing structural integrity while preserving the intricate bead-weaved pattern.

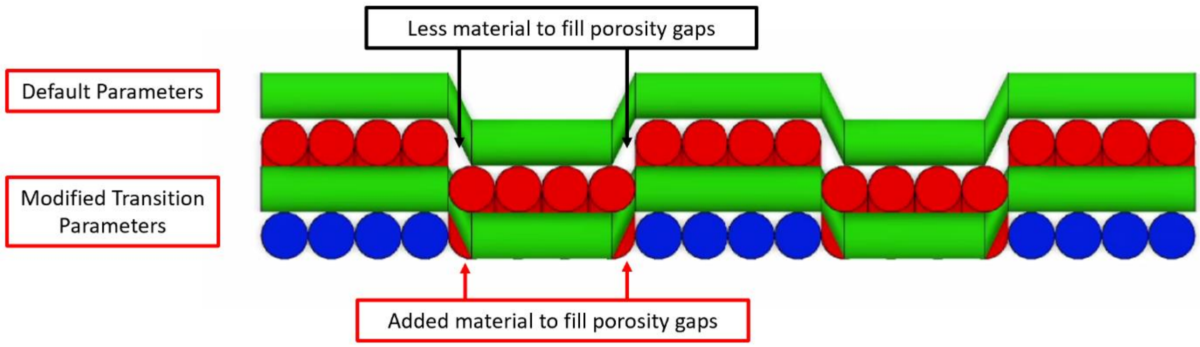

Figure 2 Side-profile of Bead-weaved printing in comparison to the Modified Transition specimen

The primary objective of introducing extra material during Z-axis transitions was to address the inherent gaps within the bead-weaved infill pattern. This experimental approach proved instrumental in mitigating weaknesses associated with these gaps, resulting in a more robust and cohesive 3D printed structure.

Traditionally, the emphasis in polymer 3D printing research has revolved around optimizing interlayer adhesion as a primary means of reinforcing the mechanical properties of printed parts. While interlayer adhesion undoubtedly plays a crucial role in determining overall strength, a paradigm shift is underway acknowledging the significance of specifically targeting Z-direction strength. This shift recognizes the importance of fortifying the structural integrity of 3D printed parts in the vertical axis, a dimension often subjected to unique stressors and critical for applications where load-bearing capabilities are paramount. A real-world application that highlights the importance of structural integrity in the Z-direction for 3D-printed polymer parts is shown with the experiments from Stepans Kobenko. Kobenko produced Ultem 9085 parts via FDM that could withstand critical loads in aircraft interior applications, with numerical and mechanical testing confirming the effectiveness of width adjustments for increased bending stiffness and load-bearing capacity [7].

The Z-direction, or the vertical axis, presents distinct challenges that merit focused attention. In many applications, 3D printed parts encounter forces predominantly aligned with the Z-axis, such as compressive and tensile loads. Neglecting the specific strengthening of this dimension may lead to compromised mechanical performance, especially in scenarios where the printed objects must withstand substantial vertical stresses. Recognizing this, the research seeks to redefine the conventional approach by prioritizing Z-direction strength alongside interlayer adhesion. The research from A. Castellanos demonstrates that incorporating Zinc Oxide nanowires as interlaminar stiffeners in woven carbon fiber polymer matrix composites significantly enhances the fracture toughness by 25-50%, indicating a promising approach for improving Z-direction strength in polymer 3D printed parts for tensile testing [8]. The strength of the part is also impacted by the raster orientation which highlights the fracture properties and overall strength of 3D-printed polymer parts, emphasizing the need for optimizing filament orientation during the FDM process to ensure structural integrity and prevent premature failures [9].

Certain applications demand a heightened focus on Z-direction strength. For example, load-bearing components in structural engineering, aerospace, and automotive industries experience forces primarily along the vertical axis. By specifically addressing the challenges associated with the Z-direction, the research aims to unlock new possibilities for utilizing polymer 3D printing in critical applications where vertical strength is a decisive factor.

The shift towards prioritizing Z-direction strength represents a pivotal advancement in polymer 3D printing research. By recognizing and strategically addressing the unique challenges associated with the vertical axis, the aim is to usher in a new era of 3D printed parts that not only excel in interlayer adhesion but also boast unparalleled strength and reliability, particularly in applications where vertical integrity is of importance. This shift opens avenues for broader applications and greater versatility in the utilization of polymer 3D printing technology. For instance, the review of advancements in additive manufacturing applications in the biomedical field, particularly tissue engineering, highlights the use of various AM technologies and polymer materials to fabricate complex structures like scaffolds with optimized mechanical properties for personalized patient care and improved implant durability [10].

The success of the bead-weaved infill pattern relies on meticulous parameter optimization, including bead size, spacing, and layer height, to achieve both aesthetic appeal and structural integrity. This study systematically explores the impact of these parameters to establish optimal printing conditions for creating intricate and mechanically robust bead-weaved structures. By introducing a novel and visually captivating approach to polymer 3D printing, the bead-weaved infill pattern adds a level of intricacy and complexity beyond conventional infill patterns, with ongoing efforts focused on refining the layer-by-layer bead placement process and enhancing overall print outcomes.

B. Bead-weaved Pattern Code Development

The development of the Bead-weaved pattern code represents a pivotal aspect of this research. This code, integral to the machine instructions, dictates the filament's deposition pattern during the FDM process. It was designed to optimize layer adhesion by strategically orienting the filament paths. The code incorporates advanced algorithms to adjust the weave pattern based on the geometry of the object being printed, thus ensuring uniform stress distribution across layers.

The unique feature of this code is its ability to dynamically alter the deposition pattern in response to the changing contours of the print object. This adaptability not only enhances interlayer adhesion but also minimizes material wastage and print time. Additionally, the code is designed to be compatible with standard FDM printers, making it easily accessible for broader application.

An intriguing facet of the approach lies in the non-recurring investment associated with the development of specialized code for the Bead-weaved structures. Unlike traditional manufacturing processes that may burden manufacturers with ongoing costs, the upfront investment in code development represents a one-time effort with enduring benefits. This investment allows for the customization and optimization of Bead-weaved patterns, introducing a level of intricacy and complexity that traditional methods struggle to achieve.

While not explicitly mentioned in the notes, it is important to recognize that the Bead-weaving process, by its nature, requires a minimum distance to avoid interference between thin layer walls. This characteristic may limit its applicability for intricate structures with extremely thin elements. However, it excels when applied to larger areas and bulkier pieces of material, where the weaving process can unfold seamlessly.

C. Materials

For this study, Polyethylene terephthalate glycol (PETG) polymer filament was selected due to its favorable mechanical properties, including high strength, toughness, and heat resistance, making it suitable for structural applications. A total of eight specimens were fabricated for each of the Default Bead-weaved group and the Modified Transition group, using a Raise Pro2 Plus 3D printer. The printer is capable of precise layering and accommodating various filament types, ensuring accurate replication of bead-weaved patterns. Post-processing involved machining on a Techno Computer Numerical Control (CNC) machine to refine sample dimensions and ensure consistency. Tensile testing was performed using an Instron tensile testing machine to assess mechanical performance, including strength and elasticity, crucial for evaluating the impact of bead-weaved patterns on part durability.

D. Machining Process

Machining of the specimens was essential to eliminate potential stress concentrators. Due to the intricate bead-weaved patterns and variations in deposition during 3D printing, the specimens did not achieve uniform volume throughout. Machining on a Techno CNC machine allowed precise control over dimensions, ensuring consistency and removing any irregularities that could act as stress concentrators during subsequent mechanical testing. This step was crucial to obtain reliable and accurate tensile strength data, reflecting the true structural integrity of the bead-weaved samples. In order to address potential stress concentrators, a rectangular shape was fabricated and subsequently machined, as shown in figure 3, referencing ASTM standard D638 [11].

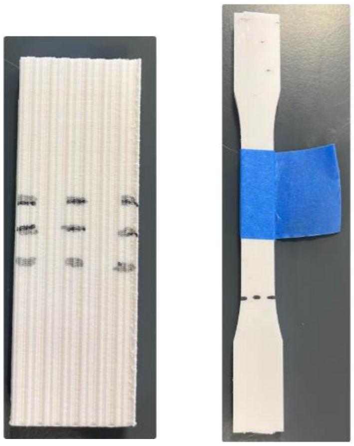

Figure 3 Machined dog-bone specimen

Results

To assess the tensile strength of the Bead-weaved structures, representative stress-strain curves were generated for each treatment. From these curves, the best represented sample group was selected to create an overlay graph with both plots for comparison. The analysis focused on key parameters such as toughness, modulus, strain at break, and yield strength:

- Toughness: The representative stress-strain curve demonstrates the material's ability to absorb energy before failure, indicating enhanced toughness in the modified samples.

- Modulus: The modulus, representing the material's stiffness, showcased improvements in the modified samples, indicating increased structural rigidity.

- Strain at Break: The strain at break, representing the material's flexibility, revealed enhanced ductility in the modified samples.

The tensile testing results demonstrate significant improvements in the mechanical strength of specimens using the Modified Transition approach compared to the default specimens. The highest Ultimate Tensile Strength (UTS) recorded for the default specimen was 20.44 MPa, shown in Figure 4, whereas the highest UTS for the Modified Transition specimen reached 31.13 MPa, shown in Figure 5. This substantial increase in UTS (by 51%) clearly indicates that the Modified Transition specimen exhibited superior tensile strength, capable of withstanding higher loads before failure.

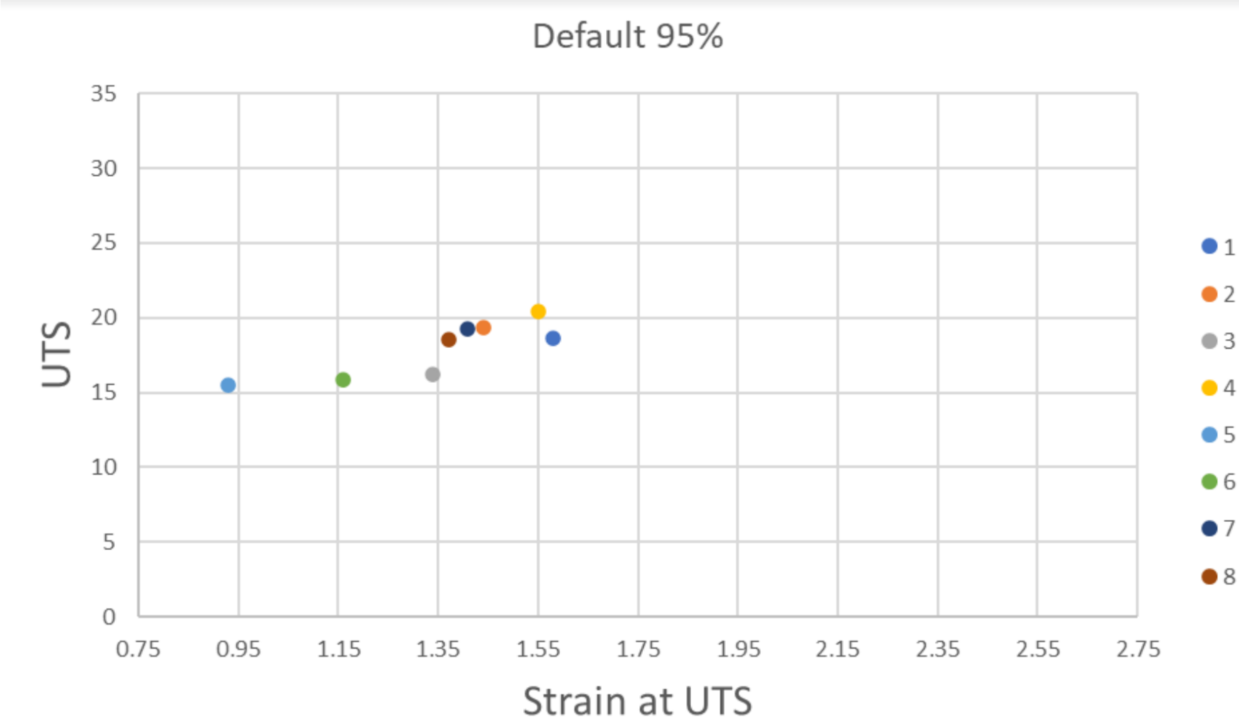

Figure 5 Default specimens' strength vs. strain graph

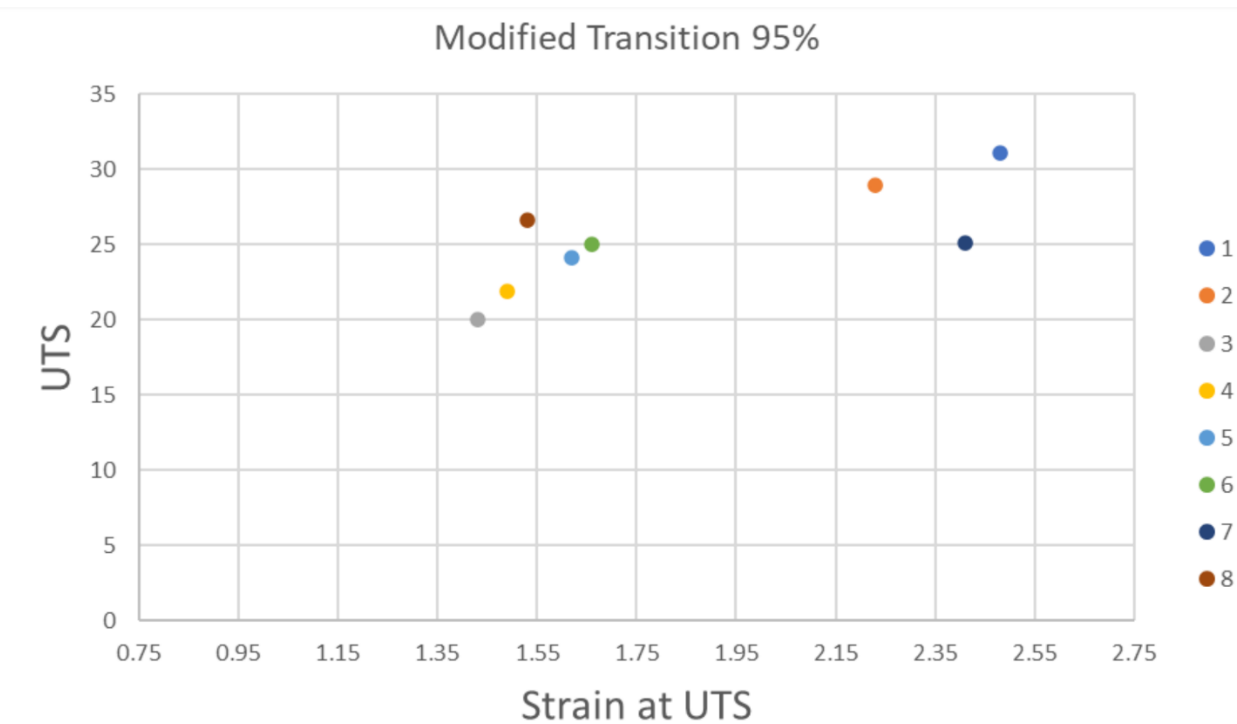

Figure 4 Modified Transition specimens' strength vs. strain graph

Moreover, the lowest UTS recorded for the default specimen was 15.51 MPa, whereas the lowest UTS for the Modified Transition specimen was 20.00 MPa. This difference underscores the consistent trend observed across all tested samples, shown in Figure 6, where the Modified Transition approach consistently outperformed the default method in terms of tensile strength. The increase in minimum UTS by 33% further reinforces the conclusion that the Modified Transition specimens were inherently stronger and more resilient under applied loads.

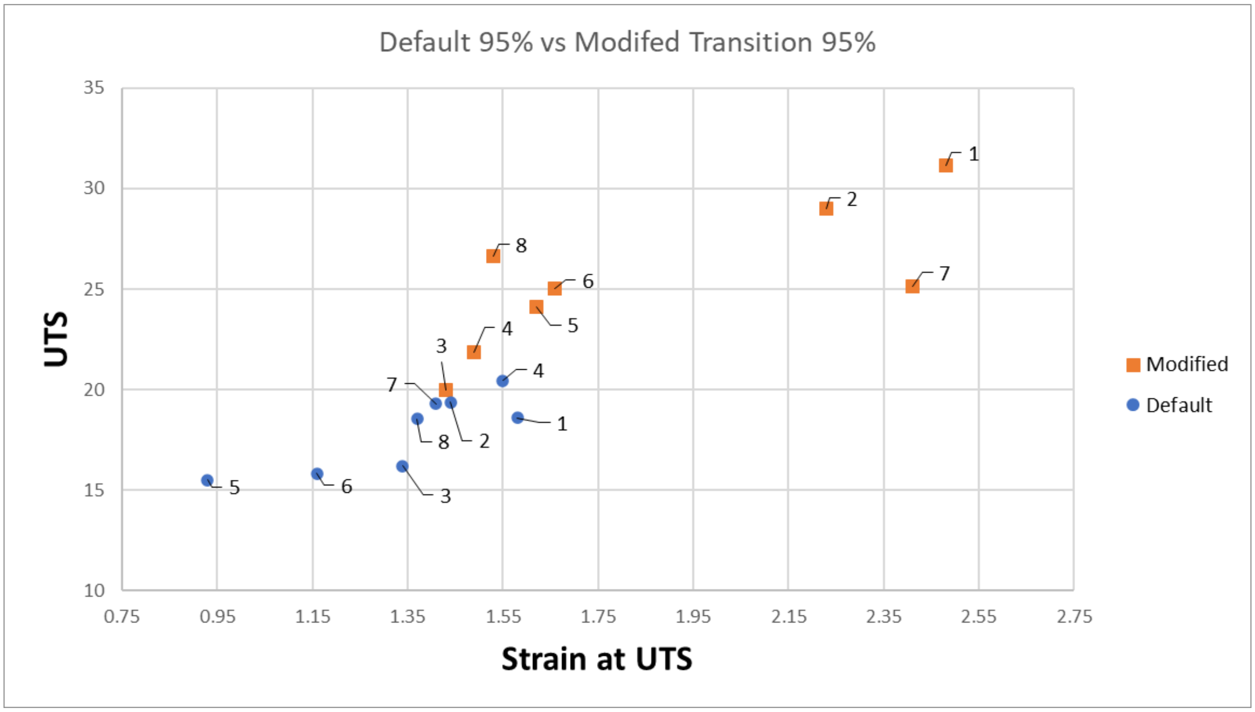

Figure 6 Default and Modified Transition specimens' strength vs. strain graphed together

The observed enhancements in tensile strength with the Modified Transition approach can be attributed to several factors. By strategically adding extra material during Z-axis transitions in the bead-weaved pattern, the Modified Transition specimens effectively minimized structural weaknesses and improved interlayer adhesion. This reinforcement mechanism prevented crack propagation and enhanced load-bearing capabilities, as evidenced by the higher UTS values obtained in the tensile tests.

The consistency in strength across different load conditions highlights the reliability and robustness of the Modified Transition specimens. This approach not only enhances mechanical performance but also ensures dimensional stability and integrity, crucial for applications requiring high structural reliability. Future research will focus on further optimizing the Modified Transition parameters to maximize strength while maintaining the intricate bead-weaved pattern, aiming to expand its applicability in various industrial and engineering sectors.

A gap in the UTS (Ultimate Tensile Strength) vs. strain at UTS graph for your polymer 3D printed parts may be due to several factors related to material properties, testing conditions, and printing parameters. One possible reason is the inherent anisotropy in 3D printed materials, where the layered structure leads to differences in strength and strain behavior along different axes. This could cause inconsistencies in how the material responds to tensile stress, especially near the UTS. Additionally, variations in filament deposition, print layer bonding, or porosity within the printed samples might affect the uniformity of the material, resulting in gaps in the data. Differences in strain hardening behavior or microstructural defects, such as voids or weak interlayer bonds, could also cause localized failure that creates discontinuities in the stress-strain response, leading to the observed gap. Moreover, testing conditions like strain rate or alignment of the sample during tensile testing might introduce variability that further contributes to this gap.

Discussion

The Bead-weaved pattern significantly enhances tensile strength, evident from stress-strain curves and analysis. The Z-direction material addition method strengthens interlayer bonding, which can be due to the reduction in porosity from the contact bonds of the beads. This highlights the potential of Bead-weaved structures for superior mechanical properties. Compared to traditional methods relying on foreign materials, the approach maximizes polymer compatibility without added complexities. Customizable strand dimensions in 3D space further enhance versatility. However, achieving balance between reinforcement and preserving pattern intricacies remains a challenge. The approach offers advantages in compatibility and versatility, with ongoing efforts to refine parameters and expand application in polymer 3D printing.

While the addition of extra material exhibited promising results in enhancing structural integrity, challenges were encountered in terms of fine-tuning the parameters for optimal outcomes. Striking a balance between reinforcing the gaps and preserving the aesthetic intricacies of the bead-weaved pattern required careful adjustment of variables such as material flow rate, deposition precision, and layer adhesion. Ongoing experiments aim to refine these parameters further, seeking to achieve an optimal compromise that ensures both mechanical strength and visual fidelity in the 3D printed objects.

Conclusion

FDM printing's flexibility in adjusting strand dimensions adds a new dimension to creativity and customization. This capability allows for variations not only in thickness but also in directionality, facilitating diverse design possibilities including unconventional bead-weaved patterns tailored for specific applications. This convergence of traditional craftsmanship with cutting-edge technology expands the boundaries of traditional weaving methods.

The research introduces a novel approach to bead-weaved patterns by strategically adding material in the Z-direction during transitions. This addresses challenges like gaps in the weave, enhancing structural integrity and capabilities beyond traditional methods. This innovative technique underscores the potential of bead-weaved structures for advanced applications across industries, enabling complex, multifunctional components.

Investing in code development for bead-weaved structures represents a forward-looking investment in advanced manufacturing. Despite challenges like distance constraints, the ability to project material in various directions and create interlocking mechanisms heralds a new era of design possibilities. This approach positions us at the forefront of innovation, offering manufacturers unique opportunities to explore and exploit the full potential of bead-weaved structures.

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