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Reviewed Paper

Compression, Shear, and Flexural Durability of Viscous Thread Printed (VTP) Foams Produced from Thermoplastic Polyurethane for Consumer Goods

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Abstract

3D printed foam is important for custom commercial and industrial applications. However, foams produced with Fused Filament Fabrication (FFF) present challenges over conventional foams in mechanical durability due to their heterogeneous microstructures, anisotropy, and susceptibility to wear. This study evaluates the performance of foams fabricated using viscous thread printing (VTP), a process variant that enables controlled porosity and coiling. Based on existing standards, we developed experimental methods to assess abrasive wear resistance, compressive, flexural, and shear durability of these unique materials. We quantified surface degradation under controlled contact conditions. Cyclic compression and shear tests evaluated structural resilience over repeated loading. Results show how density, surface finish, and filament interlayer bonding impact wear resistance and failure modes. The validated methods provide insights into the behavior of foamed FFF materials for applications requiring repeated loading and enhanced service life, such as biomedical and industrial applications.

Introduction

Recent advances in additive manufacturing enable the creation of architected materials with density gradients, porosity variation, and differential mechanical responses across custom shaped objects [1]. As a subset of architected materials, 3D printed foams are a growing field of research important in commercial and industrial enterprises. However, foams produced with Fused Filament Fabrication (FFF) present challenges over conventional foams in mechanical durability, anisotropy, and susceptibility to wear due to their heterogeneous microstructures. In contrast, conventional foams are often produced in bulk volumes with more isotropic mechanical properties with better characterized durability properties. Although work on conventional foams has found that test method variations and specimen preparation impact durability evaluations [2]. While the capabilities of FFF foams are useful for applications in cushioning, orthotics, impact protection, and noise damping, several studies have highlighted the formation of weak interlayer adhesion, structural gaps, and stress concentration points in FFF foams [3]. These issues collectively reduce the durability of FFF foams under cyclic loading, abrasion, and long-term compression; making them less attractive for consumer goods than conventional foams. These issues are particularly critical in use cases where foams experience repeated or multidirectional loading over extended periods. Thus, there is a need for characterization of FFF foam durability to achieve the desired benefits of greater customized foam production without the drawbacks of durability concerns when compared to conventional foams. Prior work has explored infill patterns, filament properties, and printing process parameters to enhance durability of 3D printed foams. An understanding of how FFF foam microstructures influence wear remains limited [4]. Existing mechanical characterization methods for conventional foams often fail to capture the progressive degradation modes unique to layer-wise printed foams across FFF systems and domains. As a result, the microstructure and durability of FFF foams can vary greatly as compared to conventional foam materials.

One way of producing stochastic foams using an FFF system is through a method known as Viscous Thread Printing (VTP). VTP involves using an FFF system to deposit filament in the viscous mode of thread instability, where the filament coils onto itself as it is deposited, and the coils are stochastically generated on a substrate [3]. In this study, we present a set of controlled experiments designed to quantify the mechanical durability of VTP foams across a range of infill densities using thermoplastic polyurethane (TPU). Thermoplastic polyurethane was chosen as it is one of the most used polymers for conventional foams used in consumer goods. Therefore, results on FFF foam produced using TPU will be the most widely impactful.

As a subdomain of FFF, VTP is useful for producing stochastic foams with randomly arranged, coiled microstructures. The average frequency and amplitude of these random coils generated by VTP may be varied by adjusting the ratio of extruder translation speed to thread extrusion speed as well as the ratio of extruder height to filament width. By varying the local, average, coil frequency and amplitude, we may vary density and porosity in the resulting foam. This variation may be used to produce stiffness gradients in VTP bodies, and this may help VTP foams improve on interlayer adhesion and stress concentration points over prior FFF foams [5]. In this work, we aim to identify key design parameters that govern failure behavior in VTP foams by integrating wear testing, dimensional measurements, and mechanical loading analysis, with the goal of informing more reliable and application-specific printed foam architectures. **Figure 1** shows VTP, study components, and example specimens.

In this paper we:

- Summarize how conventional and VTP PU foams are produced and tested
- Describe how VTP foam durability is measured and compared to existing foams
- Present results and insights on VTP foam durability

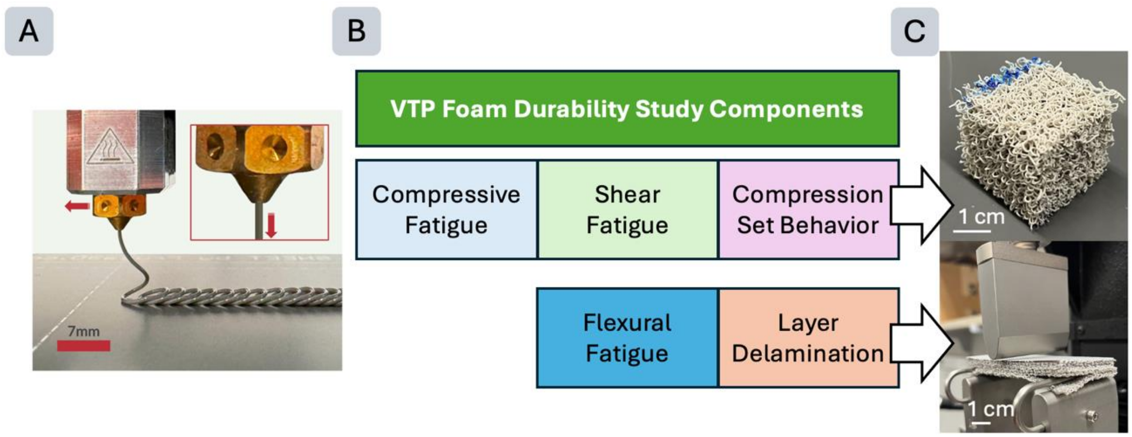

Figure 1. (A) Side view of extruder and thread during Viscous Thread Printing (VTP) showing the unidirectional motion of the extruder and the coiling of filament [3]. (B) The durability study consists of five component measurements. (C) Three study components use VTP foam cubes, and two study components use VTP foam bars.

The remainder of this paper is organized as follows. The background reviews prior and related work on the durability of 3D printed foams in relation to conventional foams. The standards section will discuss relevant metrics for foam durability testing. The testing section will describe our tools for evaluating VTP foam durability, and the results section will review key outcomes. Finally, a discussion and conclusion will summarize insights derived from our results on VTP foams produced with TPU.

Background

Foams are used in shock absorption, thermal, acoustic, or other domains due to their strength to weight ratio, physical properties, and unique cellular microstructure. As a result, foams are used in protecting fragile objects, packaging electronics, and transporting goods. The high porosity and low density of foam make it ideal for lightweight structural components, seals, and packaging. However, foam's lightweight and porous properties often relate to its low mechanical strength and poor durability [5]. This means that the fatigue life of foams is often relatively low compared to other materials. Foam fatigue life is often the lowest among all the components that make up a mechanical system. Therefore, improving the durability of foam used in a system is often the most efficient way to impact the fatigue life of a system with foam [6].

Foam manufacturing is currently being disrupted by new methods and materials. Additive manufacturing of foam is one way in which the foam industry is changing. VTP is a subset method of FFF able to produce stochastic foams from conventional, low-cost, FFF printers. The foams produced from VTP are comparable to conventional foam mechanical properties and microstructure, but the manufacturing steps are fundamentally different [3]. Most conventional foams are manufactured by the combination of blowing agents with fluidized polymer chains in chemical reactions. In this process, ambient gases are absorbed by a mixture of viscous chemical reagents. The chemical mixture solidifies as it expands and then trapped gases are released once the foam cells expand and break, resulting in a porous structure [2]. In VTP, a continuous thread of filament is coiled onto itself such that a porous microstructure is generated without the need for a blowing agent. While both conventional foams and 3D printed foams may be manufactured to have the same modulus or strength, the way in which each material is manufactured has impacts on the resulting strength [3]. **Figure 2** shows a microscope image of both conventional TPU foam and VTP foam to visually compare these two microstructures.

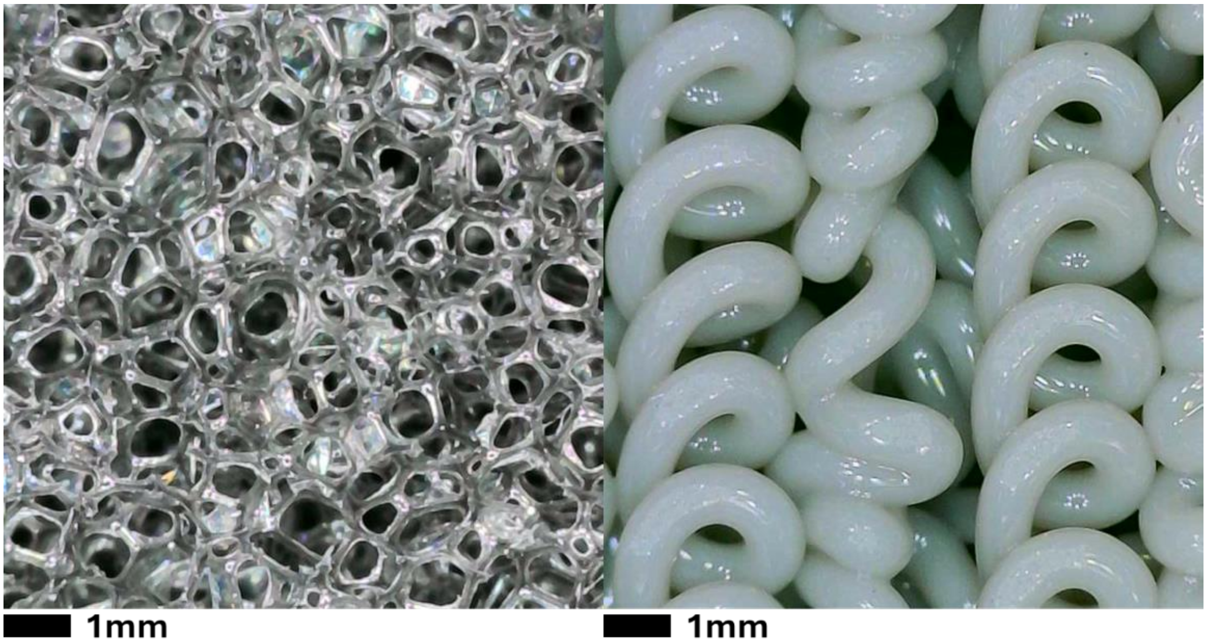

Figure 2. Microscope images of conventional open-cell polyurethane foam (left) and VTP foam (right) microstructures.

Conventional polymer-based foams have relatively uniform and isotropic cellular structures. Their fatigue damage increases as cell walls rupture, plastic deformation occurs to the microstructure, or a loss of elasticity occurs under repeated loading. Because of their homogeneous microstructure, fatigue tends to progress diffusely, with stress distributed more evenly throughout the material. While they may soften or degrade over time due to thermal and mechanical cycling, their homogeneous nature helps delay the onset of localized failure under uniform loading conditions.

In contrast, VTP foams with TPU may exhibit anisotropic mechanical behavior due to their layered construction and semi-patterned internal geometry [4]. Fatigue damage in these materials is often driven by delamination at the interlayer boundaries, crack initiation at print defects, and stress concentrations along edges. These factors suggest that 3D printed foams are more prone to localized fatigue and early failure along weaker axes. However, they offer the advantage of tunable mechanical properties, allowing designers to optimize fatigue performance through controlled geometry, material gradients, and directional reinforcement. If the localized failure issue of 3D printed foams was better understood, we could benefit from the advantages of tunable stiffness without the concern for durability.

Standards for Testing 3D Printed Foams

We examined existing practices and standards for evaluating the durability and strength of conventional polyurethane foams to assess whether the same methods would be applicable to our 3D printed TPU foams. In this study, we looked standards by the International Organization for Standardization (ISO) as well as standards D2240 and D3574 from the American Society for Testing and Materials (ASTM). Both are independent standards on how to evaluate the performance of foam. The ASTM standards cover a wide range of properties important to foam. This includes density, IFD (Indentation force deflection), CFD (Compression force deflection), Compression Sets, Tensile Strength, Tear Strength, Air Flow, Fatigue (Static, Pounding, Roller Shear, Caster), steam autoclave impact, heat aging (dry or wet), and other factors. While each of these factors are significant for specific applications, based on the use-case, only a few factors may be key to determining whether a particular FFF foam will be useful. In this study, we are interested in the factors of the foam's robustness that correspond to its usage in human interactions and consumer goods. For this use case type, we care about the mechanical properties of the foam and its response to stresses around that of hundreds of newtons in force per square centimeter. This approximate stress range corresponds to the force imparted by the average person's weight [8]. **Table 1** shows a subset of all studies considered in the durability evaluation of VTP TPU foams and how they impacted our experimental design as well as their limitations for use in FFF foam studies in general.

Standards Used in Designing the VTP Foam Durability Study			
Standard	**VTP Durability Component(s)**	**Impact**	**Limitation Noted by Authors**
ASTM D2240 [9]	Surface Hardness	Modulus measurement and strain rate	Gradient Density Foam not considered
ASTM D3574 [10]	Compression and Shear Fatigue	Setting testing bounds, magnitude of stress	Anisotropic foams not covered
ISO 1856 [11]	Compression Set	Setting testing bounds, time duration of tests	Creep behavior in FFF foams
ISO 8067 [12]	Flexural Fatigue	Flexural specimen size, shape, and bounds	Separation of shear and flexural terms

Table 1. Standards used to design the VTP foam durability study, their impact, and limitations of each standard for FFF foam evaluation.

Testing of VTP Foam Samples

A universal testing machine (UTM, Instron 68SC series) and a custom high-cycle fatigue testing machine were used to evaluate the VTP foam samples produced in this work. The results from the independently calibrated UTM and our custom fatigue testing machine were compared against one another in compression and flexural loading. The results were within the margin of accuracy on the UTM load cell after cyclic testing in both systems. This provided us with confidence that our custom fatigue testing machine was capable of producing the same cyclic stresses as the UTM. The custom fatigue testing machine was produced by attaching a fixed displacement toolhead onto the end of a sawzall power tool. The sawzall and the toolhead were mounted into a rigid box made from bars of aluminum extrusions.

In this work, we tested the durability of five different VTP foam densities at 0.020, 0.050, 0.101, 0.202, and 0.504 g/cm3. We refer to these specimen densities as relatively very low, low, medium, high, and very high density respectively to simplify references to these different density levels. The bulk material of the filament was NinjaTek NinjaFlex TPU at 85A durometer, 12 MPa tensile modulus, and density of 1.19 grams/cm^3. Each individual VTP test specimen, cube or strip, was cut from a homogenous block of uniform VTP parameters using a bandsaw. The low and high density VTP specimens were the focus of our analysis and intermediate densities were tested to ensure that interpolation was correct. Five specimens at each density for each shape (cube and strip) were produced as assessed to ensure repeatability. We assessed the range of durability in the specimens by studying the response of low & high density VTP TPU foams.

VTP Foam Durability Results

The VTP foam durability test results show the impact of several key VTP design parameters. At relatively high VTP foam density, the rate of modulus degradation is lower. As the coils of VTP foam shrink, the behavior of the viscous thread changes and the resulting microstructure approaches that of conventional FFF TPU. The compression set of the printed material will converge on conventional FFF TPU as VTP design parameters approach those of standard FFF. This shows that VTP may be considered a subdomain of the greater FFF design space where viscous thread instabilities play a role in deposition of filament threads [7].

In this work, we obtained stress-strain curves of each homogenous VTP foam density under evaluation for compression, shear, and flexural fatigue using the UTM and a custom fatigue testing machine,. Using a set of vice blocks, we placed different densites of homogenous VTP foam under a fixed strain to obtain compression set data. Select plots are included in the following sections to demonstrate the observed impact of VTP foam design parameters.

Compression Fatigue

Stress-strain curves are important for assessing the fatigue life of foam materials because they show how the foam responds to mechanical loading over time and usage. Key properties such as stiffness, elasticity, yield point, and energy dissipation are captured in a stress-strain plot. Foams often experience complex loading and unloading cycles, and the shape and evolution of the stress-strain curve during repeated deformation can indicate progressive damage mechanisms like cell wall buckling, or plastic deformation. By analyzing changes in hysteresis, modulus degradation, or residual strain across cycles, we may predict how long the foam will maintain its mechanical integrity under use in a human body weight application. A value of 220 N was used for loading on the ball of one foot for an average human body [8]. This level of force ensured our measured stress-strain response may be used in fatigue life evaluation in consumer goods, such as shoes. **Figure 3** shows key results from the stress-strain compression testing of the high density VTP foam over the first 1000 cycles. **Figures 3 and 4** shows the difference in stress-strain response of a high and a low-density VTP foam cube specimen after printing and at 1E5 cycles of 220 N. **Figure 6** shows the change in the modulus of VTP foam cubes at the 220 N loading for 1E5 cycles as plastic deformation changes. Since foam is generally not viscoelastic, the point at which modulus is measured is important and must be held constant across comparable specimens. Prior work has stressed comparable, conventional foams at the same initial force levels to be compared against these VTP foams [3]. Stress-strain curves for intermediate VTP foam densities in each test condition approximate a linear interpolation of the results between high and low densities.

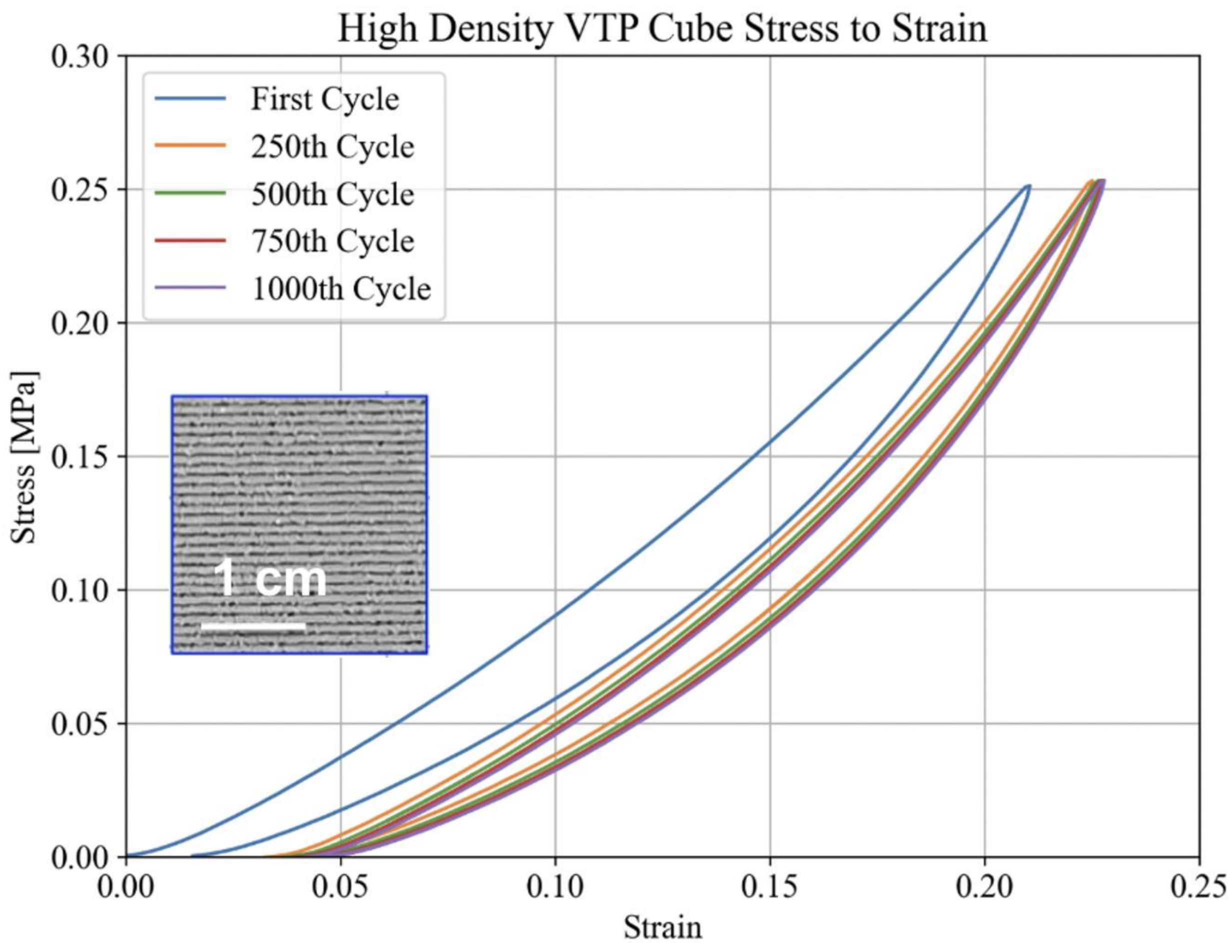

Figure 3. Stress-Strain Curves for a high density VTP foam cube produced with TPU over the first 1000 cycles of 220 N compression at 250 cycle intervals. The modulus linear fit lines are applied to the strain range shown in the plot.

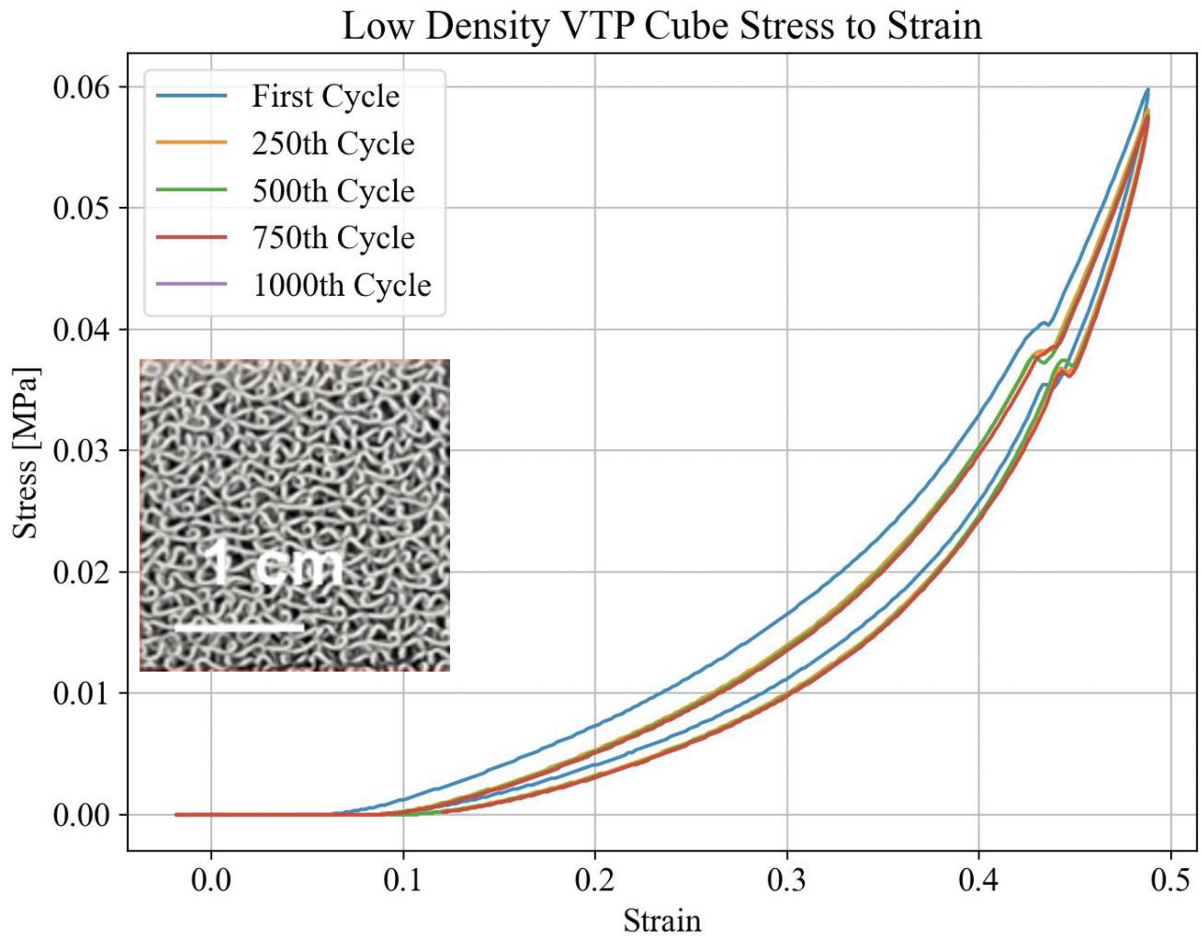

Figure 4. Stress-Strain Curves for a low density VTP foam cube produced with TPU over the first 1000 cycles of 220 N compression at 250 cycle intervals. The modulus linear fit lines are applied to the strain range shown in the plot.

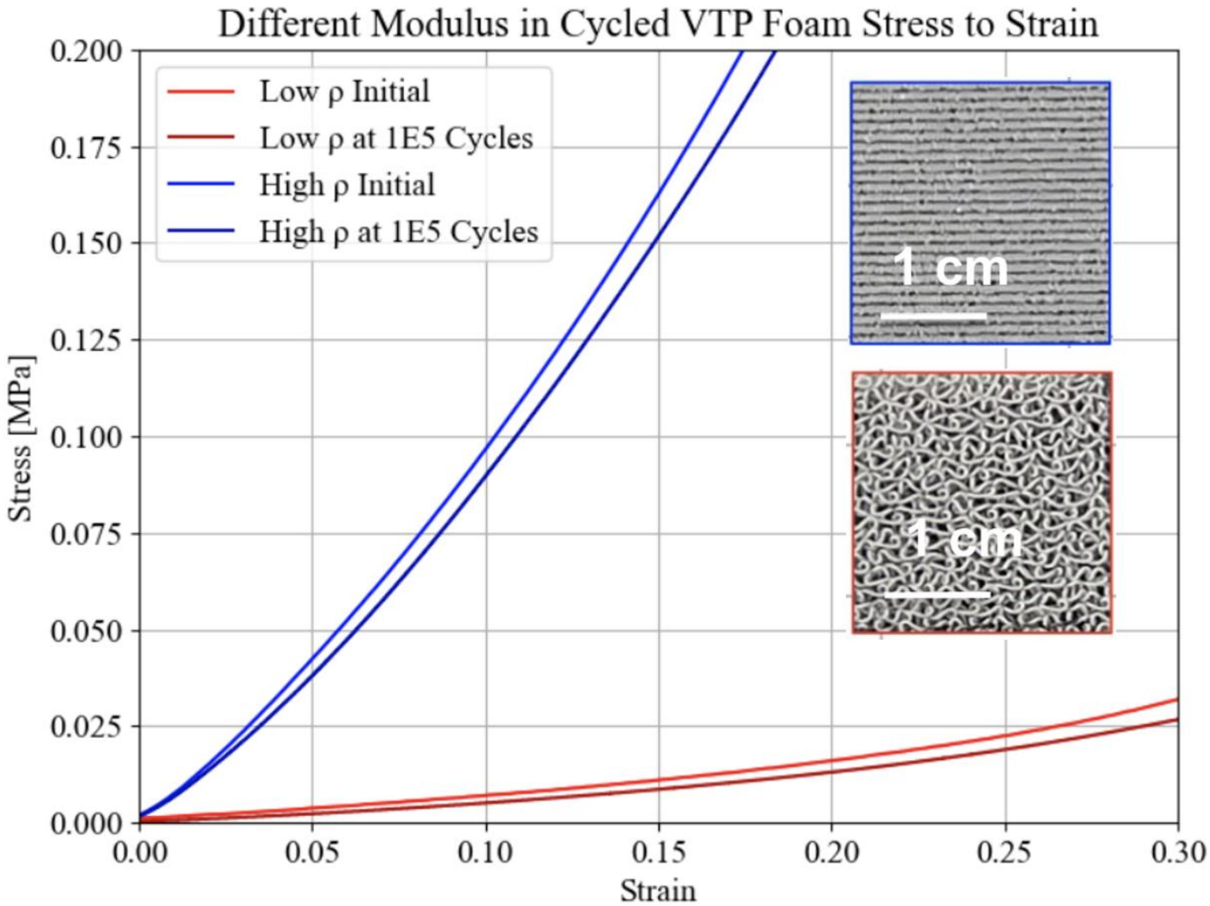

Figure 5. Selected stress-strain plots for high and low density VTP TPU samples after printing and after 1E5, 220 N compression cycles. The linear modulus of the high and low density VTP TPU cubes at 10% strain are 800 ± 5 kPa and 50 kPa ± 5 kPa respectively. Uncertainty in the measurement lies within the width of the lines and is not denoted by the legend.

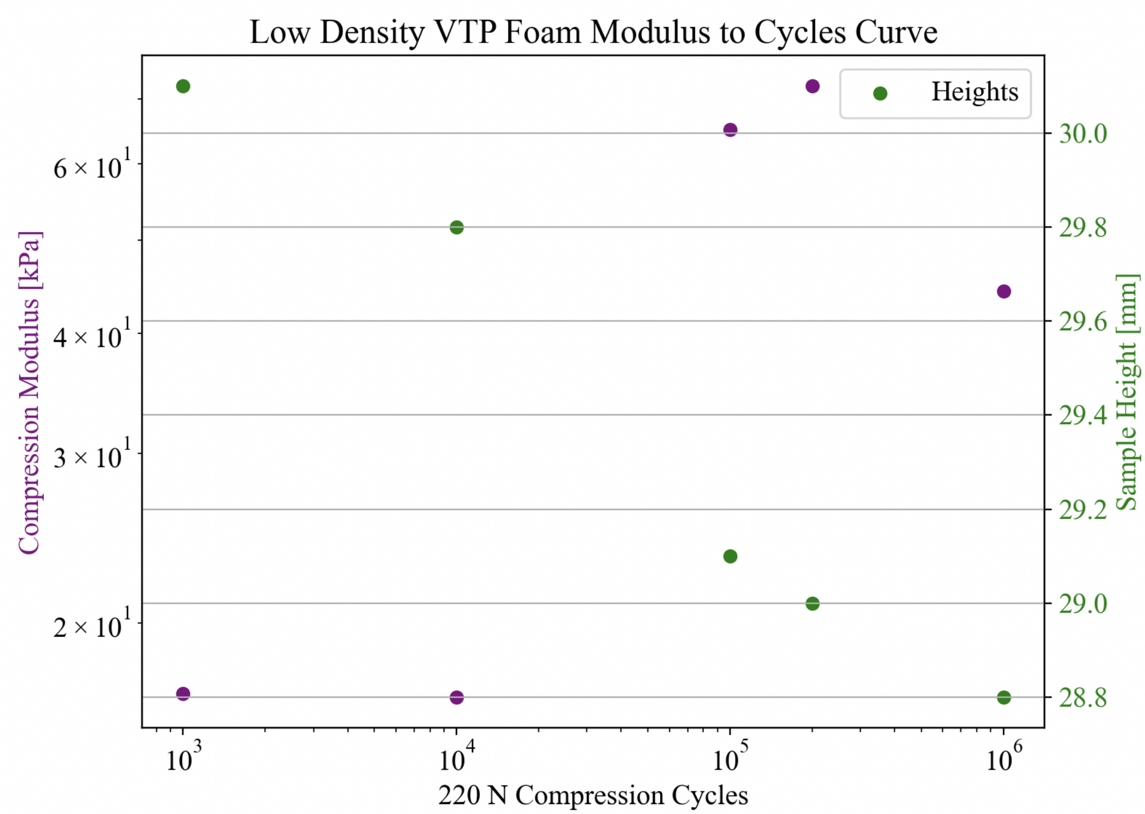

Figure 6. Young's Modulus to Cycle Number in compression for low density VTP TPU foam. The right-side Y-axis describes the unstressed sample height at each number of 220 N compression cycles. Notably, modulus increases for a time as cycles increase. This implies VTP foam densification, which is supported by the change in sample height.

Shear Fatigue

We tested the impact of cyclic shear stress on the shear modulus of high and low density VTP foam. This test was guided by ASTM D3574. We placed 30 mm cubes of each VTP foam density in a holder that fixed one side of the cube and applied a shear strain to the entire cube. A shear strain of 15% was set to achieve an equivalent displacement to a 200 N sliding force along the free side of the cube. This was done for 10, 100, 1000, and then 10000 cycles using the custom fatigue testing machine. At each cycling interval, the shear modulus was measured with a shear lap modulus test on the UTM system. The shear modulus was found to have changed negligibly for this stress level.

Higher stress levels in cyclic shear testing are expected to cause a measurable breakdown in interlayer VTP bonding. However, we wanted our experimentation to ensure that durability results across test types were representative of the same environment, namely partial body weight loads. Therefore, we did not continue shear fatigue testing at a higher stress magnitude to demonstrate degradation in shear modulus. This practice mirrors existing standards that test a desired stress mode and checks for a measurable plastic deformation. As polymer scientists are aware, TPU exhibits strong hysteresis, rate dependence and softening. Prior work has developed a constitutive model capturing these features of TPU stress-strain behavior, including nonlinear hyperelastic behavior, strain rate dependence, hysteresis, and softening [13]. These constitutive models should be considered when reviewing the limited strain results of this work as shown in **Figure 7** below on shear durability. Our low-density TPU VTP strips exhibited >10% plastic shear deformation after 1000 cycles and this plastic shear deformation was consistent at 1E5 cycles and above.

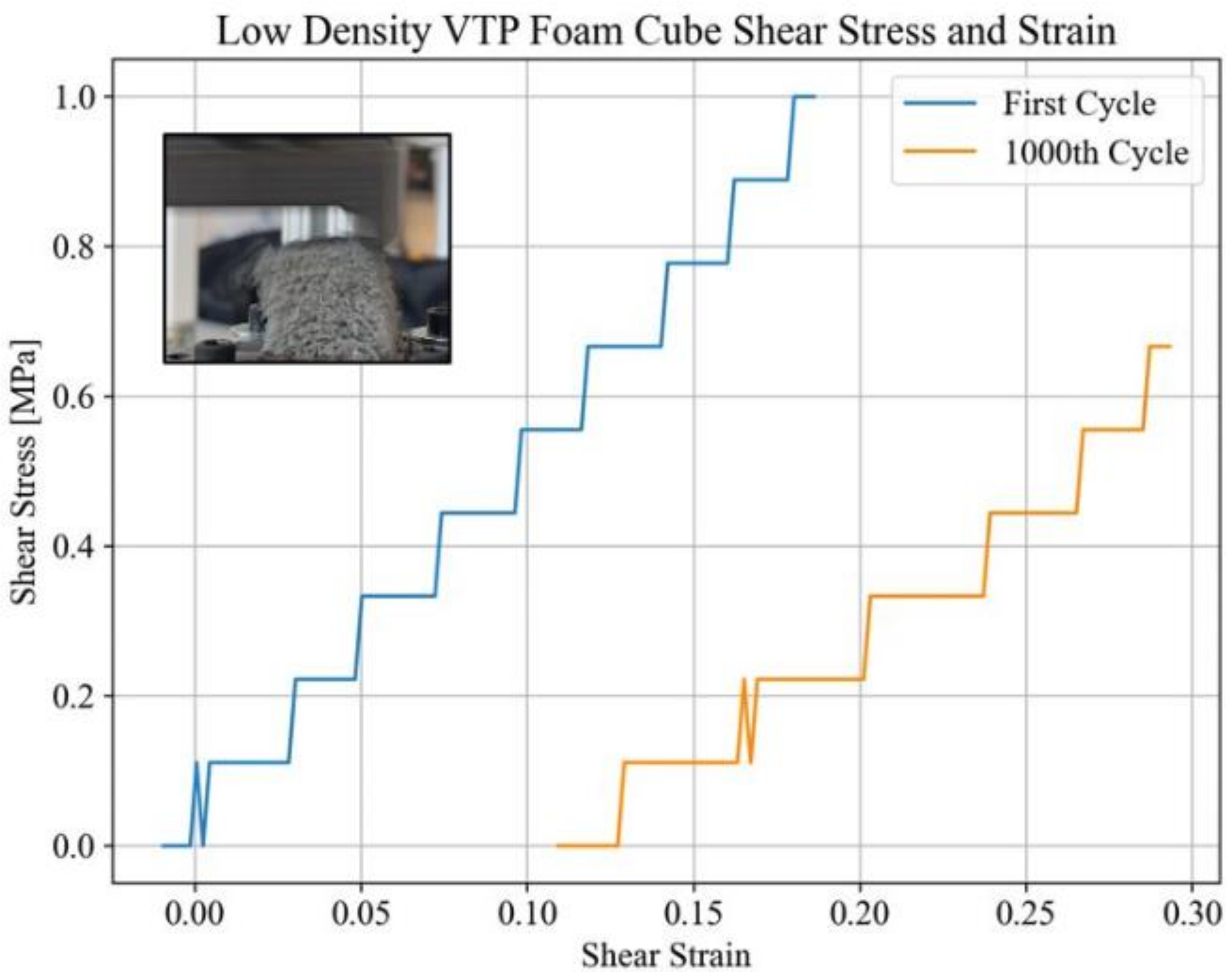

Figure 7. Shear stress and strain for a cube of low density, TPU VTP foam with >10% shear plastic deformation at 1000 cycles of 15% strain using a custom fatigue testing machine.

Flexural Fatigue

We tested the impact of repeated flexural stress on the shear modulus of bars of high and low density VTP foam. Each bar was 85 mm by 40 mm by 10 mm thick. A different aspect ratio was used for foam specimens than provided in ASTM D3574 since the flexural strain rate would be uncharacteristic at the prescribed stress level necessary to test human force rates [8]. We placed a bar of each VTP foam density in a holder that fixed one side of the specimen and applied a flexural strain. The flexural strain was set at the equivalent displacement to a 10 N force into the center of the bar fixed on each end. This was done 10, 100, 1000, and then 10000 times using the custom fatigue testing machine. At each cycling interval, the flexural modulus was measured with a three-point bend test on the UTM system. The flexural modulus was found to have changed negligibly for this stress level.

Compression Set

Compression set is a measurement of how much a material retains its shape after extended periods of time at a fixed, uniaxial, strain condition. This measurement is often used in quantifying foams for consumer goods, such as shoes and mattresses, to ensure that the foam does not compact too quickly under consistent usage [14].

Polyurethane and neoprene foam blends of a similar density and stiffness will exhibit 15% to 30% of plastic strain based on ambient conditions over one day of loading to 50% strain [12]. The VTP TPU foams produced in this study exhibited between 5% to 10% of plastic strain deformation after one day of loading at 50% strain. After being placed in a 50% strain state for over 2.5 months, the VTP TPU foam produced in this study at high density saw a 16% plastic strain and the VTP TPU foam at a lower density saw a 26% plastic deformation strain. These results show that the VTP TPU foam is able to withstand a significant constant strain over a long period of time relative to human interaction without substantial plastic deformation.

Discussion on Use of Durable FFF Parts and VTP Foams

The durability of FFF components in an application depends on further characterization, specific to that application. Conventional materials and foams with refined production methods and tighter tolerances on mechanical properties are more likely to be used by engineers in new systems and products than novel foam methods. Therefore, durability characterization of FFF foams will improve its likeliness for use by other engineers and scientists.

The durability of any material is dependent on the usage, intrinsic properties, and design implementation. For application-specific, durability testing of foams, it is crucial to quantify the range of stresses at which durability information is desired and how the foam interacts with other materials in a system. For example, testing a foam at a relatively low stress level may find that the durability of a foam greatly exceeds its designed lifetime usage. However, the same foam at twice the density may require a higher testing stress level to be representative and that alternative foam may not exceed its designed lifetime usage. This insight drives how conventional foams are currently used in consumer goods, and this impacts how FFF parts and VTP foams may be used in such applications.

The wear and tear of VTP foams shows new forms of degraded microstructures when compared to conventional foams. As our understanding of how these degraded microstructures influence mechanical properties and ongoing deterioration improves, the development of new reinforcement and repair strategies may prove beneficial. During testing VTP foams, it was found that interlayer bonding was the primary point of failure. Individual threads of TPU did not sever, instead the weaker and thinner interthread bonds formed by hot deposition of the coiled thread severed first. A study varying the VTP parameters to increase the thickness of these bonds is likely to improve this factor of durability. **Figure 8** shows a pair of shoes with VTP TPU insoles and resulting damage of a low density VTP insole after 5E4 steps. By bolstering the interlayer bonding strength of FFF parts generally by annealing specimens, we observed that modulus was negligibly changed for increasing durability. This was similarly found in related work on VTP TPU soft hand and finger models [15].

Figure 8. (Left) Shoes with VTP TPU insoles. (Right) Insole after 50,000 steps

Conclusion

This paper discusses the durability of VTP foams based on existing standards. The work demonstrates the potential of VTP foams for robust applications. These foam structures may now be used in applications with required mechanical properties between bulk conventional foams and architected materials. This was accomplished by measuring and improving the durable use of the VTP microstructure under a range of deformation modes. This type of generating FFF foam may be used in more rigorous commercial and industrial applications without the concern for incidental or early mechanical failure. The study presented in this paper demonstrates the complex non-linearities in the stiffness and durability of foam. We may predict the load and cycles to cause failure in VTP foams by understanding these non-linearities and their impact on failure modes. We hope to provide durability study methods for others working with 3D printed foams in general through a better understanding of VTP foam failure modes. Future work will expand on the benefits of 3D printed foams by demonstrating VTP foams with many materials produced from a range of different FFF systems by selecting specific properties that can address more specific applications, such as the durability of shapes under multidirectional loading.

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References

[1] Utsumi, H., Isobe, M., Hiraide, T., Obata, M., Ohkubo, K., & Sakai, S. (1998). *Durability of flexible molded polyurethane foams*. *Journal of Cellular Plastics*, 34(6).

[2] Hager, S. L., & Craig, T. A. (1990s). *Fatigue testing of high-performance flexible polyurethane foam*. Technical abstracts, Polyurethane Foam Association.

[3] Emery, B.*, Snapp, K. L.*, Revier, D., Sarkar, V., Nakura, M., Brown, K. A., Lipton, J. I. (2024). *Foams with 3D Spatially Programmed Mechanics Enabled by Autonomous Active Learning on Viscous Thread Printing*. Advanced Science, 11(44), article 2408062.
DOI: 10.1002/advs.202470270

[4] Ge C, Priyadarshini L, Cormier D, PanL, Tuber J. A preliminary study of cushion properties of a 3D printed thermoplastic polyurethane Kelvin foam. Package Technol Sci. 2018;31:361–368. https://doi.org/10.1002/pts.2330368 GE ET AL .

[5] Kuipers, T.; Wu, J.; Wang, C. C. L. “CrossFill: Foam Structures with Graded Density for Continuous Material Extrusion,” *arXiv*, 2019.

[6] Cheng, D.-Y.; Tai, W.-C.; Liao, Y.-C. “Photocurable Foam for Three-Dimensional-Printed Porous Structures,” *ACS Applied Materials & Interfaces*, 2024.

[7] Gallaire F, Brun P-T. 2017 Fluid dynamic instabilities: theory and application to pattern forming in complex media.Phil. Trans. R. Soc. A 375: 20160155. http://dx.doi.org/10.1098/rsta.2016.0155

[8] Hamill, J., Knutzen, K. M., & Derrick, T. (2021). *Biomechanical Basis of Human Movement* (5th ed.). Wolters Kluwer.

[9] ASTM International. (2021). *Standard Test Method for Rubber Property—Durometer Hardness* (ASTM D2240-15[2021]).

[10] ASTM International. (2017). *Standard Test Methods for Flexible Cellular Materials—Slab, Bonded, and Molded Urethane Foams* (ASTM D3574-17).

[11] International Organization for Standardization. (2018). *ISO 1856:2018 – Flexible cellular polymeric materials — Determination of compression set*.

[12] International Organization for Standardization. (2018). *ISO 8067:2018 – Flexible cellular polymeric materials — Determination of tear strength*.

[13] Qi, H.J., & Boyce, M.C. (2005). Stress–strain behavior of thermoplastic polyurethanes. *Mechanics of Materials*, 37(8), 817–839.

[14] ASTM International. "ASTM D1056-14: Standard Specification for Flexible Cellular Materials—Sponge or Expanded Rubber." *ASTM International*, 2014, www.astm.org/d1056-14.html.

[15] J. Miske, B. Emery and J. Lipton, "Viscous Thread Printing (VTP) for Production of Soft Robotic Fingers," 2025 IEEE 8th International Conference on Soft Robotics (RoboSoft), Lausanne, Switzerland, 2025, pp. 1-6, doi: 10.1109/RoboSoft63089.2025.11020838.