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VOXEL BASED MULTI-MATERIAL 3D PRINTING USING FUSED DEPOSITION MODELING

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ABSTRACT

As additive manufacturing matures from being mostly for rapid prototyping to creating useable components, new methods of printing are giving users even more capabilities. One of the main advantages of 3D printing is its customizability, being able to print complex shapes and structures from a 3D model with ease. Multi-material printing allows for the creation of parts with a variety of material properties, which are crucial for biomedical applications (e.g., prosthetics). For these applications, stress concentrations at material interfaces can lead to parts being much weaker than intended, limiting their applications. By creating a gradual boundary between materials, the effect of stress concentrations can be reduced while also controlling mechanical properties. This can be accomplished by using voxel (3D pixel) based multi-material printing. Gradients can be created by depositing different material proportions and patterns. If the voxels are small, they blend in together to create a smooth big picture. While the voxel method has been used with Polyjet 3D printing, fused deposition modelling (FDM) is widely available, affordable and offers a wider library of materials that can be high load bearing. To obtain polymer parts with tunable stiffness based on the voxel based FDM printing methodology, two thermoplastic polyurethane (TPU) materials with different hardness (75D and 85A) were selected. This research focused on testing the printing parameters to get the desired printing topology while optimizing material deposition. Voxel size was set to 1 mm^3 and voxels were randomly distributed through the samples. A set of samples were then manufactured ranging from 0%, 30%, 50%, 70% and 100% of the soft polymer. Compression and cyclic testing were employed to assess the effectiveness of the voxel methodology for stiffness tuning. It was found that the proportion of each material in the sample greatly affected the mechanical stiffness and stress distributions within the parts.

1 INTRODUCTION

Globally, around one in ten amputees cannot access prosthetics and orthotic services. In 2017, the World Health Organization (WHO) estimated that 40-47 million people worldwide require prosthetics and/or orthotic services. This is likely to increase, as most amputations are due to diabetic foot ulcers and vernacular diseases associated with aging. As the rates of diabetes increase alongside an aging population, these lower limb amputations will also likely increase [1]. For lower limb amputees, amputations are particularly debilitating as it directly impairs their mobility and agency. Prosthetic inaccessibility exists largely because prosthetic sockets, which serve as the interface between limb and prosthesis, are expensive and must be custom-made by a prosthetist [2]. A solution that has been suggested is the use of 3D printed prosthetic sockets due to the ability to manufacture intricate geometries. However, a significant challenge in socket manufacturing is achieving an accurate fit for the patient's residual limb and accommodating changes in this fit over time. Failure to achieve a proper fit can lead to injuries and mobility limitations for the user.

Currently, most sockets are manufactured by casting negative molds onto the patient's residual limb, which is expensive in materials and labour costs [2]. However, if a 3D scan of a patient's residual limb were to be provided to a 3D printer, this process could be optimized. As far as the authors are aware, research into affordable 3D printed prosthetic sockets has shown that they can be effective and inexpensive alternatives to handmade sockets. In 2020, Van der Stelt et al. conducted a study in Sierra Leone where they provided amputees 3D printed sockets costing $15 USD, showing that 3D printed prosthetic sockets could be effective and cheaply manufactured in developing countries [3]. In 2021, their research on strength testing 3D printed transtibial prosthetic sockets demonstrated that a socket 3D printed from tough PLA withstood static testing, and only failed after 2.3 million cycles via fatigue failure [4]. While additional research is needed to ensure structural strength, another challenge is lowering the pressure interface for sensitive areas of the residual limb, which is essential for ensuring comfort and injury prevention [5]. One method is using multiple materials in socket manufacturing. Doubrovksi et al. (2015) proposed a voxel-based methodology where a socket could be discretized into voxels (3D pixels). Each voxel would be designated a specific material, and by manipulating the volume fraction of these voxels, it would be possible to customize the mechanical properties across the entire volume, thus enabling precise control over interface pressure [6]. As far as the authors are aware, research into voxel-based printing has been limited to printing with PolyJet resin printing. In 2023 Kaweesa et al. used TangoBlackPlus with VeroWhitePlus and obtained mechanical properties between the two by varying the material proportions [7]. Although this method is advantageous due to the high printing resolution, both PolyJet printers and their printing materials are expensive, with the cheapest being around $350 USD/kg. Alternatively, fused deposition modeling (FDM), which is an affordable 3D printing technique has the potential to be used for larger scale manufacturing with the voxel-based methodology. FDM printers also have a wider availability of thermoplastics to choose from, such as thermoplastic polyurethane (TPU), which can be manufactured to have a very wide variety of stiffnesses. Therefore, determining if FDM printers could print voxel-based composites is of interest to produce large scale tailorable stiffness parts such as those used in prosthetic sockets.

In this study we investigate the relationship between material proportions controlled by voxels, and the mechanical properties of the 3D printed sample. This represents the first step towards establishing a precise manufacturing method based on the mechanical relationship between the deposited proportions of different voxelated materials. This approach holds promise not only for enhancing the comfort of prosthetic sockets but also for addressing other applications requiring meticulous control over mechanical properties.

2 METHOD

2.1 Material Selection

As a large stiffness gradient was desired, TPU filaments of varying stiffness were chosen. Additionally, the use of two TPU filaments ensures proper material adhesion. The softer filament was NinjaTek's NinjaFlex 85A TPU filament (USA), with the other being NinjaTek's Armadillo 75D TPU filament (USA). According to the manufacturer specifications, the 85A filament has a tensile modulus of 12 MPa, while the 75D filament has a tensile modulus of 396 MPa.

2.2 Sample Preparation

The study has two goals: to correlate material voxel proportions to mechanical properties, and to assess the effect of cyclic loading on the performance of the sample in compression . Therefore, five sample groups were defined by the proportions of each material in their samples. Table 1 below shows the composition of each sample group.

Table 1. Material Composition of Each Sample Group Tested

Sample Group	85A TPU Composition (%)	75D TPU Composition (%)	Sample Numbers
75D-0	100	0	1-5
75D-30	70	30	6-10
75D-50	50	50	11-15
75D-70	30	70	16-20
75D-100	0	100	21-25

To create the sample models, MATLAB code was used to randomly generate cubic STL models made up of 1 mm^3 voxels. The voxel distributions within these models were randomized, with only the proportion of voxels between the two models being controlled. Once generated in MATLAB, the STL files were exported to Fusion 360 where each model was cut into cylinders 10 mm in height and 15 mm in diameter. The volume ratios of voxelated volumes were checked to ensure correct material proportions with a deviation no more than $\pm$ 0.5% of the desired ratio. Once shaped, the STL files were sliced using the software IdeaMaker. Next, a Raise3D E2 multi-material printer was used, with the nozzle printing the 85A TPU having a temperature of 240°C, and the nozzle printing the 75D TPU being at 225°C. The bed temperature was set to 50°C, with an XY size compensation for contours and holes of 0.4 mm and -0.3 mm respectively. Two sets of the 25 samples were printed, one set for compression testing and the other for the cyclic compression testing.

2.3 Testing Procedure

Compression testing was used due to its relevance to the prosthetic socket application. The samples were preloaded to 0.1N before being tested thrice to 500N to check for elastic consistency. Samples were tested to 20 MPa to acquire the stress-strain curve and ensure fidelity of their mechanical behaviour to referenced TPU. Testing was performed using an Instron 5900R load frame and a displacement rate of 5mm/min. Only the data up to 10% strain was analyzed. The sample with the median stress-strain curve was chosen to be the representative sample of each sample group. For cyclic testing, the samples were set to load to 250N, then unload to 5N, and repeat the cycle 100 times. An initial preload of 0.1N was used, with a strain rate of 2.3mm/min.

3 RESULTS AND DISCUSSION

3.1 Compression Testing

Results of the static compression tests are shown in Figure 1. While the filament manufacturer reported tensile, not compressive modulus, a rough comparison of the measured Young's moduli of the 75D-0 and 75D-100 sample groups to the tensile moduli can be done. The median modulus for the 75D-0 sample group was 13.3 MPa, deviating by only 10.8%, while the 75D-100 group had a median modulus of 453.4 MPa, deviating by 14.5%. The complete engineering stress-strain curves (Figure 1.a) demonstrated that no sample experienced failure, with the 75D-100 group showing no signs of yielding. From our tests, it is not feasible to determine which sample group would exhibit the highest resistance to breakage, as no failures occurred. Therefore, the analysis was limited to up to 10% strain.

Analyzing the representative curves from Figure 1 b), all samples except for the 75D-100 group experienced an initial toe region, with an inflection occurring at around 3-4% strain. Although these initial toe regions partially depended on surface irregularities which will be controlled in the future, a plausible cause for their elongated toe region is the sample void content. When loaded, it is possible that some initial voids collapsed during the first 2-3% strain, before the samples begin to effectively resist the load. Upon visual inspection of the 75D-50 and 75D-70 samples, voids were visible within the stiffer sections, lending weight to this hypothesis. The presence of voids will affect the measured properties and will require further exploration and quantification in future research.

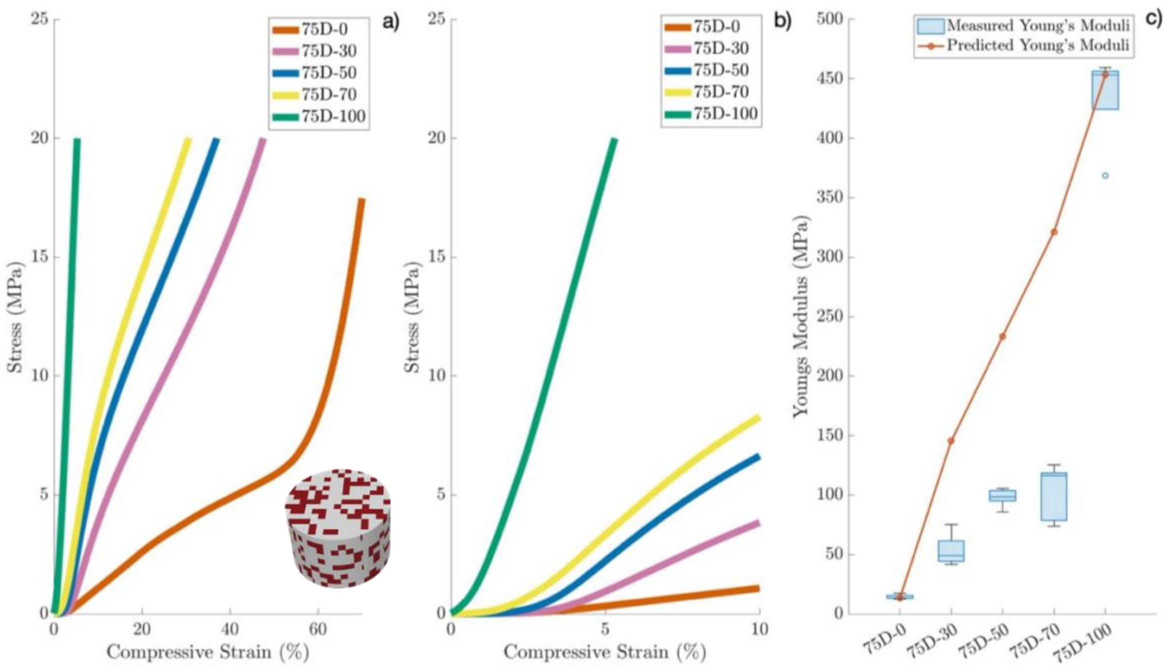

Figure 1. Results of compression testing a) Full engineering stress-strain curves of each sample group with an example of a voxel based STL. b) Engineering stress-strain curves of each sample group up to 10% strain. c) Measured Young's moduli of each sample group

The measured Young's moduli in sample groups 1-5 had median Young's moduli of 13.3 MPa, 49.3 MPa, 98.5 MPa, 117 MPa, and 453 MPa, respectively. From these median Young's moduli, as well as visually inspecting Figure 1 b), the voxel-based samples have intermediate properties to the two filaments. Comparing to the TPU stress-strain curves reported by Shin et al. (2022), the voxel-based samples behave similarly to commercial TPUs of varying Shore hardness [8]. Although the filler behaviour is not elastic, as a rough approximation, a rule of mixtures approach has been applied in Figure 1 c). This highlights that the voxel-based samples have a much lower than expected stiffness, with the 75D-70 sample group in particular having a median Young's modulus around 36% of the predicted modulus. A possible cause is that the interface between materials is not satisfactory, weakening the samples. The void content in the voxel-based samples may also be higher than in single material prints. An increase in voids seems likely, as the voxel-based printing involves plenty of sharp angles and material boundaries where voids tend to form.

3.2 Cyclic Testing

For the cyclic testing, force-displacement plots for the 1st, 5th, and 100th cycles were made to compare sample behaviour under cyclic compression loading. The force-displacement curves for the representative samples are shown in Figure 2. Initial cyclic testing has been performed; however, the load cell's sensitivity caused a slight overload of samples. Despite that, this preliminary testing is sufficient to determine sample behaviour and to correct printing parameters. One observation was that some stiffening occurred between the 1st and 100th cycles. However, the most noticeable change was for the 75D-50 sample group, where the force-displacement fell in line with the 75D-70 sample group for the 100th cycle. This is not surprising, as compression testing showed that these two groups had similar stiffnesses, with statistical overlap between them seen in Figure 1 c). Another observation was that the toe regions shrank under cyclic loading, and that the hysteresis of the curves was reduced by the 100th cycle. This might suggest that some of the voids in the sample were collapsed by the 100th cycle, which would partially explain why stiffening was observed. However, more extensive cyclic testing is required before drawing conclusions.

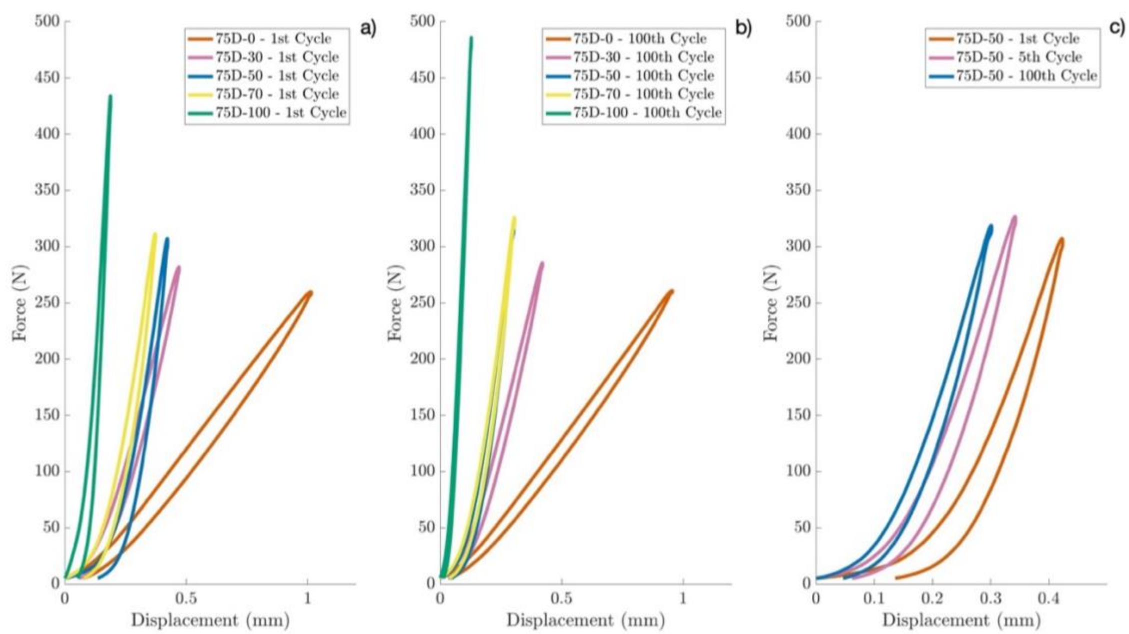

Figure 2. Cyclic compression force-displacement curves for a) the 1st cycle b) the 100th cycle c) the 1st, 5th, and 100th cycle for the 75D-50 sample group

3.3 Discussion and Future Research

With this initial testing, it was observed how the voxel-based composites behaved like a TPU with stiffnesses between the 85A and 75D TPU, with no unexpected failures or severe deviations under cyclic loading. However, the relationship between the proportion of materials seems to be non-linear, which could be attributed to inaccurate material deposition due to selected printing parameters, increased void content, and/or possibly the interfacial strength of the two materials. Testing is needed to determine the cause and to improve both the quality and consistency of the printing. Lin et al. (2021) showed that optimizing the printing parameters, particularly the melt extrusion ratio and the printing speed of TPU, can help reduce the impact of voids and had success in both reducing pore sizes and increasing print strength closer to that of an injection molded sample [9]. The reduction of the toe region during cyclic testing might suggest that voids were a cause of the toe region for static testing, but cyclic testing needs to be expanded before conclusions can be drawn. Additional mechanical characterization including tensile, bending, and fatigue testing, as well as assessment of the interface between the materials, may be beneficial. However, these initial results suggest that voxel based multi-material 3D printing could be used to tailor the mechanical properties of devices such as prosthetic sockets once sample quality and consistency is improved.

4 CONCLUSION

The work presented in this paper is the first step towards developing a printing and software approach capable of translating desired stiffness profiles into a voxel-based bitmaps, therefore controlling the material proportions within a volume to achieve a desired stiffness. This paper has shown that these TPU based voxel-composites do behave as a TPU material with properties in between the 85A and 75D TPU base materials, and that they do not deteriorate quickly under cyclic loading (i.e., up to 100 cycles). However, the stiffness of these samples were below what was expected, attributed to an increased void content produced during the 3D printing process, which would weaken the manufactured samples. Future research will focus on investigating the cause and improving the quality of these voxel-based multi-material samples. Once that has been accomplished, these samples can undergo tensile, bending, and fatigue testing to create an accurate model that will allow FDM 3D printing of tailored structures such as prosthetic sockets.

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