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An exploration of 3D printed freeform kerf structures

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ABSTRACT

This study presents the use of a 3D printing method to create kerf structures that can be formed into complex geometries. Kerfing is a subtractive manufacturing method to create flexible surfaces out of stiff planar materials such as metal or wood sheets by removing portions of the materials. The kerf structures are characterized by the kerf pattern, such as square interlocked Archimedean spiral and hexagon spiral domain, cell size, and cut density. By controlling the kerf pattern, spatial density, cell size, and material, the local properties of the structure can be controlled and optimized to achieve the desired local flexibility while minimizing the stresses developed in the kerf structure. Since subtractive manufacturing limits the patterns and materials that can be considered in kerf structures, FDM 3D printing is explored to fabricate kerf structures using polymers, such as Polylactic acid (PLA) and Thermoplastic polyurethane (TPU), where it is possible to vary microstructural topology and materials within the kerf structures. 3D printing enables the combination of the two different polymers and tuning printing factors to create multifunctional kerf structures. The multifunctional kerf structures can then be actuated using non-mechanical stimulations, such as thermal, to shape them into complex geometries.

Keywords: Kerfing, flexible planar structure, spatial stiffness, FDM 3D printing, PLA, TPU, kerf structures

1. INTRODUCTION

Freeform structures, beyond simple geometries, find many engineering applications in aerospace, civil, mechanical, and biomedical engineering [1-4]. In that regard, there has been a growing interest to optimize structural designs in favor of functional efficiency, saving material and production costs, and achieving aesthetic design. This would require an understanding of the interaction between various complex geometries, their functionality, and processing method.

Traditionally origami, kirigami, and lattice structures have been used to create structures of complex geometries out of planar surfaces [5]. Complex shapes created from the origami and kirigami techniques depend on forming folds. These techniques are useful for very thin surfaces which limits their applications. Also, origami and kirigami are very intricate and labor-intensive processes [6].

Another method of creating complex geometries out of rigid planar materials is called kerfing or relief cutting. Kerfing is a subtractive manufacturing process, which involves cutting or removing material to create locally flexible structures from relatively stiff planar mass-produced materials such as processed woods, metals, and alloys [7]. Wood and metal plates are capable of providing structural integrity but are relatively stiff making it difficult to mold them into complex shapes. Kerfing reduces the local second moment and polar moment of an area and changes the local slenderness of the solid panel. The deformations in the kerf panels are dominated by the bending and twisting of the cut components in different directions [8] [9]. With this technique, the kerf planar structures can be morphed into any desired shape with controlled anisotropy and flexibility [10]. The kerf structures can also undergo bending and twisting about multiple axes [11].

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The kerf planar structures are composed of individual kerf unit cells. A kerf unit cell comprises a continuous flow of slender prismatic beams with a rectangular cross-section. This pattern allows flexibility and multiple shape changes within the cell. Each kerf unit cell can undergo multiple deformations through combinations of bending, twisting, and elongation/contraction. The kerfing method has been extensively studied for wood materials. Chen et. al. [8] studied the mechanical deformations of kerf panels out of medium-density fiberboard with two different kerf patterns and three different cut densities. The desired freeform flexible geometry can be achieved by varying kerf cut patterns and densities.

With advances in manufacturing such as 3D printing, the kerfing method can be applied to other materials such as polymers and composites, which can open the possibilities of using kerf structures in many engineering applications beyond architecture and art and craft. Additive manufacturing (AM) enables the creation of kerf structures using multiple polymer materials. Thus, not only the geometrical parameters but also the material properties can be varied within the same kerf structures to obtain variable flexibility throughout the structures. In this research, FDM 3D printing method is used to generate kerf structures and their performance is evaluated. An example of a 3D-printed PLA planar kerf structure is illustrated in **Figure 1.**

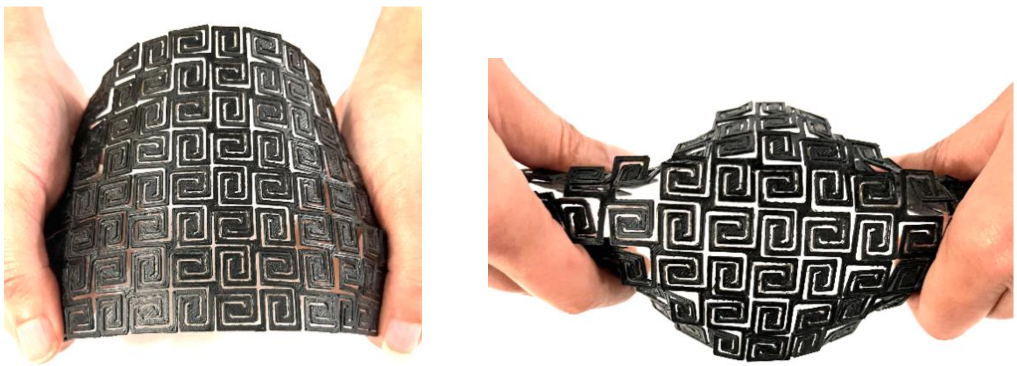

Figure 1. 3D printed PLA kerf structure

Fused Deposition Modelling (FDM) is one of the most popular AM techniques used for fabricating components made from polymers and composite materials [13]. Previously, Pattinson et.al. [14] used FDM 3D printing to fabricate flexible mesh materials with tailored mechanical properties. This research can be used to 3D print medical devices such as externally worn and implantable tissue support devices. Melnikova et.al. [15] 3D printed textile-based flexible structures using FDM and Selective Laser Sintering (SLS) manufacturing processes using different polymer materials like ABS and PLA. Wang et.al. [16] fabricated 2D sheets capable of forming into non-developable surfaces using commonly available 3D printer and PLA. Sarakinioti et.al. [17] fabricated large-scale 3D printed façade panels with complex mono-material geometry with exceptional mechanical and thermal properties.

This research aims to explore the use of 3D printing to fabricate planar (2D) kerf structures using different polymers, i.e., Polylactic Acid (PLA) and Thermoplastic Polyurethane (TPU) thermoplastic filaments. PLA is a shape memory material that can be thermally activated. This study also presents printing bilayer kerf cells using PLA and TPU together, to create multifunctional kerf structures that can be reconfigured into complex geometries with a thermal actuation and retaining the reconfigured shapes upon removal of the actuation.

1.1 Kerfing Geometry and Material

We consider two kerfing cut patterns: square interlocked Archimedean spiral [8] and hexagonal for the kerf unit cells, see **Figure 2**. These patterns are relatively easy to arrange to form large-scale flexible panels which can be molded into desired freeform shapes. The unit cells with square and hexagonal cut patterns have a side length of 1 in. and a thickness of 0.125 in. Fillets of 0.02 in. radius are included in these unit-cell models for all corners to improve their performance by avoiding failure at the junctions (sharp corners). In all unit cells, the kerfing patterns are formed by arrangements of straight prismatic bars with rectangular cross sections. The cross-section area of beam segments in square and hexagonal kerf cells is 0.125 in. x 0.1 in.

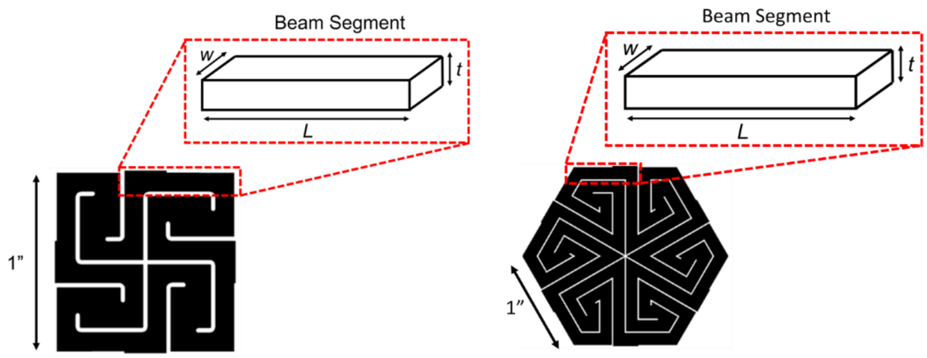

Figure 2. Square Archimedean (top) and Hexagonal (bottom) kerf cut patterns

For fabricating the kerf unit cells and panels, PLA and TPU filaments are used. PLA is characterized by high mechanical strength and rigidity [18], great optical properties [19], excellent manufacturing capability, and biocompatible and biodegradability. PLA finds its application in consumer goods, biomedical devices, and components (surgical sutures, bone screws, bone plates, etc. [20]). TPU is a thermoplastic elastomer consisting of linear segmented block copolymers composed of hard and soft segments [21]. TPU exhibits high tensile strength and flexibility, wear resistance, transparency, machinability, and chemical resistance [21]. TPU finds its application in the automotive industry, medical applications such as surgical gloves, synthetic veins, and blood bags, etc. [22]. As PLA and TPU differ highly in material properties, it presents an interesting prospect of exploring their use in kerf structures.

The 3D printing process parameters used for printing the kerf unit cells are given in **Table 1**. The filaments used in this study are manufactured by OVERTURE 3D. The printing parameters (speed and temperature) are chosen based on the printing recommendations by the manufacturer.

Table 1. 3D printing parameters of kerf unit cells (PLA and TPU)

Process Parameters	**PLA**	**TPU**
Print Temperature (°C)	210	220
Bed Temp (°C)	60	60
Print Speed (mm/s)	40	20
Infill Density (%)	100	100
Flowrate (%)	100	100
Layer Height (mm)	0.2	0.2
Raster Angle	45°	45°

The 3D-printed square and hexagonal kerf unit cells are shown in **Figures 3** and **4**.

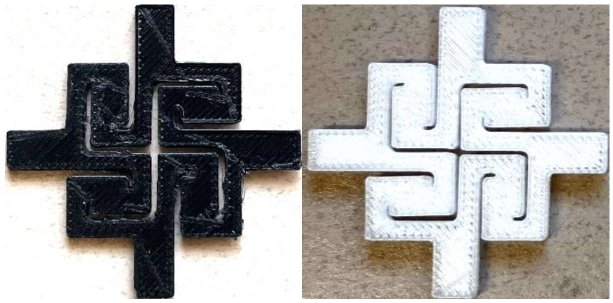

Figure 3. PLA (left) and TPU (right) square kerf unit cells

Figure 4. PLA (left) and TPU (right) hexagonal kerf unit cells

1.2 Experimental tests on 3D printed kerf unit cells

In order to determine the response of the kerf cells to mechanical force, all the kerf cells are subjected to uniaxial tensile force until failure in an Instron 5984 Floor Standing Universal Testing Machine using displacement control. One arm of the unit cell is fixed, and the opposite arm is stretched at a displacement rate of 0.04 in/s. For ensuring the repeatability of these tests, the tests are repeated 3 times for all cut patterns. The results of these experimental tests are illustrated in **Figures 5** and **6**.

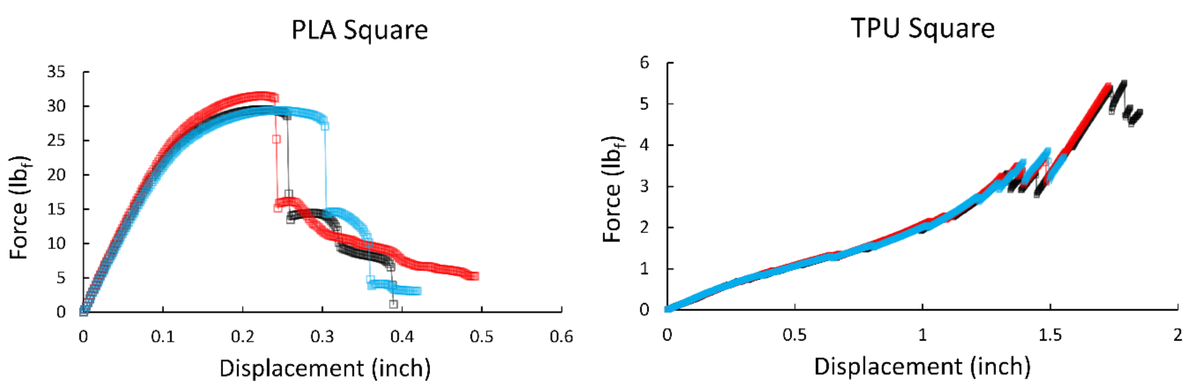

Figure 5. Force - Displacement curves for PLA and TPU square kerf unit cells

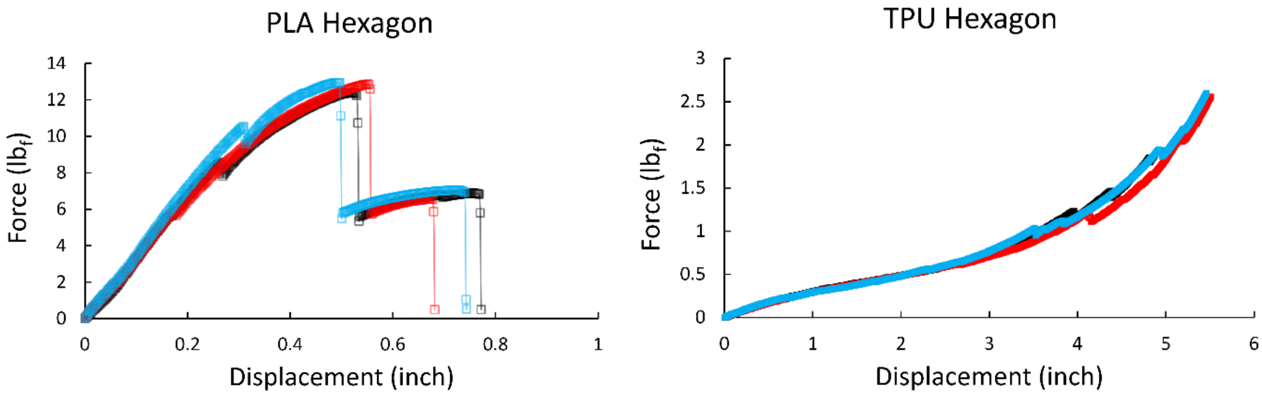

Figure 6. Force - Displacement curves for PLA and TPU hexagonal kerf unit cells

From **Figures 5** and **6**, it can be inferred that for uniaxial loading, PLA kerf cells exhibit high stiffness and small deformation before failure. It can be observed that the square kerf cells have higher stiffness (lower flexibility) as compared to the hexagonal kerf cells for the same material. The flexibility of the kerf cells depends on the geometrical parameters (*L*, *t*, *w*) of the beam segments in the kerf cells, see **Figure 2**. This can be attributed to a lower value of the slenderness *L/w* ratio, where *L* is the length (*L*) and *w* is the width (*w*) of the longest beam segment in the unit cell, for the square unit cell as compared to the hexagon unit cell, making it easier for the hexagonal unit cell to undergo in-plane bending. As PLA has a higher elastic modulus as compared to TPU, the flexibility of TPU kerf cells is much higher than the PLA kerf cells.

In the case of TPU kerf unit cells, as TPU is a soft and flexible material, the unit cells do not experience tensile failure as compared to PLA unit cells. TPU kerf cells exhibit hyperelastic material properties with high tensile strength and strain failure. The experimental tests performed on the TPU kerf unit cells show a displacement of approximately 10 times that of failure displacement of PLA kerf unit cells and they regain their original shape after the tensile load has been removed. The failed PLA specimens are shown in **Figure 7**.

Figure 7. PLA square (left) and hexagonal (right) kerf unit cells after failure

Using kerf cells, large-scale kerf 2D planar structures can be designed and fabricated. In-plane and out-of-plane forces can be applied to these structures deforming them into complex freeform structures. The advantage of using 3D-printed polymer kerf structures is the fact that multiple materials can be used to achieve local flexibility within the kerf structure or to create bilayer kerf structures for easy reconfiguration by non-mechanical stimulation. 3D printed kerf panels are shown in **Figures 8** and **9**.

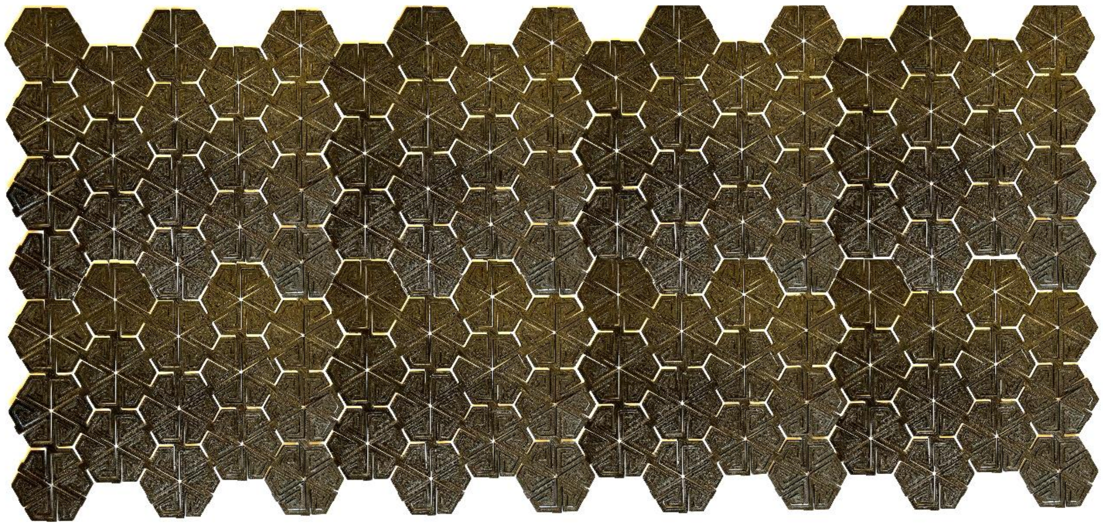

Figure 8. 3D printed PLA hexagonal kerf panel

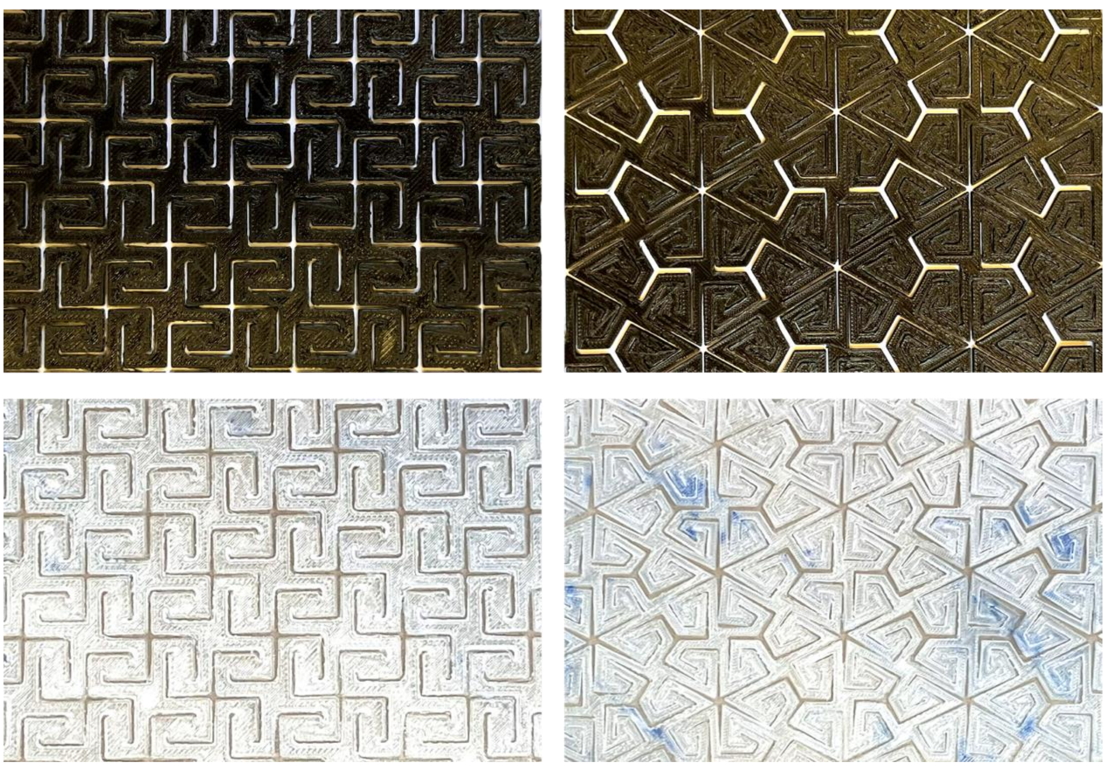

Figure 9. 3D printed PLA (top) and TPU (bottom) kerf panels

2. THERMAL RESPONSE OF KERF CELLS

In the previous section, we explored printing kerf structures and testing the deformability of kerf cells that are 3D printed with two different polymers (PLA and TPU). The main purpose of kerf structures is for their easy shape reconfigurations into freeform structures of complex geometries. This section explores printing bilayer kerf cells, out of PLA and TPU, that can be used for shape reconfigurations using thermal stimulation. FDM 3D printing of kerf cells become more useful in bilayer structures since the shape change and deformations can be fine-tuned using not only material constituents but also raster angles (printing paths) and temperatures at printing time, that are not controllable in laser cutting kerfs. These kerf cells are fabricated as bilayer strips of PLA and TPU and the difference in the thermal expansion coefficient of the two different materials leads to deformations triggering shape change. When these two materials are layered, since PLA is a shape memory material, once activated it has the capability for shape change and retention (actuating layer) while contacting TPU restrains its deformation (restraining layer). While designing bilayer kerf unit cells and panels for a specific application, many factors need to be considered such as material type, layering order, layer thickness, number of layers, etc. 3D-printed bilayer kerf unit cells are illustrated in **Figure 10**. The black color layer is printed using PLA and the transparent layer is printed using TPU. The printing parameters used for printing are given in **Table 1**.

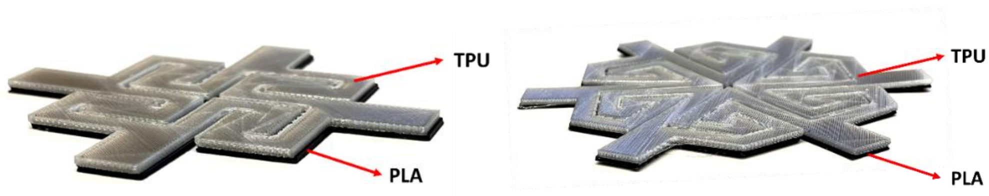

Figure 10. 3D printed bilayer square (left) and hexagonal (right) kerf cells

The total thickness of the bilayer kerf cells is 0.125 in. with a PLA layer thickness of 0.05 in. and a TPU layer thickness of 0.075 in. for both square and hexagonal kerf cells. The kerf cells are completely immersed in a water bath at a temperature of 100^{o}C for 1 min. The obtained deformed shapes are illustrated in **Figure 11**. Upon removal from the high-temperature bath, shape retentions are seen due to the shape memory effect of the material.

Figure 11. Deformed shape of bilayer square (top) and hexagonal (bottom) kerf cell subjected to thermal load

CONCLUSION

We have explored the use of FDM 3D printing for fabricating flexible kerf structures that are moldable into freeform surfaces. These planar kerf structures are composed of similar unit cells. The mechanical response of these unit cells is used to design large-scale kerf panels with increased flexibility. Kerf panels have been fabricated from PLA and TPU polymers. Using multi-material kerf panels enables higher flexibility in the regions undergoing high distortions and stresses. The thermal response of the polymer materials can be used to trigger shape changes in the kerf structure. We have also explored printing bilayer kerf cells out of TPU and PLA and demonstrated the shape changes and retentions by thermal actuation. The use of bilayer kerf cells will allow for designing large-scale kerf panels that can be reconfigured into various freeform shapes by non-mechanical actuation, i.e., thermal, electrical, light, etc.

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