RESEARCH ARTICLE

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Study of the Behavior of 3D Printed Thermoplastic Elastomers Structures Aimed at Emulating Traditional Polyurethane Foams

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The present paper introduces a preliminary analysis and the recent development of three-dimensional (3D) printed thermoplastic polyurethane (TPE-U) as a replacement of polyurethane (PU) foams that has led to a recyclable product. Among the various 3D printing techniques available, the team focuses on *Fused Deposition Modeling* (FDM) because of its simplicity, affordability, and versatility in printing geometries and recyclability of materials. Four thermoplastic polyurethane (TPU) elastomers with different stiffness (in the range of Shore A) are used. Therefore, through the combination of different printing geometries, modulation of the main printing parameters, and different materials, an attempt is made to simulate the mechanical behavior of PU foams, which are commonly used for the production of paddings. The mechanical evaluation, by means of dynamic mechanical analysis (DMA), of the of 3D printed specimens has highlighted a qualitatively different and potentially superior behavior with respect to that of PU foam.

1. Introduction

Nowadays, polyurethanes (PUs) are used as everyday life products, being one of the most important classes of polymers that keep changing the quality of the human life, and the principal consumption of PUs is in the form of foam.[1] Low density and thermal conductivity combined with their interesting mechanical properties make PUFs excellent thermal and sound insulators, making them also optimal as structural and comfort materials. Despite the broad range of applications, the production of PUFs is still highly petroleum-dependent and nonrecyclable. In that sense, the processing of PUFs will face a turning point in the near future, necessary due to the need of new raw materials and the development of new technologies, such as three-dimensional (3D) printing.[2] Thermoplastic polyurethanes (TPUs) are known to have excellent impact properties and abrasion resistance and are therefore excellent candidates as elastomeric materials in energy absorbing structures. TPUs can be processed in the same manner as traditional thermoplastic and may be 3D printed. It must also be noted that the 3D printed manufactures may be vastly improved by the manipulation of printer variables such as layer height and nozzle diameter.[3] The fused deposition modeling (FDM) technology is of particular interest because it allows complex shapes to be created with minimal material waste and without the need to use a mold (thus eliminating the cooling time within the mold and reducing fixed costs). In order to assess the energy absorbing potential of the 3D printed TPU, it is necessary to understand their compressive behavior. PU foam shows three deformation regions: linear elasticity, plateau, and densification (**Figure 1**). For small compressive strains, the behavior is linear as the cell walls of structure are undergoing simple bending. As deformation progresses the cell walls begin to buckle, which produces the characteristic plateau, and then finally, the opposing cell walls come into structure increases steeply, resulting in stiffness of the parent material.[4]

In this work, new challenges are outlined for the production of manufactures that can replace traditional PUFs, with the aim of producing materials with similar or better properties but capable of being recycled.

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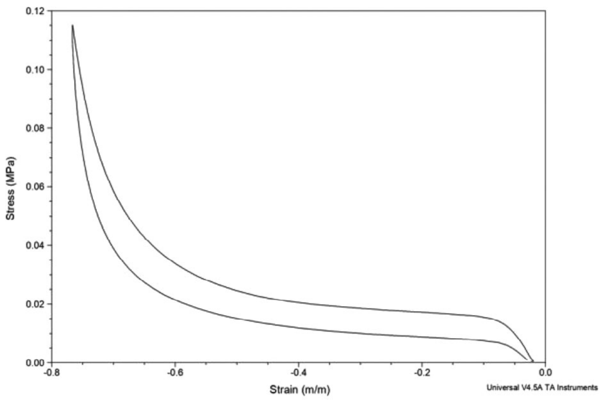

Figure 1. Stress–strain plot about polyurethane foam THW80.

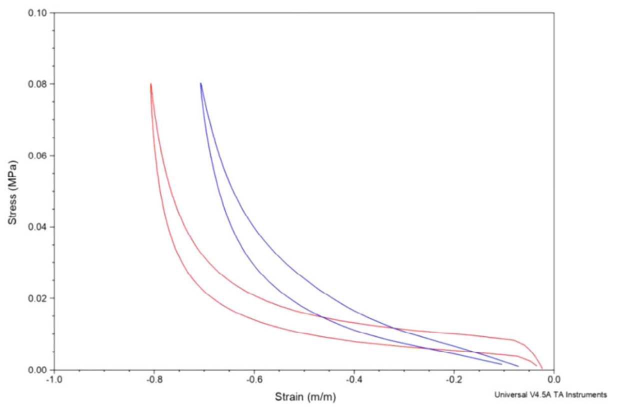

Figure 3. Overlap of stress-strain plot about polyurethane foam (red) and three-dimensional (3D) printed thermoplastic polyurethane (TPU) Shore A 80 R4 (blue).

2. Experimental Section

The PU foam THW80 used as a reference was provided by CyTech s.r.l. Four TPU filaments with different stiffness were used. Specifically, TPU93, commercially called FlexMark9 (TreeD Filaments, Italy), TPU80, called Filoflex 80 A (FiloAlfa, Italy), TPU70, FlexMark7 (TreeD Filaments, Italy), and TPU63, X60 Ultra-Flexible Filament (Diabase, USA) were used in this work. All the filaments used had a diameter of 1.75 mm. Specimens for characterization were 3D printed with a Mustang M400 printer (Vepram Vetoplast s.a.s.) at 230 °C, with a heated bed at 40 °C, 20 mm s^{-1} printing speed, 0.2 mm layer height, 15% infill, and using a nozzle diameter of 0.4 mm. All the specimens were printed with three different geometry (**Figure 2**): with two different deposition angles 0° and 90° (R2), with three different deposition angles 0°/60°/−60° (R3), and with four different deposition angles 0°/90°/45°/−45° (R4).

Mechanical compression tests were performed with the Q800 mechanical dynamic analyzer (TA Instrument, USA) with a probe characterized by a 15-mm diameter. Mechanical tests were conducted under force control at a constant temperature of 35 °C, with a force rate of 18 N min^{-1} to 17.8 N, which corresponds to the instrumental limit value for the compression stage and at the same rate to 0.1 N for expansion. To evaluate the response of the different specimens to stress, ten cycles of compression and expansion were performed.

3. Results and discussion

3D printed specimens were characterized by dynamic mechanical analysis (DMA) in compression mode to compare the mechanical behavior against PU foam. TPU Shore A 93, 70, and 63 have proven not to be comparable to foam, indeed the three characteristic stages (elastic deformation, cell collapse, and densification) are not prominent features in the stress–strain plot. The reason can be found in a *buckling* effect due to the overlap

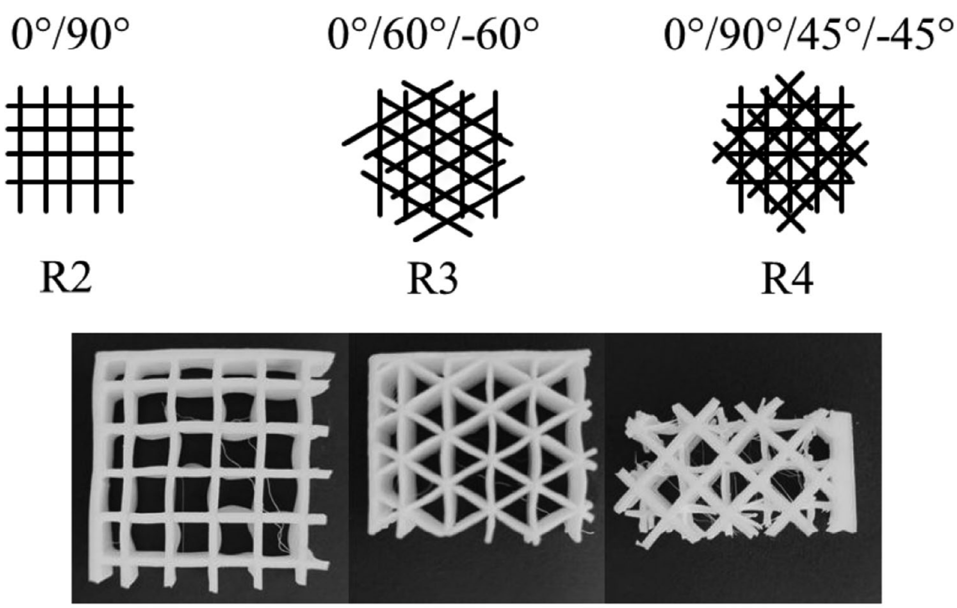

Figure 2. Filament deposition pattern.

and collapse of layers, that leads instantly to a compact and stiff structure. Instead, a slightly better response was reported by the TPU-93-R4 specimen, as it revealed a similar trend to the foam, highlighting the importance of the geometry used in the printing process, which can significantly change the properties of the manufacture. TPU Shore A 80 has led to a significant improvement, exhibiting the desired trend for each specimen with a different deposition angle. Therefore, by modulating the printing parameters, geometry, and material stiffness, it is possible to produce 3D printed manufacture that follows the same trend as PU foams; making it possible to modify and adjust the material response following compression and expansion cycles. **Figure 3** shows the overlap of the behavior of PU foam and that of 3D printed TPU Shore A 63 following cyclic stress in compression and expansion.

4. Conclusion

The aim of the work, i.e., the search for a possible 3D printed substitute for flexible PU foams, was pursued by manufacturing 3D printing of TPU filaments with different stiffness values, keeping the printing conditions, the filling, and the printing geometries unchanged. All samples have been characterized by dynamomechanical tests. Among these, TPU80 showed the most similar behavior to that of traditional PU foam. In conclusion, it can be affirmed that by modulating the rigidity of the material and the printing geometry, it is possible to achieve a deformation trend following loading/unloading cycles that is almost identical to that obtained from THW80 foam, but with the huge advantage of producing a recyclable material with elastomeric properties.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of the present work are not available because they are part of ongoing studies. Data may be available on request from the corresponding author.

Keywords

3D printing, additive manufacturing, filament deposition modeling, polyurethane, polyurethane foams, thermoplastic elastomers

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