3D Printing with Flexible Materials – Mechanical Properties and Material Fatigue

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3D printed objects are nowadays not only used in prototyping, but also in small-scale production down to lot-size 1. While different 3D printing techniques can be applied for this purpose, a large amount of products is prepared by the simple and inexpensive fused deposition modeling (FDM) technique, applying a polymer which is molten, pressed through a nozzle, and deposited layer-by-layer on a printing bed and on the previous layers, respectively. This technology, however, has the disadvantage of often insufficient mechanical properties due to the available materials and due to the construction method, which often supports air cavities inside objects, reducing the adhesion between neighboring strands and thus the overall mechanical properties. Such problems can partly be solved by chemical after-treatments. Here, the authors report on tensile tests and load changes of the soft FDM materials FilaFlex and PLA soft (PLA = polylactic acid) in comparison with common PLA. They also show the different inner structure of objects 3D printed from these materials and their correlation with mechanical properties and material fatigue.

1. Introduction

3D printing is an additive manufacturing method, enabling the production of prototypes or usable objects from diverse materials, such as polymers, metals or ceramics. Typical 3D printing techniques are stereolithography (SLA), selective laser sintering (SLS), PolyJet Modeling (PJM), or fused deposition modeling (FDM), of which the last technique is most widely applied especially in the low-cost segment. FDM printing often uses acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA) as printing materials, while nowadays there are also elastic materials or filaments with increased mechanical properties available.

The mechanical properties are generally an important parameter of 3D printed parts. Modifying them can, for example, be done by chemical or heat treatment or by combining 3D printing with other production techniques, for example, textile fabrics. While these approaches to increase, for example, the elastic modulus or the compressive strength are often reported in the literature, fewer studies deal with the static and dynamical properties of elastic 3D printing polymers, possibly since they are usually more complicated to handle, the softer they are. Here, we compare two elastic FDM printing materials with PLA as a typical rigid polymer and report on their behavior under tensile tests and load changes.

2. Results and Discussion

Firstly, tensile tests were performed with the samples under investigation. Figure 1 depicts the results, averaged over three specimens per sample. While rigid PLA breaks at approx. 2% strain, PLA soft can be elongated by approx. 12% before breaking. FilaFlex, finally, did not break before the maximum possible elongation of the tensile tester (150%) was reached. On the other hand, the stress at break also differs significantly between the three samples. This first test already indicates the large differences between the three filaments, as could be expected due to their different material compositions. While PLA is a thermoplastic material, PLA soft contains additional additives or fillers to make it more flexible, and FilaFlex, finally, is a thermoplastic elastomer consisting of alternating soft and hard segments, in this way the here visible elastomeric properties at room temperature with thermoplastic properties when heated.

It should be mentioned that measurements of the pure filaments give qualitatively very similar results, indicating that the behavior found for the printed samples stems from the different materials, not mainly from different printing quality. Next, load change experiments were performed on the FilaFlex samples. The most interesting question is whether this material is purely elastically deformed or also plastically, that is, whether after each elongation cycle the original state is reached again. The results for one of the FilaFlex specimens are depicted in Figure 2. While generally all curves show similar hysteresis loops, it is clearly visible that the starting points are shifted from one loop to the next, that is, the samples are more and more plastically elongated during the experiment.

Measuring this plastic deformation, the overall length or the original FilaFlex samples of (99.1 ± 0.1) mm (of which 80 cm were elongated since 10 mm on each side were clamped) was...
increased to \((125 \pm 5)\) mm directly after the 10th elongation cycle and \((116.5 \pm 2.9)\) mm on the next day.

The cycle-dependent elongation is presented in Figure 3. Here, the stress correlated with half the maximum elongation used in this experiment (i.e., 75%) is given for increasing and decreasing strain. The stress decreasing with the number of load cycles in both halves of the hysteresis loops is clearly visible, underlining the aforementioned finding that a plastic deformation occurs in addition to the elastic one. This residual strain is usually attributed to microstructural material damages due to deformation compared to the undistorted state of the virgin material.\(^{[15]}\)

To investigate this idea further, microscopic images were taken of the fracture surfaces (in case of PLA and PLA soft) or cross-sections prepared by a sharp blade (in case of FilaFlex which did not break), respectively. Exemplary images are depicted in Figure 4.

The differences between these cross-sections are obvious. For rigid PLA, there are large air cavities visible, especially for higher layers farther away from the heated printing bed (upper part of the image). Similar cavities are also visible for PLA soft, again indicating low inter-strand adhesion. For the latter, the color change from pure green to white areas indicates stress whitening before complete break.

The cross-section of the FilaFlex sample, however, looks completely different. Besides small air bubbles, no cavities are visible. This finding remains identical for the samples after load change experiments, indicating that no larger material damages occur during this process.

### 3. Conclusion and Outlook

In this study, the mechanical properties of 3D printed samples from PLA, PLA soft, and the thermoplastic polyurethane FilaFlex were investigated. While PLA showed brittle failure at only 2% elongation, PLA soft broke after stress whitening at 12% strain. The FilaFlex samples could not be destroyed by up to 150% elongation, but showed a residual strain in load change experiments. Microscopic images revealed that PLA and PLA soft samples included large air cavities, in this way severely reducing the adhesion between neighboring polymer strands inside the sample, while the cross-sections of the FilaFlex samples were completely filled by the polymer, even without visible borders between neighboring strands.

Future investigations are necessary to reduce the air cavities in the two less elastic materials by optimizing the printing parameters and to investigate the relaxation of the residual strain after different load change parameters more in detail.

### 4. Experimental Section

For the experiments, rigid PLA filament, PLA soft (Shore hardness \(\sim 93\) A \(\sim 43\) D) (both FilamentWorld, Neu-Ulm, Germany) and elastic FilaFlex (a thermoplastic polyurethane (TPU) with Shore hardness 31 D \(\sim 82\) A), Recreus Industries, Elda/Alicante, Spain) were applied. Three specimens per material were used for the investigations.

3D printing was performed using an FDM printer Orcabot XXL (Prodim, The Netherlands) with a nozzle diameter of 0.4 mm and a layer thickness...
The infill density was set to 100% (rectilinear pattern, raster angle $\pm 45^\circ$ with respect to the long sample axis). The heating bed temperature was always 60°C, the nozzle temperature was 210°C (for PLA) or 245°C (for FilaFlex), respectively.

Printed samples had lateral dimensions of 100 mm x 200 mm and a thickness of 1.6 mm. These values were used to avoid possible deviations of layer height and printing bed temperature, as they may occur for larger samples, and checked with an electronic caliper gauge (TCM, Hamburg, Germany), showing that the average cross-section area of the rigid PLA samples was 7% higher than provided in the CAD file, while it was 2% higher for PLA soft and 3% lower than in the construction in case of FilaFlex. These deviations were used to calculate stress values from the forces measured during mechanical evaluations.

The latter were performed in a Sauter TVM-N universal testing machine (Kern & Sohn GmbH, Balingen-Frommern, Germany). For microscopic investigations, a digital optical microscope VHX 600 (Keyence, Neu-Isenburg, Germany) was used.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

3D printing, FDM, FilaFlex, PLA soft, tensile tests