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Challenges on extrusion-based additive manufacturing of thermoplastic polyurethane

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Abstract

Fused filament fabrication (FFF) offers rapid production capabilities with user-friendly operation and cost-effectiveness, yet challenges in printing with thermoplastic polyurethane (TPU) persist. This study identifies causes of print defects in FFF-TPUs and their relation to process parameters, by visually analysing samples produced with various TPU materials. Extrusion temperature, printing speeds, filament cooling, overlap, and extrusion flow are subject to evaluation. Common issues include filament entanglements, under-extrusion, stringing, or geometric deviations. Among other approaches, results highlight the importance of slow, constant print speeds and careful optimization of extrusion temperature.

1. Introduction

Fused filament fabrication (FFF) has become one of the most widely used additive manufacturing techniques, due to its ability to rapidly produce complex shapes, user-friendly operation, cost-effectiveness, and potential environmentally friendly features (Awasthi and Banerjee 2021). FFF is a layer-based process in which material is extruded through a nozzle in a semi-molten state. To convert a 3D CAD model into machine code, a slicer software is used, where various process parameters can be tuned to each material's specific characteristics. Besides the nozzle, an extrusion system is typically composed of a feeder, a hot end, and cooling fans (Figure 1(a)). The feeder mechanism, which is responsible for directing the filament into the hot end, is either mounted on the extrusion head (direct drive extrusion) or connected to the hot end by a flexible tube that guides the filament (Bowden extrusion), as shown in Figure 1 (b-c), respectively.

In FFF, the mechanical properties of parts are significantly influenced by parameters such as extrusion temperature, printing speed, infill type, layer thickness, and build orientation (Xu et al. 2020). Recently, the process has found various applications across industries such as architecture, aerospace, and the medical sector, but certain drawbacks still need to be addressed (Altıparmak et al. 2022). Namely, components can exhibit weak interlayer strength, low dimensional accuracy, size limitations, and poor surface quality (Wickramasinghe et al. 2020).

Classified as a thermoplastic elastomer (TPE), thermoplastic polyurethane (TPU) is a multiphase block copolymer formed by rigid (diisocyanate) and flexible (polyol) domains, which allow for rubber-like elasticity and the processability of thermoplastics (Hohimer et al. 2017).

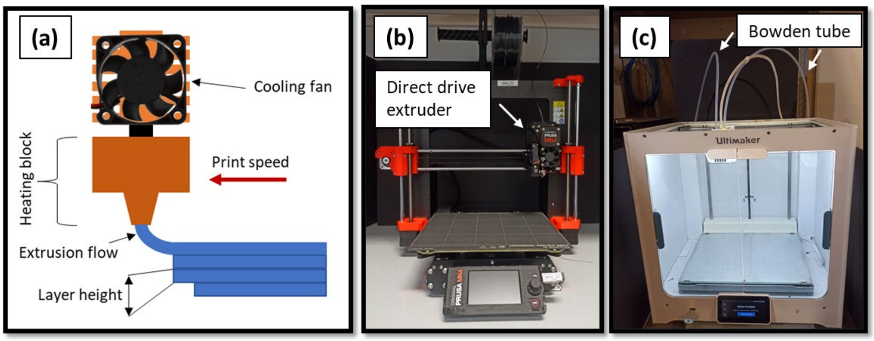

Figure 1: Fused filament fabrication process: (a) schematic illustration of relevant process parameters; (b) a direct drive extrusion machine, Prusa Mk4; (c) a Bowden-based extrusion machine, Ultimaker S5.

TPU is known for its flexibility, low elastic modulus, and the ability to undergo substantial elongation before fracture (Vidakis et al. 2021). Fused filament fabricated thermoplastic polyurethanes (FFF-TPUs) have been proposed for applications such as cushioning, wearables, footwear, and medical devices (Geng et al. 2023; Awasthi and Banerjee 2021). Moreover, current developments propose to expand their utility into promising areas such as flexible electronics (Papazetis and Vosniakos 2019), pneumatic actuators (Salem et al. 2018), and non-pneumatic tires (Wang et al. 2020; Sardinha et al. 2022). Nevertheless, the inherent softness of these filaments poses significant challenges in controlling their extrusion flow, and can cause unpredictable viscoelastic deformations, which then compromise the manufacturability of geometrically intricate structures (Mian et al. 2024; Perry et al. 2022). Commonly reported issues of FFF-TPUs are related to material oozing and stringing effects, and solutions proposed are related to the fine-tuning of extrusion temperature and print speed or limiting reverse movements of the feeder motor that pull the filament away from the outlet nozzle (retraction) (León-Calero et al. 2021; Awasthi and Banerjee 2021). Even so, parameters that promote manufacturability often conflict with those needed for adequate mechanical integrity, and trade-offs are often required. Notably, TPU filament materials can vary widely in composition, making it difficult to establish consistent processing parameters for achieving reliable mechanical properties. Moreover, available information often lacks methodology support and there is still a lack of consensus among sources regarding some issues and potential solutions. For instance, various research suggests extrusion temperatures for FFF-TPUs ranging from 190°C to 250°C (Arifvianto et al. 2021; Kasmi et al. 2022). This variability, coupled with the fact that different polymer chain compositions have distinct thermal activation and dissociation requirements, and that thermal degradation can occur between 110°C and 270°C (Zia et al.

2007), highlights the inconsistencies and emphasizes the need for further studies on the subject.

In this study, the authors investigate how FFF process variables affect the manufacturability of TPU parts. The experiments involve testing various combinations of machines and materials, followed by a qualitative visual analysis to identify common issues and types of macroscopic defects observed in FFF-TPUs. Particular attention is given to extrusion temperature, printing speed, cooling fan speed, deposition overlap, retraction, and extrusion flow amount. During the analysis, the authors explore parameter adjustments to optimize TPU part production conditions, aiming at facilitating parameter pre-selection for future mechanical characterization studies of these materials.

2. Materials and Methods

For the experiments performed in this work, two different FFF machines were used, a Bowden-based Ultimaker S5 that uses 2.85 mm filaments, and a Prusa MK4 which is equipped with a direct drive extrusion and uses 1.75 mm filaments. Concerning tested materials, TPU 95A from Ultimaker®, and Filaflex 95A were printed in the Ultimaker S5, and Flexfill TPU 92A and 98A, as well as Smartfil TPU 93A were printed in the Prusa MK4. According to the 3D printer, the slicer software used to prepare the machine files was either the Ultimaker Cura 4.11.0 or the PrusaSlicer 2.7.1. Among the tested parameters, extrusion temperature was varied according to each material, but always between 200ºC and 240ºC. Printing speeds of up to 100 mm/s were attempted, but when evaluating the effect of other process parameters, a constant speed of 25 mm/s was used. The filament cooling was also assessed, varying the cooling fan speed on three different levels (0%; 20% and 100%). Besides these, deposition overlap up to 100%, and extrusion flows up to 190% were also subject to evaluation.

3. Results and Discussion

In FFF, the filament inside the heating unit of the extrusion head should be viscous to a point that it can be continuously deposited, yet sufficiently cooled above this region so that it can be pushed by a driving force. Achieving this delicate balance is particularly challenging when working with flexible polymers which, in the case of the experiments performed in this work, often resulted in nozzle clogging issues. In addition to nozzle clogging, filament entanglement-related issues, like the example shown in Figure 2(a), are also very common. This study supports common understanding that avoiding retraction, a standard practice for stiffer materials, can significantly reduce print failures associated with filament entanglement and nozzle clogging. Even without the use of retraction to withdraw material from the nozzle outlet, excess material can still drip from it, potentially leading to over-deposition issues. When this occurs on the outer surface of a part, the phenomenon is commonly referred to as stringing (Figure 2(b)). The macroscopic defects observed in Figure 2(c), often referred to as blobs, represent another common occurrence of excess filament on the outer surface of produced parts. In the example of Figure 2(d), a tensile specimen produced with a concentric infill pattern accumulates excess material in its narrow section, affecting the study of material properties. Furthermore, in patter-based designs as the part in Figure 2(e), excess material can create unintended features and may even result in a distinct pattern, difficult to distinguish from the structure itself.

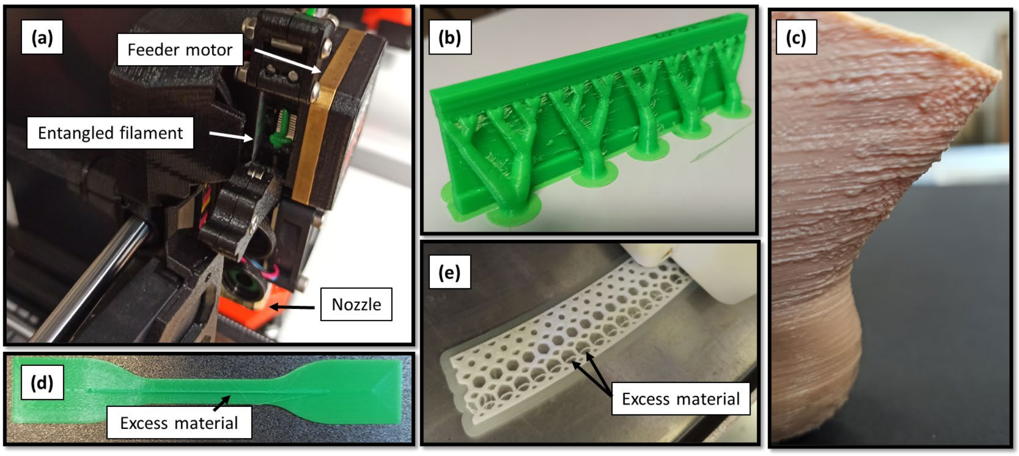

Figure 2: Examples of most common issues found when 3D printing TPUs: (a) Filament entanglement inside a direct drive extrusion system of a Prusa Mk4; (b) Stringing effect using Flexfill TPU 92A; (c) Material blobs in a part made of Filaflex 95A; (d) Accumulation of excess material in a tensile specimen produced with a concentric infill pattern; (e) Excess material deposited with a pattern when producing a cellular structure.

Alongside retraction, printing speed, extrusion temperature, and extrusion flow are also deeply linked with printing defects. The top view of specimens seen in Figure 3(a-c) demonstrates that insufficient extrusion temperature can result in thin line widths, reducing the bonding capacity of the material. At lower temperatures, viscosity may not be adequately reduced, making it challenging to effectively push the material out of the nozzle. This can lead to incomplete or uneven material deposition, emphasizing the significant influence of parameters such as temperature on TPU flow behaviour. Furthermore, despite 200°C being reported as a suitable working condition for similar materials (Arifvianto et al. 2021; Hohimer et al. 2017), this temperature consistently resulted in a clogged nozzle.

Figure 3(d-g) show the layers of a specimen and illustrate the effects of slight variations in filament cooling fan speed (0-20%) and extrusion temperature (235°C to 240°C). Increasing the filament cooling had a limited impact on promoting a defect-free surface, while reducing the temperature noticeably decreased interlayer irregularities. This may suggest that, for Flexfill TPU 92A printed at 240°C, the material may begin to degrade, impacting the bonding between layers. The top view of samples in Figure 3(h-j) shows the importance of slow printing speeds when using elastomers, which is aligned with previous literature (Kasmi et al. 2022). Moreover, this example also shows that, under certain production conditions, excessive filament cooling might not be beneficial for material bonding.

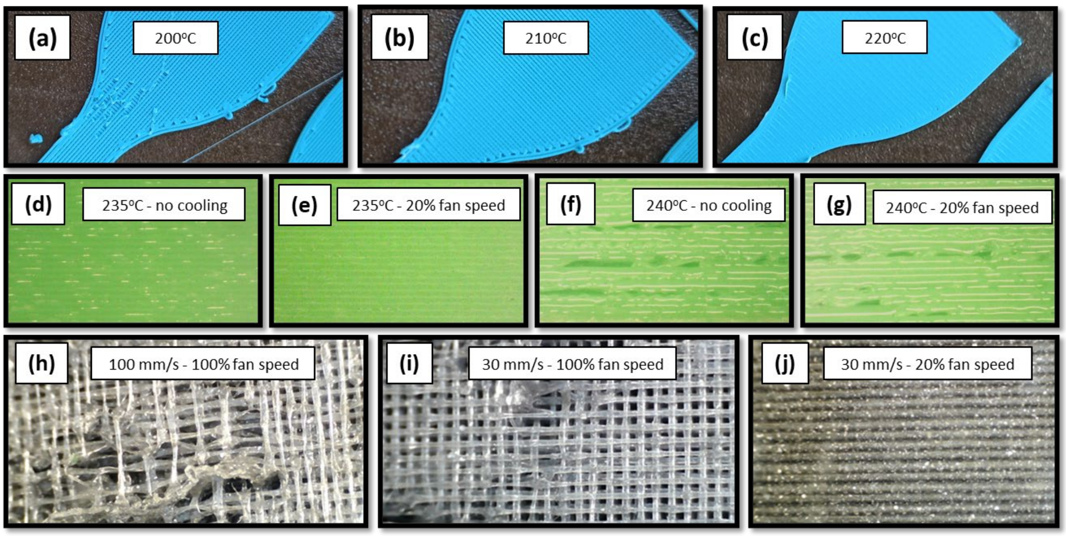

Figure 3: Amplified views of specimens produced in a Prusa Mk4 with: (a)-(c) Smartfil TPU 93A; (d)-(g) Flexfill TPU 92A; (h)-(j) Flexfill TPU 98A.

Figure 4(a-e) illustrate how adjustments in extrusion flow and deposition overlap can compensate for problems related to under-extrusion. The top view of specimens in Figure 4(a-c) reveals examples of under-extrusion issues. Figure 4(b) demonstrates how gaps between deposited infill and walls can be corrected using an overlap, a commonly available slicer parameter. Figure 4(c-e) show how the extrusion flow parameter can be adjusted to regulate filament feeding, offering a valuable option when temperature, speed, and cooling settings have already been carefully evaluated.

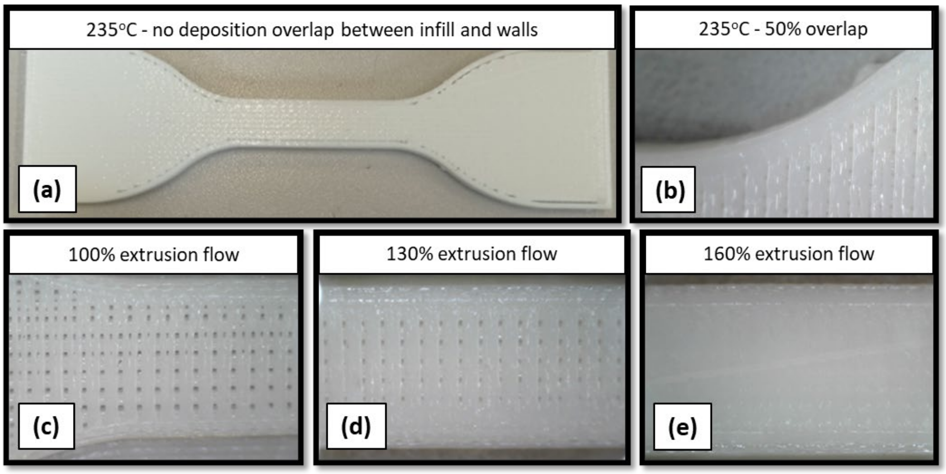

Figure 4: Samples of tensile specimens produced with TPU 95A in the Ultimaker S5: (a) Representation of lack of material generating gaps between infill and walls; (b) Amplified view of a specimen produced with overlap between infill and walls; (c)-(e) Amplified view of equivalent samples produced with variable extrusion flow.

Due to their inherent flexibility, tall and slender structures are particularly challenging to produce using TPUs. Figure 5(a-b) demonstrate the common occurrence of geometrical inaccuracies caused by lateral forces imposed on the tip (current layer) of a part by the extrusion head. In general, successful strategies for addressing the challenges of producing tall and slender FFF-TPU structures involve increasing the contact area between parts and the build plate and reducing printing speed and acceleration. Using anchors or additional support structures that increase the second moment of area of parts can also be effective. Figure 5(c-d) illustrate how the problem of wobbling encountered in test specimens was resolved by creating a very thin grid connecting multiple specimens. The multiplications of connected specimens stabilize the structure during fabrication, and the grid can be easily removed after printing.

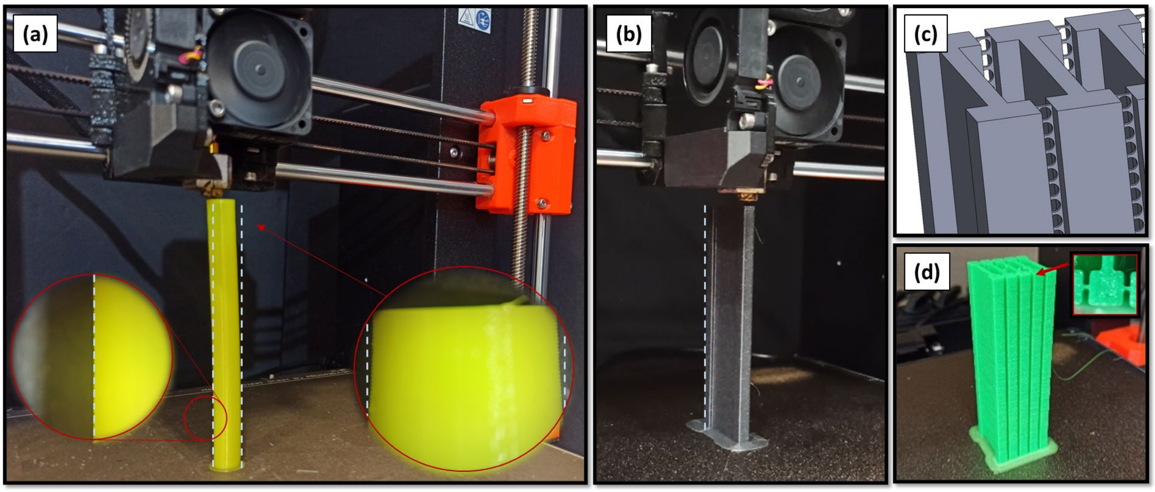

Figure 5: Examples of the instability while printing tall and slender structures: (a) Tower of Smartfil TPU 93A with differences in geometrical accuracy caused by wobbling; (b) Test specimen of Flexfill TPU 98A; (c) CAD model of the very thin sacrificial grid connecting specimens; (d) Five connected specimens of Flexfill TPU 92A.

4. Conclusions

In this study, various causes for printing defects in FFF-TPUs are identified, and their relationship to process parameters is discussed. Among the identified issues, under- and over-extrusion are highlighted as the most common. To address this type of issue, the authors advise using very slow and constant print speeds, along with iterating through small extrusion temperature intervals, as temperature had a significant influence on sample quality regardless of the material used. Additionally, considering design for manufacturing aspects such as optimizing part positioning to minimize retraction or travel movements can significantly reduce visible defects in FFF-TPUs.

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