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Experimental testing and characterization of additively manufactured CF-PEEK dies for complex profile in polymer profile extrusion

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Abstract

Polymer extrusion has the ability of mass-products with complex cross-sections. However, final die geometries and profiles are achieved after several die design changes and iterations which result in high development costs to manufacture new dies. The integration of polymer additive manufacturing (AM) in the extrusion production value chain has the potential to enable polymer extrusion for small batches and highly customized products. The present work investigates the experimental capability of additively manufactured Carbon Fibre (CF) Polyether-Ether-Ketone (PEEK) dies produced by the Fused Filament Fabrication (FFF) process. The challenge of polymeric dies or soft tooling is represented by their limitations with respect to the demanding process conditions of polymer extrusion. The experimental testing in this work was performed on a single screw extruder and wet calibration setup using four different screw speed levels. The cross section of the die profiles has circular features including non-uniform wall thickness. The extruded materials are Acrylonitrile butadiene styrene (ABS) and Polypropylene (PP). The study characterized the dimensional and surface topography of the produced extrudates by means of a micrometre and a 3D confocal microscope, respectively. The result indicates that CF-PEEK AM dies can withstand the demanding process conditions of polymer extrusion, maintaining the desired cross section within product specifications and surface roughness parameters of arithmetical mean height (Sa) with average and standard deviation of 2.3±0.8 µm for PP and 2.7±1.1 µm for ABS.

Additive Manufacturing, Polymer Extrusion, Fused Filament Fabrication, Tooling

1. Introduction

The ability of polymer extrusion for mass production can be achieved after several iterations of the die design process. These optimization loops are needed because the polymer melt flow in the die exit is subjected to process problems such as polymer swell, melt fracture, and drawdown effect. Flexibility and responsiveness have not been achieved so far in polymer extrusion where different die designs and specific polymer yielded different products quality. AM allows for the flexibility to manufacture complex shapes, offering the possibility to accelerate the manufacturing process chain. Therefore, polymer AM die (soft tooling) enables polymer extrusion for small batches and highly customized products.

Recent studies in injection moulding indicates positive outcome from soft tooling [1]. In the field of polymer extrusion, soft tooling has not been widely implemented as hard tooling (metal AM). Hard tooling in polymer extrusion shows positive results in terms of dimensional accuracy and mechanical strength[2]. In a previous study on soft tooling in extrusion, a conical die design was manufactured using the CLIP (Continuous Liquid Interface Production) process, and extruded 1 km of products [3]. In a recent study on extrusion AM dies, a free form 2D cross section was introduced to achieve a streamlined die design manufactured using metal AM which indicated smoother strain path at die inlet compared to flat die design [4].

In the present work, a CF-PEEK die was manufactured using FFF. A previous work in CF-PEEK die demonstrated the capability to extrude 165 meters of extrudates with L-profiles [5]. In the present work, the experimental testing of CF-PEEK die was performed adopting a more complex profile (Profile MEK-02), which consists of two circular features connected by a horizontal line. In addition, the profile MEK-02 here exhibits a variable thickness throughout the cross section.

2. Materials and Methodology

Experimental testing was performed in a single extruder machine with wet calibration set up as shown in Figure 1.

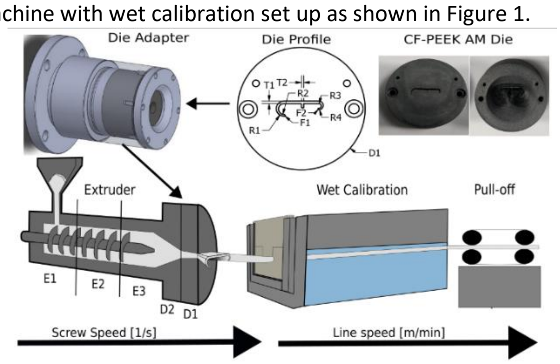

Figure 1. Experimental set up with die profile design dimensions in mm; D1=55.8, R1=3.5, R2=2.5, R3=2.0, R4=1.1, T1=1.2, T2=1, F1=0.4, F2=0.3

Figure 1 shows the selected die profile with two circular features (R1-R2 and R3-R4) and non-uniform wall thickness. The non-uniform wall thickness is identified by T1, T2, F1 and F2. The wall thickness of R1-R2 and R3-R4 varies from 0.4 mm to 1 mm and from 0.3 mm to 0.9 mm, respectively. The extruded materials are PP-Eltex and ABS-Terluran. The process temperature setting parameters in each zone are shown in Table 1. Zones E1, E2 and E3 correspond to the process cycle phases in the extruder which are feeding, melting, and melt-conveying, respectively, as shown in Figure 1. A die adapter is required for CF-PEEK die to be fitted to the extruder at D2. Heat ring and temperature sensors are located in correspondence of D2 and D1 to heat up and to maintain the temperature at die adapter and at the die, respectively.

Table 1. Process Temperature setting

Material	Temperature of Zone[°C]				
	E1	E2	E3	D2	D1
PP-Eltex	190	200	205	215	215
ABS-Terluran	170	175	180	190	195

As observed in Figure 1, a wet calibration system consists of calibration slides, water bath and pull-off unit. Calibration slides were designed oversized by 800 µm from the original dimension of profile. The objective of the experiment is to investigate the effect of screw speed on the final surface quality and wall thickness homogeneity of the manufactured extrudates. In the design of experiment, the screw speed was kept at the same value for both materials while the line speed was tuned to match the characteristics of polymer melt flow from the die outlet. Polymer swell is more pronounced as the screw speed increases, while line speed provides the draw down effect. PP has a more shear thinning effect, while ABS is more viscous. Therefore, it is more manageable to maintain the same screw speed for both materials and adjust the line speed to balance the polymer swell and the draw down effect.

3. Result

As observed in Table 2, the line speed of ABS is higher than PP, since ABS is more viscous compared to PP and required more drawdown effect. In each combination of screw speed and line speed, it extruded around 2.5 meters of extrudates. Polymer melt of ABS at n= 1.2 [1/s] was not stable making not possible to maintain stable line speed for more than 3 minutes. It was observed that the polymer melt was jammed in the calibration slides due to polymer swell effect.

Table 2. Experimental testing parameters

Run ID	screw speed (n) [1/s]	line speed [m/min]	time [min]	extruded [meters]
Material: PP-Eltex				
1	0.3	0.40	6	2.4
2	0.6	0.55	6	3.3
3	0.9	0.70	5	3.5
4	1.2	0.80	5	4
Material: ABS-Terluran				
5	0.3	0.40	6	2.4
6	0.6	0.55	5	2.5
7	0.9	0.73	4	2.9
8	1.2	0.85	N/A	

As observed in Figure 2a, the surface roughness was measured in five points both in the horizontal and extrusion direction respectively using 3D confocal microscope with 20x magnification. Figure 2b shows the surface topography of PP-Eltex extrudates produced with a screw speed of 0.3 [1/s]. As observed, the surface topography of extrudates consists of layers with shallow valleys. The CF-PEEK die, manufactured with FFF, has surface topography of ripple features with sharp peak and sharp valley [5]. Surface topography of CF PEEK AM die influences the surface characteristics of extrudates in the beginning of experiment at lower screw speed of PP. The sharp valley smoothens out by the deposit of polymer molecules as screw speed increases. The layers in extrudates are aligned with the extrusion direction rather than the ripple of FFF, therefore, the extrusion process parameters as well as cooling effect have more prominent influence on the surface quality of extrudates.

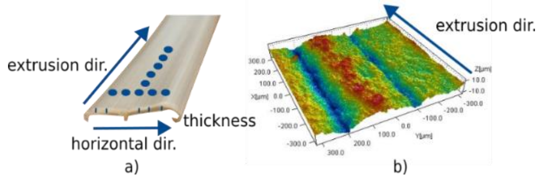

Figure 2. a) measurement strategies b) surface topography of extrudates PP-Eltex at screw speed of 0.3[1/s]

As observed in Figure 3a) and 3b), the lowest surface roughness for PP and ABS are from screw speed at 0.9 1/s and 0.3 1/s, respectively. The cross-section of ABS extrudates manufactured at screw speed of 0.9 1/s is better compared to 0.3 1/s. The overall average of Sa and its standard deviation for PP and ABS are 2.3±0.8 µm and 2.7±1.1 µm, respectively. Wall thickness measurement of extrudates at screw speed of 0.9 [1/s] was performed using a micrometre in five different areas. The average of wall thickness and the standard deviation of PP and ABS are 1.40± 0.04 mm and 1.20± 0.01 mm, respectively.

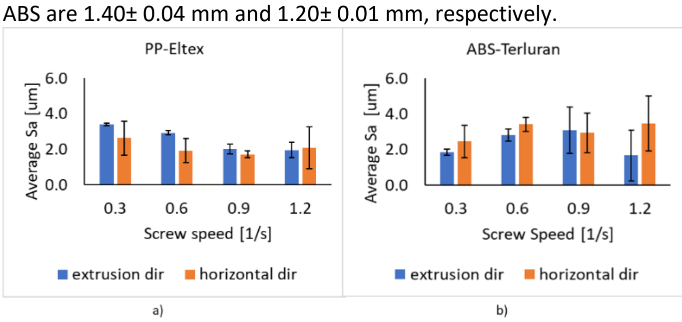

Figure 3. Bar chart of average Sa with standard deviation in error bar for two materials of a) PP-Eltex; b) ABS-Terluran.

4. Conclusion

The study shows that CF-PEEK dies additively manufactured using FFF was able to extrude complex profile extrudates with circular features and non-uniform wall thickness. Extrudates of ABS at screw speed of 0.9 1/s has the best cross section and meets the nominal wall thickness. As the future study, the calibration slides with oversized of 1 mm and 1.2 mm are recommended, to overcome the polymer swell problem at speed of 1.2 [1/s]. The die head pressure and velocity are feasible to be predicted by flow simulation, then validated by experimental testing data.

Acknowledgements

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