Joint Special Interest Group meeting between euspen and ASPE
Advancing Precision in Additive Manufacturing
KU Leuven, Belgium, September 2023
www.euspen.eu

Influence of surface roughness parameters of additively manufactured die on the extrudates in polymer extrusion

A.H. Aimon[1], G.Tosello[1], D.B.Pedersen[1], M. Calaon[1]

[1]*Technical University of Denmark (DTU), Department of Civil and Mechanical Engineering, Kgs. Lyngby, Denmark*

ahaai@dtu.dk

Abstract

Additive manufacturing (AM) provides flexibility for manufacturing complex geometries, allowing for the creation of streamlined die designs with free-form geometries. However, polymer-based AM dies (soft tooling) have mechanical and thermal properties limitations, which may impact their ability to withstand the process conditions involved in polymer extrusion. A study was conducted on carbon fibre (CF) and polyether-ether-ketone (PEEK) composite dies produced via the Fused Filament Fabrication (FFF) method. Experimental testing of CF-PEEK AM die in polymer extrusion was performed with acrylonitrile butadiene styrene (ABS) and polypropylene (PP) extruded material. The surface characterisation of the CF-PEEK AM die replica, and the extrudates were characterised using 3D optical and confocal microscopes. Surface roughness parameters used in this study are height parameters (Sa and S10z) and functional surface parameters (Spk and Svk). Despite the distinctive ripple features of the FFF process with the peaks and deep valleys, the surface roughness parameters (Sa, Spk, and Svk) of the extrudates, measured on both extruded materials, are 6-8 times lower compared to the CF-PEEK die. It was observed that the surface topography of CF-PEEK AM die only impacted the surface roughness of the extrudates, particularly at the beginning of the experiments. As the screw speed increased, process parameters and cooling processes started to play a more significant role, exerting a greater influence on the surface quality of the extrudates.

Additive manufacturing, soft tooling, surface roughness, extrudates

1. Introduction

The integration of additive manufacturing (AM) into the die design process offers the advantage of producing a single piece of streamlined die, eliminating the need for assembling multiple plates. This single-piece die design provides greater flexibility in introducing transition zones from the die inlet to the die exit, resulting in improved melt flow and reduced pressure drop [1]. Furthermore, soft tooling is well-suited for small-scale production batches that meet the minimum required properties for application testing. A conical die design, inspired by the streamlined die design, was manufactured using a polymer-based AM of Continuous Liquid Interface Production (CLIP) process and extruded 1000 meters of product, highlighting its durability and functionality [2].

This study employs the FFF process to manufacture a CF-PEEK die with a profile design of circular features and non-uniform wall thickness. The previous study reported the experimental testing of the same die profile design and the extrudates' Sa value with four increased screw speeds [3]. In the present work, extensive surface roughness parameters (Sa, S10z, Spk, and Svk) of CF-PEEK AM die replica and the extrudates were obtained to analyse the influence of soft tooling surface roughness on its extrudates.

2. Material and Method

The die design profile comprises circular features (R1-R2) and non-uniform wall thicknesses of R1, R2, and TA, as shown in Figure 1 a). CF-PEEK die was printed with the die exit oriented flat (XY) on the platform with the build direction along the Z axis shown in Figure 1 b). The printed die (Figure 1 c) and d)) exhibits a single piece of streamlined die design.

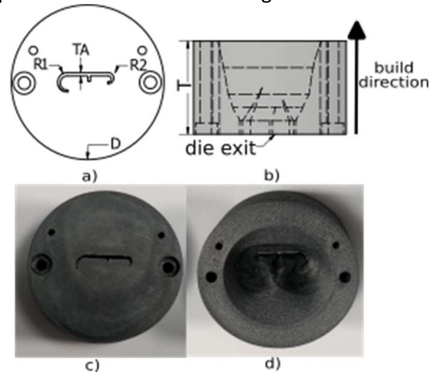

Figure 1. a) profile die design with R1=3.5, R2=2.0, TA=1.2, D=55.8, T=35 in mm b) build direction c) printed die exit view d) inlet view.

Figure 2 a) shows the replica from the die exit with a channel length of around 13 mm, manufactured using RepliSetGF1, a rapid-curing silicone for a 3D high-resolution replica. Experimental testing was performed in four varying screw speeds with PP and ABS as extruded materials. The extrudate of ABS at a screw speed of 0.9 1/s is shown in Figure 2b). Surface characterisation of replica and extrudates was performed using 3D optical and laser confocal microscopes, with 20x magnification. Ten-point measurements were performed for each extrudate, five at the extrusion direction and five at the horizontal direction. A six-point measurement was taken at a replica within a 3-6mm area of the die exit to evaluate how the die's surface quality affects the extruded product. The surface roughness parameters include the arithmetical mean height

(Sa), ten-point height (S10z), reduced peak height (Spk), and reduced valley depth (Svk). The images were levelled and form removed. It was observed that the images contained a significant amount of noise, which was subsequently eliminated. In line with the standard procedure ISO 25178-2, a filter with cut-off values of λs=0.25μm was applied.

Figure 2. a) CF-PEEK die replica; b) extrudate of ABS

3. Result

Figure 3 a) illustrates the surface topography of the die from the replica image, which has been inverted by enabling measurement of the replica mode in the microscope to generate this representation. The topography has distinctive ripple features with peaks and deep valleys. The ripple width is directly linked to the layer thickness of 150 µm from FFF printing process parameters. The extrusion direction is perpendicular to the ripple direction in CF-PEEK die. Furthermore, extrudates of ABS have more streaks than PP, representing the extrusion direction of polymer melt flow (Figure 3 b) and c)).

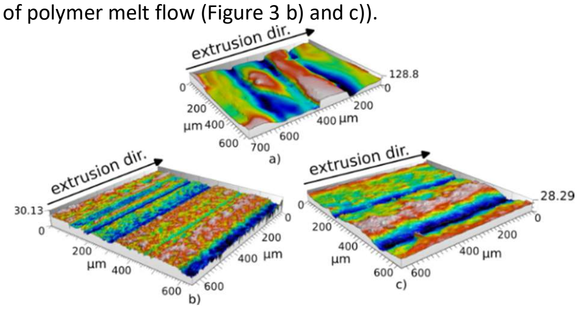

Figure 3. Surface topography a) CF-PEEK die replica b) extrudates of ABS at n=0.3 [1/s] c) extrudates of PP at n=0.3[1/s]

Table 1. Average surface texture parameters (Sa, S10z, Spk, and Svk) and the standard deviations of replica and extrudates

Parts	Sa[µm]	S10z[µm]	Spk[µm]	Svk[µm]
Die replica	18.5±1.8	112.6±4.0	18.5±6.3	24.6±2.3
Extrudates-PP	2.3±0.8	18.9±7.5	2.9±1.6	3.1±1.9
Extrudates-ABS	2.7±1.1	25.1±8.1	2.7±2.0	4.4±2.5

Table 1 indicates the average surface roughness parameters and their standard deviation from the repetitive measurements. CF-PEEK die has a considerably high value of Svk, with lower values of Sa and Spk. Considering the extrusion direction, the peak surfaces of CF-PEEK die mostly interacted with the polymer molecules more than the valley surfaces. The surface roughness parameters (Sa, Spk, and Svk) values of extrudates, both PP and ABS, are lower by a factor of 6-8 compared to CF-PEEK die. This suggests that the overall surface parameters of the die do not have a significant influence on the surface quality of the extrudates.

Figure 4a) and b) presents the average surface parameters and their standard deviation as a function of increasing screw speed. The trend reveals that the surface roughness parameter of PP becomes smoother with an increase in screw speed, while ABS exhibits an increase in roughness with a significantly higher value of Svk. At the beginning of extrusion, polymer molecules of PP experienced a scrubbing effect where they started to settle in the valleys, resulting in a smoother surface as the extrusion process progressed. During the extrusion of ABS, polymer swell was observed at a screw speed of 1.2 1/s, causing the polymer melt to jam at the calibration slides. In Figure 4b), the Svk value is notably high at screw speeds of 0.9 and 1.2 1/s. Therefore, it is recommended to use a lower screw speed setting for ABS compared to PP to achieve optimal surface quality.

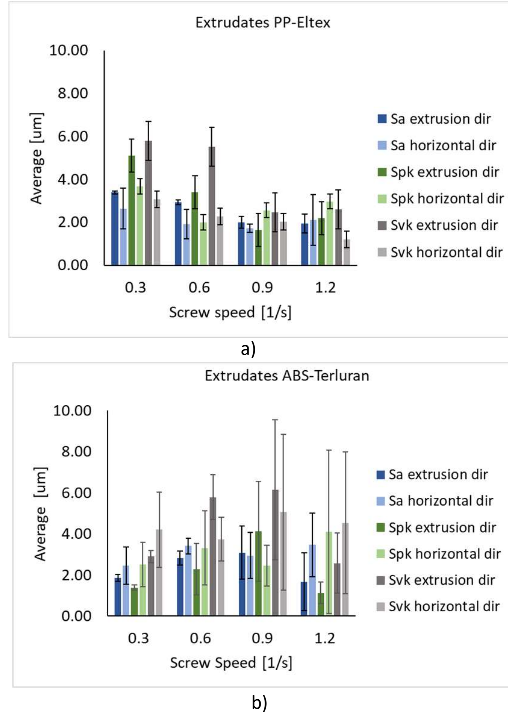

Figure 4. Extrudates surface texture parameters with average and standard deviation in error bar a) PP-Eltex b) ABS-Terluran

4. Conclusion

The CF-PEEK die has a rough surface finish due to distinctive ripple features, particularly high Svk, while Sa and Spk values are lower. In contrast, the extrudates' surface roughness parameters (Sa, Spk, and Svk) (PP and ABS) are 6-8 times lower than the CF-PEEK die. PP extrudates show improved surface roughness as speed increases due to the scrubbing effect at the start of extrusion. However, extrusion of ABS revealed polymer swell at a screw speed of 1.2 1/s, leading to a significantly high Svk value at speeds of 0.9 and 1.2 1/s. Process parameters and cooling rate become more influential as screw speed increases, affecting the surface quality of extrudates.

Acknowledgement

This research was undertaken in the context of the European Training Network DIGIMAN4.0 project ("DIGItal MANufacturing Technologies for Zero-defect Industry 4.0 Production", https://www.digiman4-0.mek.dtu.dk/) supported by Horizon2020, the EU Framework Programme for Research and Innovation (Project ID: 814225).

References

[1] S. C. Lieber, A. P. Varghese, R. Tarantino, and A. Tafuni, "Additive manufacturing for plastic extrusion die tooling: A numerical investigation," *CIRP J. Manuf*, 2023.

[2] A. Turazza, A. Davoudinejad, M. Calaon, D. B. Pedersen, and G. Tosello, "Towards the integration of additively manufactured photopolymer dies in the polymer profile extrusion process chain," *Procedia CIRP*, vol. 93, 2020.

[3] A. H. Aimon, G. Tosello, D. B. Pedersen, and M. Calaon, "Experimental characterization of additively manufactured CF-PEEK dies for complex profile in polymer profile extrusion," *23rd Euspen International Conference,* 2023.