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Additive manufacturing of soft tools – Application of carbon fiber filled PEEK to polymer extrusion dies production

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Abstract
The ongoing improvements within material development of polymer-based additive manufacturing is resulting in an ever growing availability of highly specialized materials supporting the expansion of the area of application towards more complex and demanding part uses. One example of such an application is the use of additively manufactured tools for polymer profile extrusion. The work presented here aims to exploit the possibilities of integrating additively manufactured carbon fiber filled PEEK tools in the tooling process chain for polymer profile extrusion. Five samples for each of three different extrusion die geometries were manufactured using a fused filament fabrication process with carbon fiber reinforced PEEK material. The dimensional evaluation of a total of 15 dies was performed to ensure the final dimensions of extrudates will be according to specifications. It was found that the process could achieve a reproducibility within 0.2% and 10% standard deviation relative to nominal dimensions depending on the features size. In terms of accuracy, absolute deviations between 10 µm and 500 µm were found depending on the considered dimensions, indicating that a correction factor should be implemented in order for the dies to comply with the geometrical tolerance specifications required to manufacture the extrudate product. The external surface roughness of the dies were evaluated showing an average Sa value of 15.6 µm with a standard deviation of ±3.2 µm across all samples. The relatively high surface roughness could potentially pose an issue when aiming for the production of extrudate products with smooth surfaces (e.g. Ra = 1-2 µm or below). Further post-processing of the internal die surface should be explored. Future work will include in-situ testing of the extrusion dies with life-time evaluation as well as dimensional and surface evaluation of the manufactured extrudate product.

Additive Manufacturing, Tooling, Fused Deposition Modelling, Fused Filament Fabrication, Profile Extrusion, Dimensional Evaluation

1. Introduction

Extensive research within the field of compatible materials for additive manufacturing (AM) is rapidly increasing the availability of specifically developed materials with enhanced properties. With new materials being more durable, temperature resistant, dimensionally stable, with high machinability, low cost or combinations thereof, many new areas of applications can increasingly be explored [1,2].

Several studies have been dealing with AM for direct tooling, both within soft and hard tooling. While metal AM tools, i.e. hard tools, have been shown to provide results equal or comparable to conventionaly manufactured tools in terms of properties relating to dimensional accuracy and mechanical strength they are currently significantly more expensive than soft tools [3,4]. However, tools manufactured using polymer-based AM technologies tend to be prone to failure when exposed to combinations of high temperature and pressure, which are the common manufacturing conditions experienced in polymer profile extrusion [5].

Apart from the developments within raw-material compositions for increased durability, fiber reinforcements is a well-know method to obtain better mechanical properties such as increased strength. For polymer parts, carbon fiber reinforcement is widely used in the production of low weight high strength mechanical components [1].

Through a fused filament fabrication (FFF) process using a carbon fiber filled PEEK feedstock, tools for polymer profile extrusions have been manufactured. The work presented in this study exploit the potential application of this particular AM process for tooling in polymer profile die production.

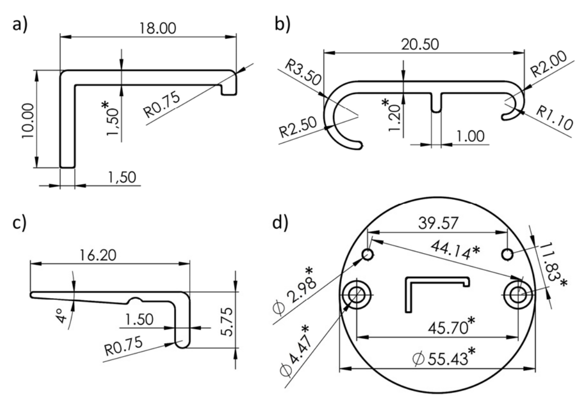

Figure 1. Extrusion die profile designs with main dimensions shown in mm: a) Profile MEK01, b) Profile MEK02, c) Profile MEK03, d) External die dimension for all three profiles as well as placement of alignment and screw holes. (*Evaluated dimensions)

2. Methodology

2.1. Carbon Fiber Filled PEEK dies fabrication

Three different profile designs, shown in Figure 1, have been designed for this particular investigation. Together they contain some of the common features found in extruded plastic profiles such as flat faces, sharp corners, circular elements, protruding parts features. The profile geometries are nested into a die body with a cylindrical shape of diameter 55.8 mm containing 4 through-holes parallel to the center axis: 2 alignment holes and 2 screw holes for the assembly in the experimental setup.

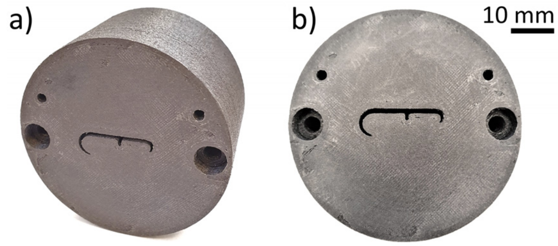

Figure 2. Example of a manufactured die, Profile MEK02 die number 4: a) Isometric view, b) Seen from the die exit. Outer diameter = 55.4 mm.

Five die specimens for each of the three profiles were manufactured using the beforementioned FFF process with a layer height of 180 µm, a nozzle diameter of 40 µm, extrusion temperature of 450 °C, a bed temperature of 150 °C and a carbon fiber concentration of 10 %wt. An example of a manufactured die is shown in Figure 2. The dies were manufactured with the profile exit face oriented towards the buildplate and the centre axis of the die placed parallel to the build direction. After manufacturing, the dies were mechanically polished to remove the raft geometry from the manufacturing process. No additional post processing has been applied.

2.2. Measurement procedure

A dimensional evaluation of the die geometries was performed using an optical coordinate measurement machine with a backlight based contrast measurement. The machine used was a DeMeet 220 with a stated uncertainty of U_{DeMeet} = ±4 µm. All measurements were performed by fitting least square line- or circle-profiles to the geometry using a Gaussian fit. Center distances of the alignment holes as well as select dimensions of the profile geometry were evaluated.

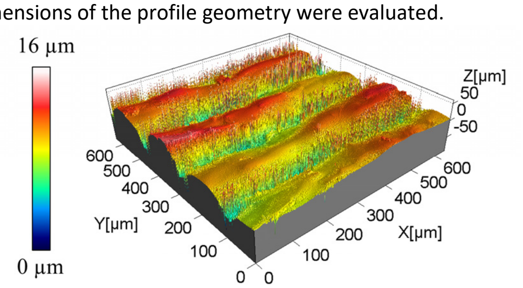

Figure 3. Example of the external surface topography on a face normal to the build direction. The line structures each represent a single layer with an extruded filament as a reminiscence from the FFF process.

Secondly, the surface roughness was evaluated using a confocal laser scanning microscope (CLSM) Olympus Lext 4100 with 20x magnification. All surface measurements have been determined according to ISO 25178-2:2012 and all data processing has been conducted using Form Image Metrology Software SPIP™. All acquired measurements were subjected to first order plane fit for levelling and S- and L-filters with cut-off values of λ_s = 0.25 µm and λ_l = 0.5 mm respectively.

3. Dimensional evaluation and data Analysis

From the evaluated dimensions presented in table 1 it can be seen that the center hole distances between alignment and screw holes have very small deviations from the nominal values. This suggests a high accuracy on the placement of features as well as overall distances. On the contrary, the diameters as well as the measured die openings are significantly smaller, suggesting a need for a correction factor when dealing with hole and slot dimensions for the applied FFF process.

Table 1. Diameters of screw and alignment holes, hole to hole center distances and profile thicknesses of selected dies. Calculated averages of diameters and distances are based on all 15 dies.

Description	Nominal [mm]	Measured [mm] Average	STD	Deviation [mm]	Deviation [%]
Thickness MEK01	1.50	1.29	0.13	-0.21	-14.3%
Thickness MEK02	1.20	1.03	0.08	-0.17	-14.2%
Diameter 1	2.98	2.48	0.11	-0.50	-16.8%
Diameter 2	4.47	3.98	0.14	-0.49	-10.9%
Distance 1	11.83	11.85	0.13	0.03	0.2%
Distance 2	39.57	39.50	0.08	-0.07	-0.2%
Distance 3	44.14	44.11	0.12	-0.03	-0.1%
Distance 4	45.70	45.69	0.12	-0.01	0.0%

From the evaluation of the external surface roughness the arithmetic mean height was found to be Sa_{avg} = 15.6 µm with a standard deviation of STD = ±3.2 µm. This is within the range generally found for this particular additive manufacturing process [6]. However, in order to be able to manufacture extruded product with a higher surface quality, a reduction of the internal surface roughness of the die should be considered.

5. Conclusion

The preliminary work presented in this study has investigated the manufacturing of extrusion dies for polymer profile extrusion by the use of a FFF process using carbon fiber reinforced PEEK. It was found that the manufactured dies fulfilled the dimensional requirements with regards to overall dimensional accuracy, precision and reproducibility. However, the geometrical features involving gaps, holes and slots in general was found to be below the specified dimensions indicating a need for a correctional factor to be applied when dealing with these types of geometries. The realised surface roughness was comparable with general values for the specific AM process, however significantly higher compared to conventionally manufactured steel dies. Thus, post processing to reduce the internal surface roughness should be considered.

Future work will focus on the application of post-processing suitable for surface roughness reduction as well as experimental testing in a production setup with subsequent characterisation of the extrudate product.

Acknowledgements

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