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Dimensional evaluation of additive manufactured polymer extrusion dies produced by continuous liquid interface production

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Abstract

In profile polymer extrusion, the die is one of the critical element of the process and it allows to produce kilometers of extrudates with very complex cross-sections at high production rates. However, the design phase of a die usually results to be a time-consuming and cost-intensive phase of the manufacturing process chain. Moreover, tight dimensional tolerances and accurate surface finish are extremely important attributes for the proper functioning of the extrusion products.
In the delopment phase of new extrudate products, Additive Manufacturing (AM) has the potential to be an appropriate technology for the manufacturing of extrusion polymer dies in order to shorten lead time and pilot production costs. Continuous Liquid Interface Production (CLIP) is a recently developed photopolymer-based AM technology and it has been selected for facing these challenges.
In this study, polymer AM dies have been produced in CE221, a photo-resin with high thermo-mechanical properties with Continuous Liquid Interface Production (CLIP). The polymer dies were tested on an industrial production line and proved to be able to withstand the demanding process conditions, yielding up to 300 m of extruded product. The capability of the newly established process manufacturing chain was demonstrated to be comparable with the conventional process chain based on machining of tool steel dies in terms of surface finish and dimensional accuracy.
The material selection for the die manufacturing was vital to prove this new concept and no tool failure occurred during the production. Manufacturing accurate tools is indeed necessary in order to meet the demanding quality requirements and this is another challenge that has to be fullfilled. A dimensional metrology study on selected features of the AM fabricated dies was performed. The analysis highlighted the most relevant issues that must be taken into account and managed before a successfull integration of the AM technology in the extrusion process chain can be realized.

3D printing, Extrusion, Polymer, Tooling

1. Introduction

In the Industry 4.0 context, the need for flexibility in the manufacturing field is becoming one of the most important attributes to be achieved [1]. With the focus of increasing the flexibility for the manufacturing of polymer profiles, AM polymer dies were fabricated and tested in an extrusion production line, aiming for a faster and more cost effective solution in new die development. Continuous Liquid Interface Production (CLIP) is a photopolymer-based AM technology developed by Carbon 3D and it was selected for this study. [2]

For this purpose, a new conical die design for the polymer AM dies was manufactured and validated on an extrusion line. A number of selected features of the AM fabricated dies have been measured and the comparison between these values with the references is presented, showing the differences detected before and after the extrusion experiments.

2. Polymer AM dies fabrication and extrusion

Three dies (named A, B, C), all having the same design were manufactured with an M2 CLIP machine by Carbon 3D in CE221, a photo-resin with high thermo-mechanical properties (see Figure 1 right). The dies were mounted on an extrusion line. Extrusion process parameters were as follows: melt temperature of 150°C and extrusion speed of 8 m/min. For comparison reasons, the conventional flat steel die with a land length of 6 mm, was tested at the same process conditions prior to the polymer AM dies (see Figure 1, left).

Compared to the flat steel die, the design of the polymer dies was changed to reinforce the structure in order to obtain a longer tool life [3]. Indeed, a conical die inlet, able to guide the flow through the die channel avoiding abrupt changes, has been added on top of the original design with a die land of 6 mm. Therefore, the overall thickness has been increased up to 15 mm. The land length was kept at 6 mm in order to keep the values of pressure as close as possible to the ones detected on the flat steel die. A polishing step was also performed on the internal surfaces of the die land, for a better finishing of the final products.

Figure 1. On the left, the flat steel die showing the profile selected for the experiments. On the right, die B with the new conical design and with the extrudate produced.

After the AM fabrication, the cylindrical lateral surfaces of the polymer dies were post-processed by milling in order to reduce their external diameter to 55.50 mm for fitting purposes. This choice was made in order to allow the dies to expand given the heat provided to them by the extruded melt polymer.

3. Polymer AM dies dimensional evaluation

The profile wall thickness on the polymer dies was measured at the die outlet in the regions represented by T_1, T_2 and T_3, along with the six diameters (D_1, D_2, D_3, D_4, D_5, D_6) as indicated in Figure 2.

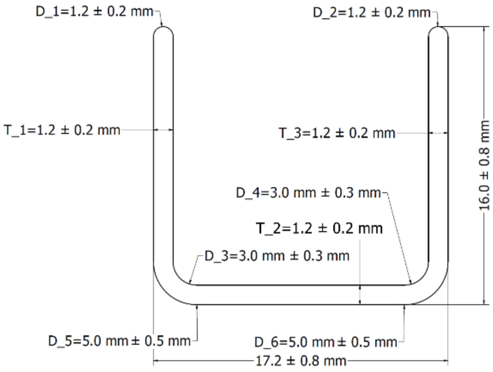

Figure 2. Nominal values of diameters and thicknesses measured on the die outlet.

The outlet die surfaces were scan with the a focus variation microscope Alicona Infinite Focus G4 using a 5x magnification lens. The measurements were performed before and after the tests and analysed using the SPIP software by Image Metrology (version 6.7.7). Three repeated measurements for each feature for all the dies were performed. The results, compared with the reference design value are presented in Figure 3.

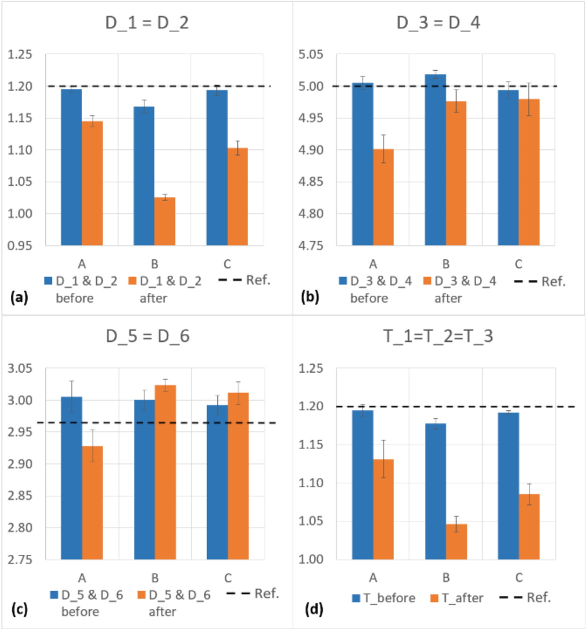

Figure 3. Measurements comparison of diameters and thicknesses before and after the experiments, showing the effects of the extrusion process on the polymer AM dies. Error bars represent the expanded uncertainty.

Expanded uncertainty was calculated following the method derived from the ISO-GUM [4]. The contributors considered for the uncertainty budget are the measurement repeatability and and the instrument calibration uncertainty for lateral measurements ($u_{cal,Alic(x,y)}$=1.4 µm). The expanded uncertainty U was obtained for each measurement result represented in Figure 3 by multiplying the combined standard uncertainty u_c by the coverage factor k (k=2 for a level of confidence of ~95%). Values of U are listed in Table 1.

Table 1. Expanded uncertainty calculated for dies A, B and C.

	Before experiments				After experiments			
Feature	D_1/D_2	D_3/D_4	D_5/D_6	T_1/T_2/T_3	D_1/D_2	D_3/D_4	D_5/D_6	T_1/T_2/T_3
$U_{exp, die A}$ [µm]	9	20	49	16	17	44	50	49
$U_{exp, die B}$ [µm]	21	12	31	14	10	35	20	21
$U_{exp, die C}$ [µm]	16	26	32	4	22	51	35	27

The blue histograms correspond to the values measured after the fabrication of the dies with CLIP. Looking at the values measured after the experiments, represented by the orange histograms, it is possible to notice a general reduction, principally in subfigures (a) and (d), with some exception for the values in subfigure (c). Despite all parts present deviations from the nominal values, all the measurements are within the specified tolerances, both before and after the extrusion process is performed.

Considering the values of thickness T_1, T_2 and T_3, as well as D_1 and D_2 which are a representation of the wall thickness, a variation of the values measured before and after the experiments was encountered. This was considered to be an effect related to the thermal expansion of CE221. The dies were reduced in diameter from 56 mm to 55.5 mm with a milling machine, i.e. less than the nominal external diameter equal to 55.8 mm corresponding to the die holder on the extruder tool block. The coefficient of thermal expansion stated in the data sheet for CE221 is 90 µm/m•°C between 100°C and 180°C. Since the tests have been carried out at 150°C, at this working temperature the calculated external diameter of the dies results to be equal to 56.15 mm (considering a room temperature of 20°C and an initial length of 55.5 mm). Therefore, due to constrain generated by the die holder, the dies features resulted in a reduction of the wall thickness at the die outlet during the extrusion process. As a consequence, it was considered that the cause of the permanent change of the features could be related to the material relaxiation due to the prolonged exposure to both the compressive stress and heat.

4. Conclusions

In this study, a dimensional evaluation for four polymer AM dies manufactured has been carried out. Direct soft tooling for extrusion dies was demonstrated to be a feasible and effective solution to reduce lead-time and production cost when the need of manfacturing prototypes or small batches of extrudates occurs.

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References

[1] H. Lasi, P. Fettke, H. G. Kemper, T. Feld, and M. Hoffmann, "Industry 4.0," Bus. Inf. Syst. Eng., vol. 6, no. 4, pp. 239–242, 2014.
[2] J. R. Tumbleston et al., "Continuous liquid interface production of 3D objects," Science, vol. 347, no. 6228, pp. 1349–1352, 2015.
[3] M. M. Kostic and L. G. Reifschneider, "Extrusion Die Design," pp. 633–649, 2006.
[4] "Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)," ISO/IEC Guide 98-3:2008, ISO, Geneva, Switzerland, 2008.