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Published in:
Proceedings of the Joint Special Interest Group meeting between euspen and ASPE Advancing Precision in Additive Manufacturing (2019)

Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Basso, A., Mendez Ribo, M., Danielak, A. H., Yang, B., Kjeldsteen, P., Valler, P., Pedersen, D. B., & Zhang, Y. (2019). 3d Printed Mold for Powder Injection Molding Process. In A. Bernard, R. K. Leach, D. B. Pedersen, & J. S. Taylor (Eds.), *Proceedings of the Joint Special Interest Group meeting between euspen and ASPE Advancing Precision in Additive Manufacturing (2019)* (pp. 71-74). The European Society for Precision Engineering and Nanotechnology.

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Joint Special Interest Group meeting between euspen and ASPE
Advancing Precision in Additive Manufacturing
Ecole Centrale de Nantes, France, September 2019
www.euspen.eu

3d Printed Mold for Powder Injection Molding Process

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Abstract
Powder injection molding (PIM) is a well-established process that allows mass production of metal and ceramic components with complex geometries. PIM allows eliminating the machining process reducing the overall production cost. This work proposes an innovative process for powder injection molding, enabling the use of this technology also when low production and high geometrical complexity of the part are required. A 3D-printed water-soluble sacrificial mold is used which allows to produce final parts with undercuts and inner channels. In this work an overview of the process chain will be presented, focusing then on the degree of complexity that can be achieved. An analysis of the surface deviation between printed parts and nominal values was carried out showing a deviation of 27 µm. Particular attention was paid to the fabrication of cooling channels, investigating the possibility to print straight pillars. It was possible to produce such a feature when diameters below 0.6 mm or higher than 1.4 mm were used. Moreover, an evaluation of the swelling behavior of the photopolymer during the dissolution process was done.

3D printing, Powder Injection Molding, Printed Mold Casting, Freeform Injection Molding

1. Introduction

Additive manufacturing (AM) has a key role in the development of Industry 4.0. Advances in AM have allowed to rethink and revise well established processes like injection molding. This work is focused on the use of additive manufacturing for powder injection molding process (PIM). PIM is used for mass production of net shape parts with complex geometry, since this process is more convenient than machining [1]. In case of prototyping or low rate production, this technology is no more affordable due to the high tooling cost. The use of PMC (Printed Mold Casting) allows to reduce heavily the mold manufacturing cost as shown by Tosello *et al.* [2], making the PIM process feasible also in case of low production. Lately the use of AM as soft tooling method for injection molding has been investigated in several works [2-5]. Conventional tooling techniques for an injection molding mold fabricates the negative shape of the desired geometry; after filled by feedstock and solidified, the part will be ejected mechanically when the mold is open. The geometry of the part is limited by the ejecting process, for example undercut should be avoided. By using a sacrificial mold insert fabricated by AM technologies, complex part can be achieved inside the mold insert, since the entire mold insert will be ejected. The AM mold will be thermally degraded [6] or chemically dissolved [7], then the powder-containing parts will be obtained. Due to the aforementioned problems, when highly customized parts are needed, or in the case of prototyping and pilot production, machining or additive manufacturing has to be chosen instead of PIM [3]. The process 3DIMs – 3D-Printing Integrated Manufacturing System, is under investigation as an innovative process for powder injection molding, making possible the use of this technology also when low production and high geometrical complexity of the part are required. In this process, AM is hybridized to fabricate a sacrificial mold and implemented to the PIM process. In this study, the complete process chain will be presented, a particular focus will be spent showing the degree of complexity that can be achieved using this innovative technology. An effort was spent investigating the possibility to fabricate sacrificial mold with pillars in order to produce parts with inner channels. Indeed, the fabrication of parts with cooling channels is of particular interest for the Danish manufacturing industry.

2. The integrated process chain

The process chain for integrating manufacturing process between additive manufacturing and powder injection molding is based on six fundamental steps (see Figure 1): 3D printing of the mold, injection molding, demolding, debinding, sintering and machining of the final part when necessary. The essential ring in the process chain is the fabrication of the mold using additive manufacturing. In this work the mold was produced by means of stereolithography (SLA) one of the VAT photopolymerization process.

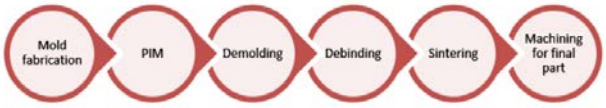

Figure 1. Process chain of 3DIMs

In SLA the liquid photopolymer is cured, layer by layer, using a UV laser beam. The printer used was a Peopoly Moai Laser SLA 3D Printer with x-y resolution of 70 µm and z resolution of 25 µm. The water-soluble resin used for the manufacturing of the mold is the IM 2.0 GP produced by AddiFab. After the additive manufacturing step, the evaluation of the geometrical quality of

the printed part was done using a DeMeet 3D CNC coordinate measuring machine and a 3D scanner from 3Shape®, the post processing of the data was carried out with GOM Inspect ® and SPIP®, two software for post processing of images. Following the mold fabrication was the injection molding. A wax-based feedstock was designed as material for the filling of the 3D printed mold. A feedstock for injection molding is a composite material where a metallic or ceramic powder is dispersed in a polymeric matrix. The content of powder in the feedstock is called solid loading, the binder occupies the remaining part in the composite. The binder system is responsible for the flowability of the feedstock during the injection and for the strength of the green body. By using wax, as primary binder in the feedstock formulation, it is possible to lower the pressure needed for the injection of the material. The use of a low-pressure injection feedstock is of particularly importance in order to allow injection without deforming the printed mold. The filling was carried out at a melt temperature of 120°C and mold temperature of 90°C. The subsequent step is the mold removal. Since in this study a sacrificial insert mold is used, the part cannot be ejected using the traditional mold opening process; in this case the entire mold is ejected and then dissolved in an alkaline solution. After the mold dissolution, the so-called green body is obtained; at this stage the part still contains the binder material that has to be removed during the debinding step. The debinding method used is a solution debinding in n-heptane approach [7]. Successively, the brown body (the part after the binder removal) is sintered to bond the powder into a solid structure. After sintering, the final part is obtained and when high surface finishing is required, machining can be done as final step.

3. Complexity evaluation

In order to evaluate the degree of complexity that can be achieved with the process, different geometries were evaluated based on test artifacts from Moylan et al. [8]. In particular, a study of the surface deviation between the printed part and the nominal value was done. Moreover, the ability to create straight pillars was also evaluated and finally the swelling behavior of the mold photopolymer during the dissolution process was investigated.

3.1. Surface deviation

The surface deviation study was achieved by looking at the difference in the dimension of the crown prep-line (bottom part of the tooth crown) of a tooth in the designed model and in the printed part for five different samples. The printed part was coated with a special spray to avoid reflections on the surface during the 3D-scan process.

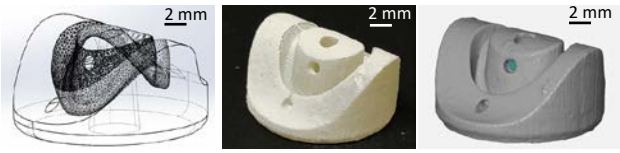

Figure 2. CAD model on the left, coated part in the center and scan model on the right.

The results of the analysis are reported in Table 1. The mean of absolute deviation between the CAD and printed sample is 27 µm with a standard deviation among all five samples of 5 µm. The surface deviation has both positive and negative values, making it challenging to compensate during the design phase.

Table 1. Deviation of the 3D printed part in µm. The measurements were taken in eight different positions around the crown prep-line surface.

Sample	P1	P2	P3	P4	P5
Position 1	38	-6	50	42	-1
Position 2	16	-12	-7	17	-33
Position 3	-45	-96	-57	4	-106
Position 4	14	10	-21	2	-41
Position 5	-64	-10	-17	-38	-74
Position 6	-7	-42	-16	-13	-23
Position 7	-27	-18	32	-22	-5
Position 8	18	-4	13	22	-3
Absolute Mean	29	25	27	20	36
Total Mean	27				
Standard deviation	5				

3.2. Pillars investigation

Several tests were made to investigate the feasibility of creating a mold with inner pillars, particular focus was spent researching the critical height and diameter in order to print straight pillars. Most likely, due to the natural vertical motion of the vat to detach from the cured part and the fragility of the recently cured material, it is quite challenging to create long straight pillars.

3.2.1. Pillars dimensional deviations

The heights and diameters deviations from the original design of five samples with eighteen pillars each were measured. Every pillar has a constant aspect ratio of 1:2 in diameter and height respectively. Figure 3 shows the deviations from the nominal values of the diameters (black) and heights (red) for the pillars.

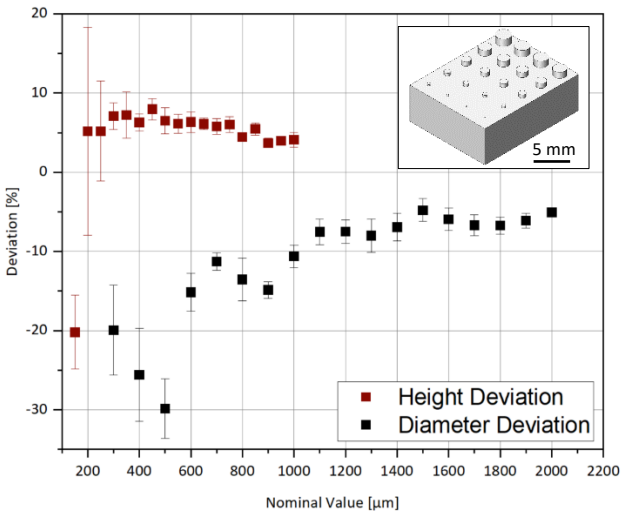

Figure 3. Diameter and height deviations of the pillars from the nominal values after printing. In the top right corner the CAD model of the part.

It is possible to observe how the deviation in diameter is more significant than the one in height. While the deviation in height fluctuate around a value of 5 % regardless the dimension of the nominal height, the deviation in diameter increases from about -30 % to around -5 % when its nominal dimension is reduced. Moreover, it is worth mentioning the standard deviation seen in Figure 3, showing a gain in printing accuracy when the dimensions of heights and diameters are also increased.

3.2.2. Pillars complexity threshold

Another focus of the research on the geometrical complexity was spent on finding the threshold height for printing straight pillars using defined diameters. The pillars diameter was varied from 0.4 mm to 1.6 mm while the height was increased from

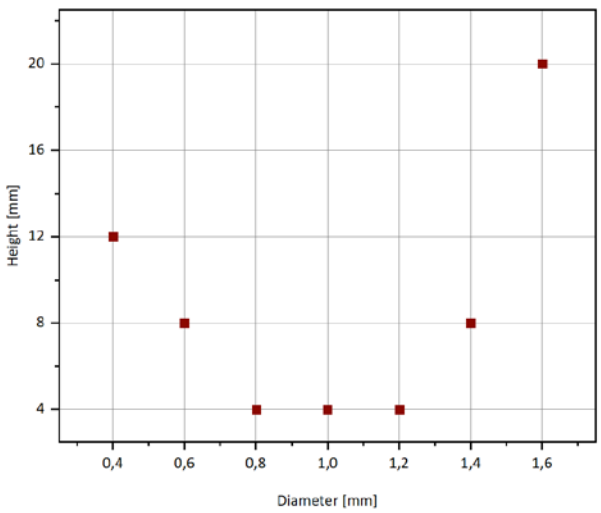

Figure 4. Threshold height for straight pillars

4 mm up to 20 mm. Figure 4 reports the threshold heights for the chosen diameters; it is interesting to observe how is possible to increase the height of the pillars either by using small or large diameters. It was observed that when the diameter is lower than 0.6 mm, even if the pillars are not straight just after the printing, they become straight due to a positive effect of the shrinkage during the post curing, see Figure 5.

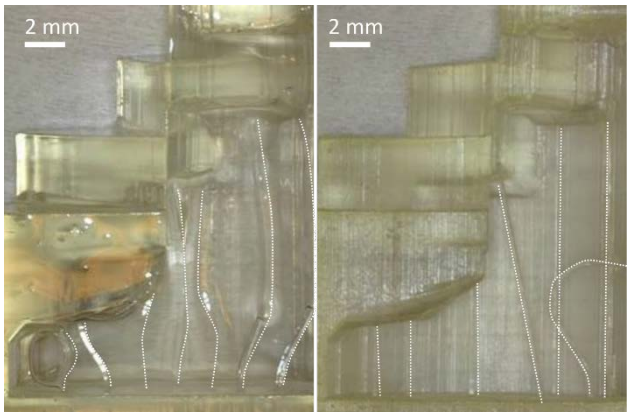

Figure 5. *Pillars after printing on the left and after post curing on the right.*

On the other hand, when the diameter of the pillar is higher than 1.4 mm, the pillar has enough strength to be able to withstand the detachment forces during the printing; in particular, when a diameter of 1.6 mm was used, it was possible to print pillars up to 20 mm in height.

3.2.3 Pillar swelling

A challenge to the creation of complex geometries with this process is the one caused by the expansion of the mold material during the dissolution step, which is also mentioned by Liska *et al.* in [9]. During demolding, swelling of the cured photopolymer was observed, causing cracks nucleation in the green body. In order to investigate the swelling of the mold during the dissolution process, the diameters of five pillars were measured at two different dissolution temperatures (50°C and 70°C) in water and in an alkaline solution. It is noticeable how the expansion of the mold is higher when an alkaline solution is used. Although a basic environment increases the swelling, this suspension is necessary in order to start the dissolution process. When the mold is submerged in an alkaline solution, it is possible to record the beginning of the dissolution indicated by a

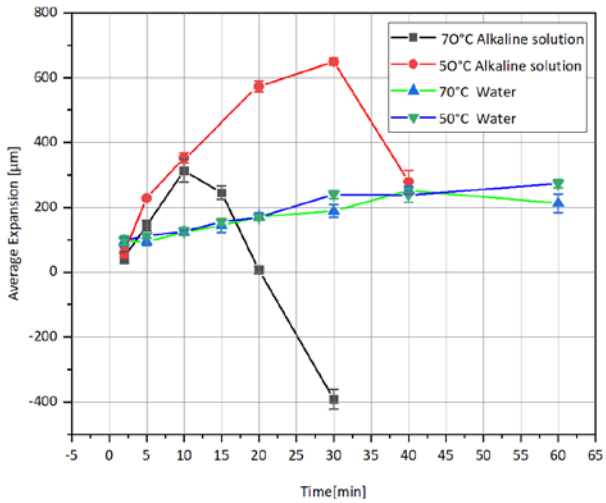

Figure 6. Variation of the diameter of pillars for different dissolution time and solutions.

diameter reduction. However when water is used it is not possible to document any decrease in diameter within 60 minutes. Both behaviors can be seen in Figure 6.

Looking at the difference between the two temperatures for the alkaline solution, a higher diameter expansion is noticed when lower temperatures are used, demonstrating the possibility to reduce the maximum expansion of the mold and accelerate the dissolution process by increasing the temperature.

4. Conclusion

This work presents an innovative process chain where additive manufacturing is implemented in a PIM process. The use of AM as soft tooling production method allows to reduce the overall cost of the process and to increase the complexity of the final part.

This study focuses on the degree of geometrical complexity sacrificial mold critical features.

The surface deviation analysis showed an average deviation of 27 µm from the nominal value. Both positive and negative deviations were detected making demanding to compensate for it during the designing.

The pillars investigation demonstrated how the deviation from the nominal value is more critical for the diameter than for the height, especially when small features are printed. Moreover, the pillars had higher printing accuracy when the dimensions of heights and diameters were increased.

From the pillar threshold height study, it was noticed how, due to a positive effect of the shrinkage during the post-curing, it is possible to increase the pillars height when diameters smaller than 0.6 mm are used. In addition, the printing of tall pillars is also feasible when the diameters are higher than 1.4 mm.

A limitation of this process is caused by the swelling behavior of the water-soluble photopolymer during the dissolution process. When higher dissolution temperatures are used the swelling is decreased. The cracks nucleation in the green body due to the mold swelling during dissolution, may be avoided by increasing the strength of the used PIM feedstock

Acknowledgment

This paper reports work undertaken in the context of project 6151-00005A funded by Innovation Fund Denmark.

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