Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 111 (2022) 97–100

www.elsevier.com/locate/procedia

12th CIRP Conference on Photonic Technologies [LANE 2022], 4-8 September 2022, Fürth, Germany

Design of additively manufacturable injection molds with conformal cooling

Jan Philipp Wahl[a,*], Jens Niedermeyer[a], Robert Bernhard[a], Jörg Hermsdorf[a], Stefan Kaierle[a,b]

[a]*Laser Zentrum Hannover e. V., Hollerithallee 8, 30419 Hannover, Germany*
[b]*Leibniz Universität Hannover, Institut für Transport- und Automatisierungstechnik (ITA), An der Universität 2, 30823 Garbsen*

* Corresponding author. Tel.: +49-511-2788-346; fax: +49-511-2788-100. *E-mail address:* j.wahl@lzh.de

Abstract

Additive manufacturing enables the production of intricate geometries including internal structures. This design freedom can be used advantageously to enhance heat transfer in injection molds by means of conformal cooling. The main goal is to reduce cycle times and to improve part quality through uniform cooling of the plastic products. This paper presents cooling design concepts for mold inserts. Their underlying approaches differ with respect to the shape and the cross-sectional geometries of cooling channels. Distinct inserts are additively manufactured by laser-based powder bed fusion (PBF-LB) of AISI 420 stainless steel. Experiments are carried out on a custom thermal test bench. Infrared thermography is used to examine the surface temperature, showing a reduction in cooling time by up to 41 % compared to conventional concepts. Additionally, the coolant flow is measured. The evaluation of the cooling characteristics reveal a critical trade-off between cycle time and uniformity of the surface temperature.

Keywords: Additive Manufacturing, Rapid Tooling, Laser-Based Powder Bed Fusion, Conformal Cooling, Injection Molding

1. Introduction

Additive manufacturing (AM) stands out for their potential to realize intricate part geometries. Thanks to the layer-by-layer building principle, for example, free-form surfaces and internal structures can be implemented that are not accessible to drilling tools due to undercuts. These possibilities are of interest for applications in tool- and mold making. Near net shape molds can thus be built and provided with optimized cooling channels. This is particularly relevant for mass production processes like injection molding. During injection molding, thermoplastics are heated and injected into cavities under pressure where the plastic melt solidifies. The cooling time until a certain temperature is reached and the final plastic part can be ejected is decisive for achieving economic cycle times. Further potential of optimized mold cooling lies in ensuring part quality due to uniform cooling of the plastic part. Especially process-induced residual stresses, which otherwise lead to distortion and part failure, can be avoided by preventing local hot spots.

Conventional cooling concepts mainly focus on inserting baffles, bubblers, heat pipes as well as spiral and copper cores in drilled holes [1]. Recent studies incorporating AM for injection molds, on the other hand, concentrate on the design of conformal cooling. In comparison to conventional straight cooling channels, the idea of conformal cooling is to adjust the distance between the coolant and the cavities tailored to the molded parts. Shinde et al. reviewed different layouts and cross-sectional geometries of conformal cooling channels (ccc) and also summarized materials as well as manufacturing strategies involving AM [2]. An alternative approach without directional cooling channels was originally presented by Au and Yu. Here, a contiguous cooling passageway is designed as an offset of the mold surface and is filled with lattice structures forming a porous scaffold [3]. Additionally, Kanbur et al. reviewed analytical and computer aided design, analysis and

10.1016/j.procir.2022.08.146

optimization approaches [4]. Further examples for computer aided design of cooling channels were presented by Jahan et al. and Faßnacht employing topology optimization [5] and neural networks [6]. Mazur et al. and Kirchheim et al. compared results from numerical und experimental analyses of additively manufactured mold inserts with ccc [7,8]. Moreover, Wonisch et al. and Vasco et al. addressed economic aspects such as production costs and cycle time for AM injection mold inserts with conformal cooling [9,10].

This study aims to contribute to the AM-oriented design process of injection molds by comparing conformal cooling concepts with one another and with conventional cooling. To this end, mold inserts with different cooling concepts are designed considering manufacturing restrictions and are produced by laser-based powder bed fusion (PBF-LB). Their cooling characteristics are evaluated experimentally with the help of infrared thermography. The emphasis lies on assessing various revealing time and temperature related criteria.

2. Material and Methods

2.1. Design of specimen

In this study, a mold insert was chosen as demonstrator that consist of pin with a draft angle of 3 ° measuring 76 mm in height and 10 mm in diameter at the tip. Similar geometries are common to form cavities for screw bosses, for example. It is particularly challenging to transfer heat from such protruding inserts through the connection base towards the solid plate of the mold solely via conduction. Therefore, three different approaches for cooling concepts were designed that facilitate heat transfer by means of convection. Two of the following AM cooling concepts are characterized by spiral conformal cooling channels. In the first concept, two channels direct the coolant from the tip of the mold insert to the outlet. In the second concept, the coolant is routed through four channels. The increased number and multilayer arrangement of channels allows their spacing to be reduced. The third concept follows the approach to maximize the cooling area conformal to the cavity wall by directing the coolant from the tip to the base through an annular gap.

For comparability of the concepts, a minimum distance to the cavity wall of 1 mm laterally and 2 mm at the tip was specified. The inlet and outlet diameter was set to 3 mm for all concepts. According to the continuity equation, the aim was to maintain a continuous cross-sectional area of cooling of 7 mm² for the flow velocity inside the AM insert to be approximately constant.

A fourth concept served as a reference for conventional cooling but was also manufactured additively. Its design is based on a straight baffle inserted in a borehole.

Prior to the dimensioning of the concepts, test specimens were designed to investigate geometric restrictions with regard to manufacturable channel diameters in dependence of inclination. All CAD models were created in Dassault Systèmes' SolidWorks software application.

2.2. Material selection and Additive Manufacturing

Nitrogen gas atomized AISI 420 (X20Cr13) powder AM420S by Höganäs AB was processed in this study. The hardenable martensitic stainless steel contains 12.5 % chromium and 0.23 % carbon. Processing this material by PBF-LB typically leads to an ultimate tensile strength of 1610 MPa after stress relieving as-built specimen according to the datasheet [11]. The nominal particle range of the supplied powder is 20-63 µm [11].

Stainless steel parts were built using a TruPrint 1000 (TRUMPF GmbH & Co. KG, Germany) with a circular build platform of 100 mm in diameter and a maximum build height of 80 mm. The built-in continuous wave ytterbium fibre laser provides a maximum laser power of 170 W at a wavelength of 1070 nm during PBF-LB. The machine is equipped with a galvanometric scanner and a f-theta lens. The focus diameter is 30 µm. The inert gas argon was used to reduce the oxygen level inside the process chamber to 200 ppm. Process parameters resulting in a volume energy density of 113.3 J/mm³ for part densities > 99.9 % were used to build the test specimens and mold inserts with a layer thickness of 20 µm. Furthermore, contour scans with reduced laser power of 70 W, 575 mm/s scan speed and 30 µm hatch offset were applied as well as a rotating chess pattern with 4 mm fields for hatching. Block type support structures with 3 mm in height were created.

2.3. Experimental Setup

Light microscope images of the test specimens were taken with a confocal laser scanning microscope VK-X1000 (Keyence Deutschland GmbH, Germany) and evaluated by edge detection utilizing OpenCV. Cooling characteristics of mold inserts with different cooling concepts were carried out on a thermal test bench. Manufactured mold inserts were heated in a furnace Top 16/R (Nabertherm GmbH, Germany) at 90 °C for 90 min and clamped against plates made of Formlabs High Temp photopolymer resin with hose nozzles connected to the inlet and outlet. Water at room temperature was directed through the mold inserts by using a submersible water pump (IREENUO 15W-800L/h). The resulting flow rate at constant power was determined by weighing the collected amount of water per minute using a precision balance (Sartorius AG, Germany). The thermal imaging camera thermoIMAGER TIM 640 VGA (Micro-Epsilon Messtechnik GmbH & Co. KG, Germany) with a system accuracy of ±2 °C was employed in order to examine the temperature of the mold insert surfaces. Hot spots and uniformity of the temperature distribution were analyzed using the TIM Connect software. In addition, the cooling time until reaching an average surface temperature of 20 °C in the area above the base was investigated. Prior to this, data from the thermal imaging camera were calibrated on the basis of surface temperatures measured simultaneously using thermocouples type K and the data logger MEMORY HiLOGGER 8430-20 (HIOKI E.E. Corporation, Japan). An emissivity factor ε=0.64 was determined for the mold inserts' surfaces. During the underlying reference measurement, glass bead blasted mold inserts were heated on a Präzitherm hot plate (Harry Gestigkeit GmbH, Germany).

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.

3. Results and Discussion

3.1. Geometrical Manufacturing Restrictions

Manufacturable diameters for PBF-LB with AISI 420 stainless steel can be derived from Fig. 1. For diameters of less than 0.5 mm, adhering powder particles significantly reduced the resulting cross section, regardless of orientation. The geometric deviation from CAD geometry was lower than 10 % for diameters d ≥ 1.25 mm at an inclination angle α ≥ 35 °. Diameters of 2-3 mm were manufactured with a dimensional deviation of less than 10 % in all orientations, whereby larger inclination angles lead to increasingly accurate results.

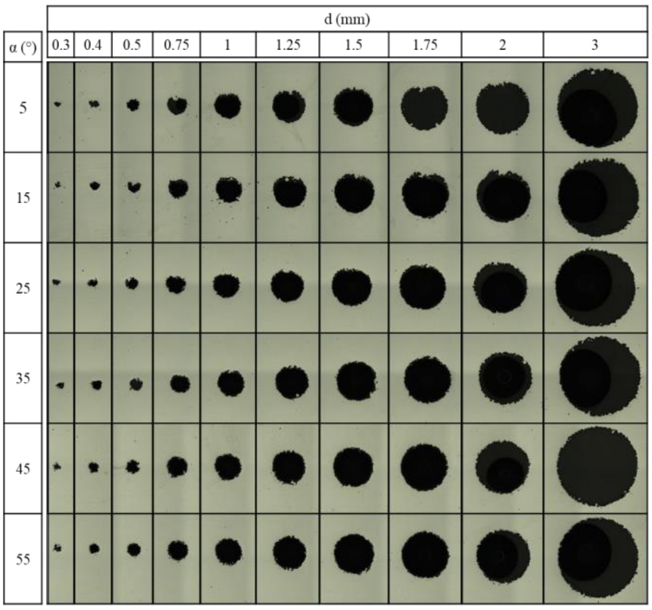

Fig. 1. PBF-LB manufactured diameters d for inclination angles α between 15 ° and 55 °.

3.2. Mold inserts with conventional and conformal cooling

The sectional views of the CAD models for AM are shown in Fig. 2. The view of the conventional concept with a straight baffle illustrates the difference to conformal cooling. The distance to the mold wall could not be kept constant due to the hole diameter. Based on the preliminary investigations in 3.1, the diameter of the two spiral conformal cooling channels was defined as 2.12 mm at an inclination of 25 °. The four multilayer conformal cooling channels were designed with a diameter of 1.5 mm at an inclination angle of 35 °. The accumulated cross-sectional area of the spiral conformal cooling channels per winding therefore remains the same for both concepts. In the multilayer concept with several small channels, however, the accumulated perimeter of the channels is larger at 18.85 mm and resembles the interface for heat transfer between the steel and fluid. The inclination of the cooling channels turned out to be a determining factor for the spacing between cooling channels. In addition, it influences the distance that fluid particles travel in the mold insert during which they are heated. A comparatively short distance results for the concept of the annular gap without windings. Defining the diameter for inlet and outlet as well as specifying the boundary condition of a constant cross section represents a significant limitation in this concept. In order to ensure the removal of loose powder particles and flow-through of the coolant by maintaining a gap of at least 0.3 mm, its cross-sectional area had to be increased towards the base.

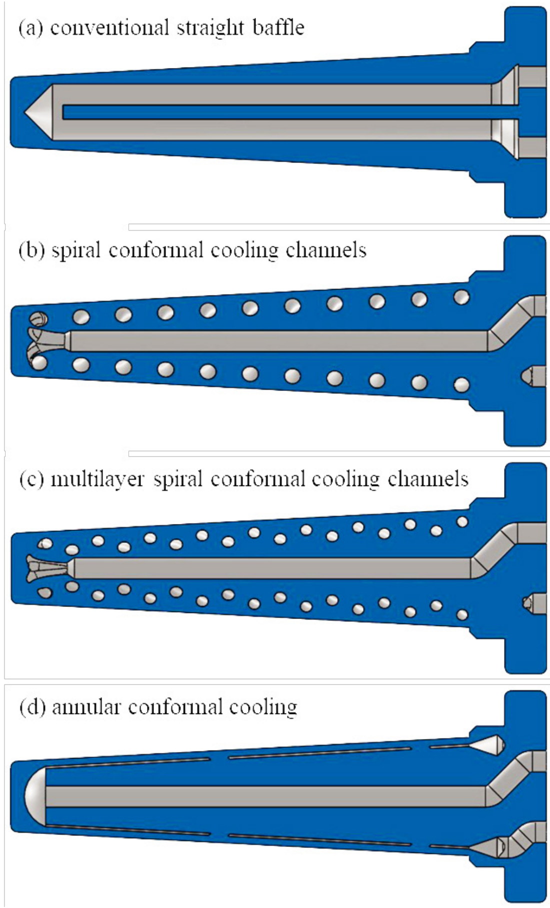

Fig. 2. Sectional CAD view of mold inserts with different cooling concepts.

3.3. Cooling characteristics

The flow rates of the manufactured mold inserts in Table 1 reveal that intricate conformal cooling concepts obviously acted as a greater flow resistance than the conventional concept with a wider and straight cooling cross section did. In comparison, more than double the flow rate (1,571 L/min) was measured at the inlet without any mold insert. Despite the highest flow rate for the conventional concept, the averaged surface temperatures indicate that conformal cooling can effectively enhance cooling. The standardized cooling times in Table 1 show a significant reduction by up to 41 % in the case of the multilayer spiral ccc concept (see Fig. 2 (c)).

Table 1. Flow rate and standardized cooling time of mold inserts with different cooling concepts

Concept	Flow rate (L/min)	Cooling time (s/10 K)
conventional straight baffle	0.734	3,70
spiral ccc	0.315	2,32
multilayer spiral ccc	0.271	2,19
annular cc	0.311	2,23

The thermographic images of the surface temperature 1 s after the start of internal cooling reaffirm the improvement of the cooling characteristics compared to the conventional concept.

Temperature plots in Fig. 3 (a)-(d) allow for the comparison of the surface temperature uniformity along a line from the tip to the base of the mold insert. The impact of spacing between cooling channels became evident in spiral ccc concepts (Fig. 3 (b) and (c)).

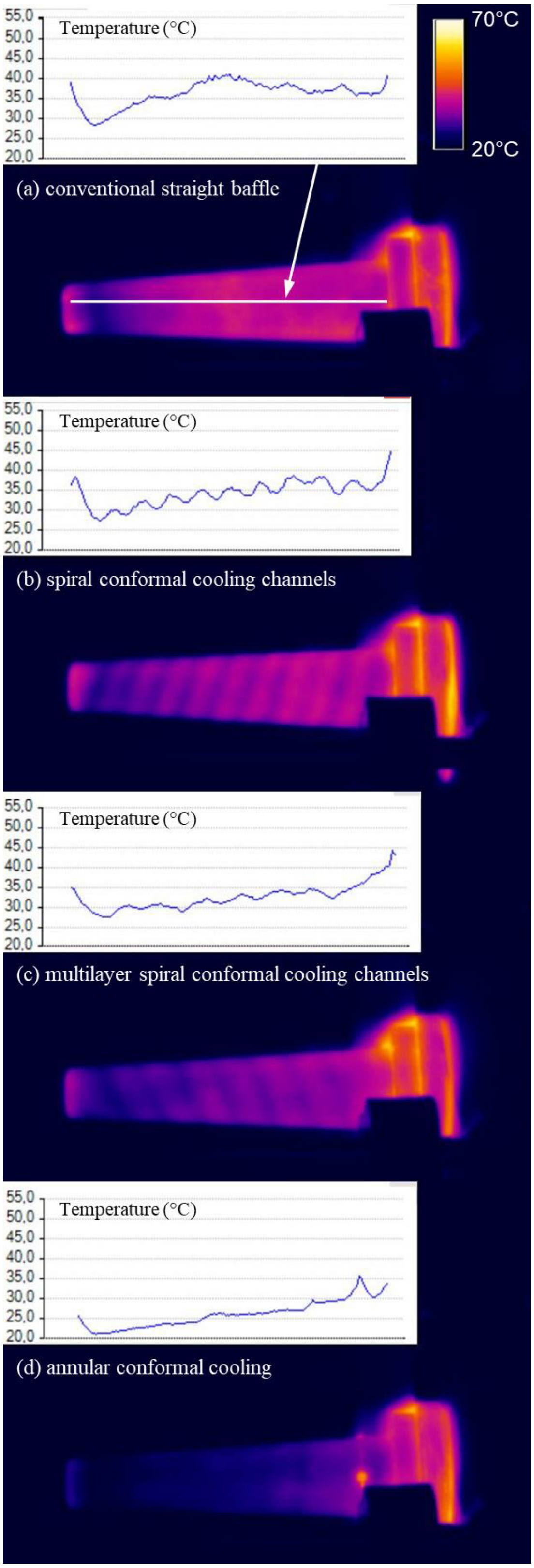

Fig. 3. Thermographic images and temperature plots of mold inserts 1s after start of internal cooling

By arranging more and smaller channels in several layers in Fig. 3 (c), the temperature gradient due to spacings was reduced. However, the measured volume flow rate decreased in return (see Table 1). In the case of the annular cooling concept in Fig. 3 (d), an even more uniform surface temperature distribution was achieved. Local hot spots were caused by porosities due to manufacturing defects.

4. Conclusion

In this study, PBF-LB has been demonstrated to be a suitable process for manufacturing injection mold inserts with intricate cooling concepts. The AM oriented design of conformal cooling concepts provided both a reduction in cooling time and a more uniform temperature distribution on the surfaces of demonstrator mold inserts. Infrared thermography was a useful method to investigate changes in surface temperature during cooling on a thermal test bench. The comparison of spiral conformal cooling channels and an annular cooling concept highlighted design and manufacturing constraints to be considered. Conceptual differences also revealed a trade-off between cooling characteristics.

The results provide a basis for the investigation of further cooling concepts regarding the layout and cross-sectional geometries. Future investigations should address the impact of the roughness of additively manufactured inner surfaces on flow behavior and consequently on heat transfer.

A next step is to test the mold inserts in an injection molding process after machining the outer surfaces and to evaluate the cycle time as well as part quality of the plastic products.

References

[1] Dangel R. Injection molds for beginners. 2nd ed. Cincinnati: Hanser Publications; 2020. p. 183-197
[2] Shinde MS, Ashtankar KM, Kuthe AM, Dahake SW, Mawale MB. Direct rapid manufacturing of molds with conformal cooling channels. RPJ 2018;24(8):1347–64.
[3] Kanbur BB, Suping S, Duan F. Design and optimization of conformal cooling channels for injection molding: a review. Int J Adv Manuf Technol 2020;106(7-8):3253–71.
[4] Au KM, Yu KM. A scaffolding architecture for conformal cooling design in rapid plastic injection moulding. Int J Adv Manuf Technol 2007;34(5-6):496–515.
[5] Jahan S, Wu T, Shin Y, Tovar A, El-Mounayri H. Thermo-fluid Topology Optimization and Experimental Study of Conformal Cooling Channels for 3D Printed Plastic Injection Molds. Procedia Manuf 2019;34:631-9.
[6] Faßnacht P. Algorithmische Auslegung von konturnahen Temperiersystemen in Spritzgießwerkzeugen durch ein hybrides System aus naturanalogen Verfahren. Dissertation. Hannover; 2014.
[7] Kirchheim A, Katrodiya Y, Zumofen L, Ehrig F, Wick C. Dynamic conformal cooling improves injection molding. Int J Adv Manuf Technol 2021;114(1-2):107–16.
[8] Mazur M, Brincat P, Leary M, Brandt M. Numerical and experimental evaluation of a conformally cooled H13 steel injection mould manufactured with selective laser melting. Int J Adv Manuf Technol 2017;93:881–900.
[9] Wonisch A, Jakobi R, Ullrich L, Gries S, Jones C, Hennebicque M. Filigrane Kanäle, maximale Effizienz: Konturnahe Kühlung mit Konstruktions-, Simulations- und Verarbeitungs-Know-How verbessern. Kunststoffe 2019;(9).
[10] Vasco J, Barreiros FM, Nabais A, Reis N. Additive manufacturing applied to injection moulding: technical and economic impact. RPJ 2019;25(7):1241–9.
[11] Höganäs AB. Datasheet AM 420S; 2020.

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.