

Thermally Optimized Injection Molds Through Multi-Material and Conformal Cooling Using DED

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Abstract

The injection molding production process demands high standards in terms of the quality of the components to be produced. These depend on the performance of the temperature management system, to achieve a uniform cavity temperature during cooling of the polymer melt. Simultaneously, short cycle times are a decisive factor for the economical production of large quantities. The requirement for an injection mold therefore consists of rapid and uniform cooling of the cavity. This research project pursues the production of a thermally optimized injection mold with multi-material and conformal cooling using the Powder-Based Direct Energy Deposition (PB-DED) process. This involves identifying zones of a mold that are exposed to high thermal loads by means of finite element analysis and subsequently optimizing them locally. Depending on the application, materials with higher thermal conductivity and additional cooling channels are integrated into the mold core. This is achieved using the PB-DED process, while the geometry elements are deposited on existing mold structures. As a result, thermal optimization for a use case from injection molding industry has been achieved. A significant reduction of the cycle time by 45% and an improved part quality could be verified simultaneously. The combination of conventional manufacturing processes for the majority of the tool and DED only for a few highly stressed core areas significantly reduces the necessary manufacturing costs. This is evaluated by a proven cost model. In addition, appropriate tool reconditioning at the end of their tool life is possible.

Keywords: Additive Manufacturing, Powder-Based Directed Energy Deposition, Multi Material, Injection Molding, Conformal Cooling

1 Introduction

As a typical mass production process, injection molding places high demands on the quality of the components produced and the cycle time required for production. Both of these aspects are highly dependent on the temperature management performance of the mold. The temperature management of a mold is highly dependent on the geometry to be produced, is decisive for its performance and is in many cases considered at a relatively late phase in the design process. The specifications are determined in particular by the process and the intended application of the component. The typically required high geometric accuracy and minimal surface defects of the manufactured component can be achieved by a homogeneous wall temperature within the cavity. At the same time, a low cycle time, as the most important parameter for economical production, can be achieved by a high cooling rate. As the cooling time accounts for the largest fraction of the injection molding cycle, it offers significant potential for savings. For the component analyzed here, the cooling time accounts for approximately 67% of the total cycle time (Figure 1). An optimal injection mold must therefore ensure rapid and homogeneous cooling of the cavity, while simultaneously providing high wear resistance. The choice of mold

material is therefore a compromise between heat conduction, stability and tool life.

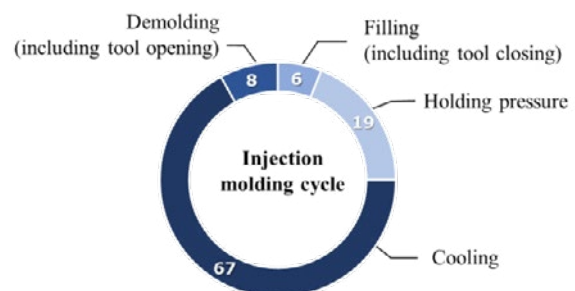


Figure 1: Time fractions of injection molding process under investigation using conventional cooling [%].

This paper describes the thermal optimization of an injection molding tool using simulation, additive manufacturing and a calculation method for the estimation of the necessary production costs. The used manufacturing machine “Modulo 400” uses Powder-Based Directed Energy Deposition (PB-DED), at which powder material is applied and melted simultaneously by focused thermal energy generated through a laser beam. The following solidification of the melt generates new layers, which are arranged above and next to each other.

1.1 Optimization approaches

Optimization of the cooling time can be achieved in particular by reducing the thermal resistance using conformal cooling channels, increasing the heat transfer properties using adapted mold materials or a bigger temperature difference between the mold and the cooling medium. [1] However, not all of these optimization approaches can be used for each application, as component and material-specific constraints have to be considered. For example, lowering the temperature increases the cooling rate and thus shortens the cycle time. But it also increases residual stresses in the component, leading to distortion and other defects. [2]

Applying conformal cooling channels offers the potential to significantly reduce cycle times while simultaneously improving component quality. [3] Nevertheless, the complex shapes of the cooling channels are not possible to produce using conventional manufacturing processes, meaning that mold cores have to be produced using additive manufacturing (AM) processes. Laser Powder Bed Fusion (LPB-F) has established itself as the industry-wide standard, although cooling channels with reduced complexity can be realized using other manufacturing processes such as PB-DED. [4] Despite that, one disadvantage of LPB-F is the limited possibility of deposition on existing structures and the geometry-specific deposition rate. [5]

Manufacturing a complete mold core from a material with increased thermal conductivity can significantly reduce the cycle time, but does not consider the local and geometry-related hotspots within the mold. A local adaptation of the material composition by means of sectioned mold inserts can map this to a certain extent. [2] However, experience in industrial implementation shows that there is also considerable potential for leakages and an increased effort required for mold maintenance. The application of multi-materials (MM) using PB-DED, on the other hand, allows the material properties to be customized with high precision, as the material is mixed locally in the form of powder, applied with a nozzle and melted by a laser. [6]

2 Objective and Methodology

The objective of the research project presented here is the thermal optimization of a complex injection mold. The optimization method is subsequently verified under industrial conditions using an exemplary injection molded component with the dimensions 150x50x50 mm³ (see Figure 2). This component features challenging geometric elements, in particular varying wall thicknesses, as well as deep cavities and sharp edges inside. The optimization is to be achieved through a combination of MM and conformal cooling using PB-DED.

In order to optimize the cycle time and reduce the distortion that occurs, local adjustments to the injection

mold are necessary. For this purpose, the conventional mold core is initially characterized and optimized using Finite Element (FE) analysis. These primary optimization steps include, for example, ensuring balanced cavity filling by relocating the sprue point. This is followed by the design and implementation of a conventional cooling system in the physical mold. Finally, the behavior of the reference tool can be simulated in a thermally transient calculation with subsequent experimental verification.



Figure 2: Injection molded component made of Makrolon 2805 with varying wall thicknesses and cavities.

Local adjustments are identified based on the results, which are implemented using PB-DED. These include the integration of cooling channels where necessary and local material changes. The material used to locally increase the thermal conductivity (CW305G) has approximately four times higher thermal conductivity with comparable tensile strength compared to comparable steels. [4] However, process- and machine-related manufacturing restrictions must be considered in this process, which must be determined previously.

The complexity of determining suitable process parameters and the programming of the required tool paths to generate the geometries for the mold and the cooling system is significantly higher than with other AM technologies. [7] One of the reasons for the higher complexity is the influence of the 5-axis kinematics used by the machine tool on the achievable dynamic of the nozzle. These require geometry-specific parameter adjustments to ensure the ability to form a stable melt pool within the narrow process limits.

The achieved savings and improvements in component quality are subsequently verified by means of experimental production tests in an industrial environment. For this purpose, the reduction in production time, the tool temperatures during production and the geometric accuracy of the manufactured components are determined. This is carried out in comparative studies for three different tool configurations. The mold is tested successively with conventional cores (reference), multi-material cores and multi-material cores with conformal cooling. Finally, the additional costs compared to a conventional mold are calculated using a self-developed cost model. This enables predictions to be made regarding the profitability of the developed solutions and shows further optimization potential for broad industrial applications.

3 Feature segmentation

As part of the feature segmentation, all known dependencies resulting from the injection mold used, the component geometry and the intended manufacturing using AM through PB-DED must be considered. In this study, the implementation is carried out in the software “Moldflow”, which was specially developed for the FE simulation and optimization of polymer injection molding processes.

In order to model the behavior of the injection mold as accurately as feasible, all other heat flows must be considered in addition to the local heat input from the molten polymer. This is achieved by simulation of the entire mold including all necessary attachments such as distribution plates, ejectors, scrapers and conventional cooling elements as well as their thermal behavior (Figure 3). In this way, a comprehensive model is created that is able to simulate the physical mold behavior as precisely as necessary.

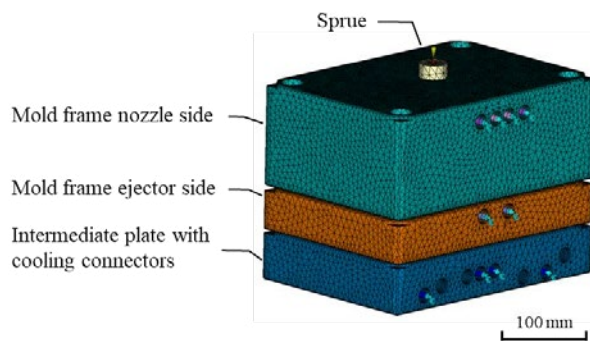


Figure 3: Meshed FE model of the mold with thermally relevant tool areas (Simulation: PEG).

This meshed mold is used to carry out iterative filling and solidification simulations of the polymer melt in order to determine the optimal process parameters and component properties. Obtained results, for example, are the necessary cycle time, occurring component distortion, shrinkage and temperature distributions in the mold and polymer.

In order to identify local zones of overheating, the calculated surface temperature distribution along the mold core is evaluated. For the mold under investigation, this reveals that the zones on top of the two small cores are significantly overheated locally, compared to the other cores (Figure 4). In a theoretically ideal cooling system, these core areas significantly increase the required cycle time because the polymer melt in local overheated mold areas also has to cool down beneath the ejection temperature. Similar results can be observed in a large number of injection molds, as comparable core areas have geometric dimensions insufficient for the use of conventional cooling approaches, such as bubblers.

In order to reduce the thermal load on the overheated core areas, the locally optimal thermal material properties and conformal cooling channels are designed initially.

Subsequently, suitable production geometries and material compositions are derived, considering the process limits of the PB-DED. Restrictions occur, for example, due to the deposition nozzle used and its interfering contour, the achievable accuracy of the additive material deposition of around 0.1 mm, minimum deposition lengths of around 3.0 mm and the technically possible material compositions limited by material properties.

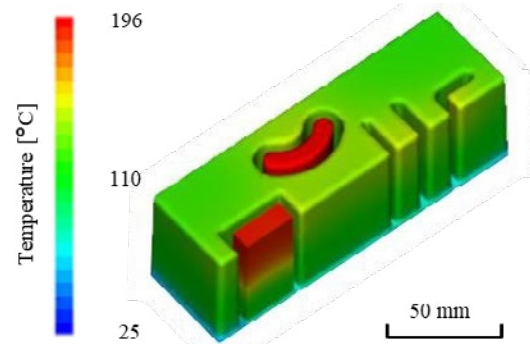


Figure 4: Mold surface temperature distribution of conventional cores (Simulation: PEG).

The implementation as a hybrid manufacturing process consisting of conventional manufacturing methods (milling, drilling, eroding) and the additive manufacturing of individual geometry elements in PB-DED offers several advantages over the production of the entire core using AM. On the one hand, there is a significant reduction in the overall processing time of the mold core due to higher material removal rates than material application rates and a significant reduction in costs due to lower machine hour rates. On the other hand, individual mould elements can also be adapted subsequently, which makes it possible to optimize existing tools that have already been manufactured using time-consuming processes.

Nevertheless, the wear resistance of thermally optimized materials is generally reduced due to lower tensile strength and hardness compared to mechanically optimized mold construction steels, with the result that subsequent repair by mechanical removal and renewed additive application must be considered when designing the optimized core element if the mold is used to produce a very high number of components. The service life cannot yet be definitively estimated, as no measurable wear has occurred in the production of 1,200 components up to now. The advantage of additive manufacturing allows the surface of the mold to be easily reconditioned, if necessary. Ultimately, such a design is a compromise between the technically possible, thermally optimal implementation and an economically feasible application.

For the mold presented here, only two different material compositions (MM) are produced for each core. If two different materials are used, there is a risk of defects in the transition zone of the mold due to thermally induced

residual stress caused by different thermal expansion behavior. The effects are difficult to determine in advance without complex simulation. However, no evidence of these effects could be observed in the mold shown. The segmentation method shown is also suitable for deriving functionally graded materials (FGM) with variable material compositions. FGM promise to reduce thermal stresses and expand the application areas, which is the object of current investigations and not yet realized. [8]

4 Production of mold cores

The areas of the mold core to be optimized result from the feature segmentation; these are applied additively from the material CW305G (CuAl10Fe1) to the less thermally stressed area made of 1.2311 (40CrMnMo7). These materials are particularly suitable due to their comparable coefficients of thermal expansion and good weldability even without a global inert gas atmosphere. While the outer contour is machined by milling and eroding (Figure 5 (a)), the cooling channels cannot be machined afterwards and must be able to be produced without support structures and be free of process-impeding defects. These can include leakage due to porosity in the vicinity of the cooling channel, blockage caused by unwanted material application, and additional dead water zones created by pores. Because of the resulting overhangs in the cooling channel, this must be achieved using the process described below. The tool path generation requires several different programming steps, which consist of specific strategies and have significant impact on the achievable tool quality.

First, the geometry of the mold core is prepared for AM by adding allowance for subsequent machining. The core is then divided into three areas for programming and production. The lower area and the cover are manufactured with 3-axes and the overhang in between requires 3+2-axis and 5-axis deposition. Due to the complex path planning in the 5-axis area, feature-related and non-planar slicing must be used, which is carried out using computer-aided manufacturing (CAM) software. The generated cutting curves from the slicing serve as a calculation basis for further programming. In addition, so called synchronization curves are used for the overhang in the cooling channel to control movement direction of the nozzle based on the geometry. The comparatively high demands on the geometric accuracy (bore cross-section, corner radii and shape accuracy) of the cooling channel and the geometry dependency in production lead to the necessity of an iterative parameter optimization of the production strategy. [4]

The first component exhibits inadequate quality of the cooling channel in the overhang, with dead water zones, uneven cross-section and porosity in its vicinity (see Figure 5 (b)). In addition, insufficient closure at the joint was observed during the process. By adding additional acceleration movements in the area of the overhang and reducing the spacing (Δz) of the individual layers in the

overhang, a sufficiently accurate surface quality and closure of the cooling channel could be achieved (see Figure 5 (c)).

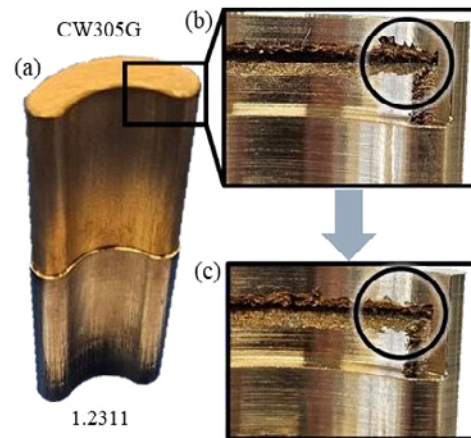


Figure 5: Machined mold core made of multi-material (a), insufficient cooling channel quality (b), optimized cooling channel (c)

Different application geometries can be generated within one track by using different angles between the application nozzle and the base material. The geometry-dependent parameters resulting from the iteration for programming similar mold cores with a curved cooling channel made of the material CW305G can be found in Table 1.

Table 1 Geometry dependency of certain parameters

Parameter	3-axis	5-axis
Δz [mm]	0.18	0.12
Track width [mm]	1.2	1.7
Side measurement of the filling [mm]	0.20	0.25
Additional acceleration movement [mm]	0.0	0.2

After subsequent machining, the mold core is subjected to a leak test to check its suitability for use in the mold (see Figure 6) where no leakages could be detected.



Figure 6: Assembled molding tool with optimized cores made of MM using 1.2311 and CW305G during the leakage test.

5 Potential for savings

The benchmark test at the industrial partner, which manufactures plastic injection molded parts and the necessary molds, shows the great savings potential of the additively optimized mold: The cooling time for the plastic injections molded part made of Makrolon 2805 was iteratively reduced by 86 % from 70 seconds to 10 seconds. This corresponds to a reduction in cycle time of 45 %, while simultaneously reducing and stabilizing the core temperatures from 130 °C to 78 °C (Figure 7). The temperature of the improved core remains stable regardless of the number of components produced. Furthermore, the geometric accuracy of the manufactured parts has been improved by reducing thermal distortion, and the process reliability of the injection molding process has been increased through better demolding of the produced parts.

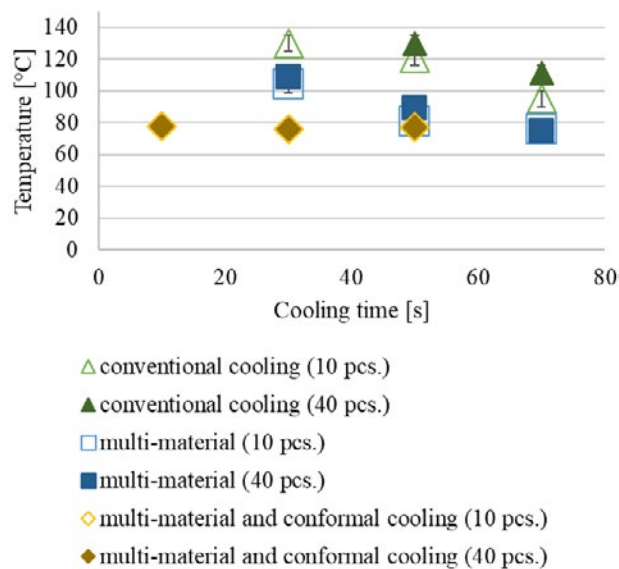


Figure 7: Overview of the core temperatures for the tested cooling configurations after 10 and 40 parts.

To evaluate costs and determine potential savings, a separate cost model was created to calculate the manufacturing costs according to the differentiated overhead calculation for the additive manufacturing process. According to this method, the manufacturing costs results from the sum of:

- direct material costs (e.g. used metal powder)
- material overhead costs (e.g. for storing the powder)
- production costs (employee wages)
- production overhead costs (e.g. room rental, energy, air conditioning system)
- machine overhead costs (using the machine)

To calculate the manufacturing costs for this additive manufacturing process, the entire production process was

segmented into work steps, necessary times were recorded, billed with hourly rates and allocated to the categories mentioned. This model includes all working steps from NC code programming to the removal and cleaning of the finished part. The individual working steps for this process were integrated into a mathematical model for calculating the manufacturing costs for all components which are manufactured with the production process analyzed. In addition, the manufacturing costs can be calculated in advance using the component volume and the number of units.

This model is used to calculate the additional manufacturing costs for manufacturing the additively optimized injection mold compared to the conventional mold. Since machining the basic mold shape is necessary for both kinds of molds, the additional costs of the optimized mold consist of the needed effort for the additive manufacturing of both multi-material cores for an optimized thermal cooling behavior. The percentage composition of the additional manufacturing costs is shown in Figure 8.

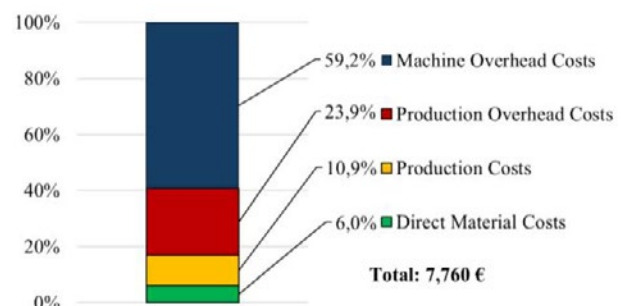


Figure 8: Composition of the additional manufacturing costs for the additively thermal optimized injection mold according to the differentiating overhead calculation.

The largest cost component is the machine overhead costs at 59.2 %. This can be attributed to the long production time of the DED system of 11.75 hours and a very high machine hourly rate of 378 €/h. The hourly machine rate is calculated from the investment costs over the machine's useful life, the space required, the power consumption and the maintenance costs. Personnel costs for operation are not included; they are part of the direct production costs. High investment costs and low utilization in 1-shift operation in research environment lead to high machine hourly rate.

The production overhead costs depend and vary strongly on the cost structure of the company. In this case, production overheads make up 23.9 % of the manufacturing costs. They serve to cover overheads like room rental, energy etc. to produce the part. With 10.9%, production costs account for the next smaller share of the manufacturing costs and result directly from the personal costs for manufacturing the optimized mold. The material costs of 6.0 % include the direct material costs, e.g. for metal powder and argon gas and the material overhead

costs, e.g. for storing the powder. Together, they make up the smallest share of manufacturing costs. In Total, the additional manufacturing costs for the optimized mold are 7,760 €.

The reduction in cycle times also results in significant financial savings potential: With an hourly machine rate of the injection molding machine of 36.00 €/h (0.01 €/second), the saving corresponds to 0.38 € per plastic part. The break-even point, at which the additional costs for the optimized mold are compensated by the savings, is 20,422 parts (Figure 9). In industrial applications, the hourly rate of the DED-machine can be reduced to 87 €/h by increasing capacity utilization from 50 to 70 percent and operating a 3-shift system. This hourly machine rate reduces the additional manufacturing costs to 4,347 €. In this case, the break-even point is already reached after 11,440 pieces.

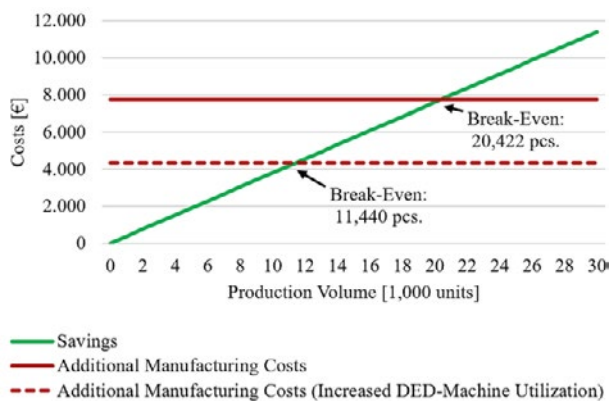


Figure 9: Break-even point at which the additional manufacturing costs for the optimized mold are compensated by the reduction in production cycle time.

6 Summary and outlook

The results presented here show that the PB-DED process is suitable for the production of thermally optimized tools in an industrial environment. Through the combination of local material adjustments by MM and conformal cooling channels, significant cycle time reductions of 45% were achieved without compromising the quality of the produced components.

The implementation of an FE-based optimization method and feature segmentation was implemented in a commercially available software solution. There were only minor limitations due to the realization as a hybrid manufacturing process consisting of additive deposition on existing structures and conventional manufacturing of the largest part of the mold. However, this is more due to the large number of manual programming steps involved in creating the necessary tool paths for the additive manufacturing system. These geometry-specific and time-consuming preparation steps are currently being transferred to partially automated NC programming cycles, which are expected to increase the practicable component complexity while reducing preparation time.

Further cost reductions can be achieved by increasing the capacity utilization of the PB-DED machine through multi-shift operation and shortening the production time, as these account for the largest share of the additional production costs of an optimized mold.

The extension of the thermal optimization method from MM to FGM promises further improvement of molding tools, in particular the reduction of residual stresses. The possibilities for implementation on the “Modulo 400” machine used at the Kiel University of Applied Sciences are currently subject of further investigations.

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