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Design of an Injection Mold with Local Placement of Heating Coatings for Warpage Compensation

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Design of an Injection Mold with Local Placement of Heating Coatings for Warpage Compensation

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Abstract: The influence of the thermal injection mold design crucially affects the geometric precision of injection molded parts. However, the adjustability of the heat flux distribution established with the conventionally used cooling channels is limited and cannot cover the variable cooling demand. The proposed approach of using heating coatings on the cavity surface to manipulate the part's cooling rate shows that it may be advantageous, due to the close and localized application to the part. A simulative optimization routine determines the necessary position and surface power of the heating coating. The objective of this methodology is to homogenize the surface temperature, inner cooling rate, and freeze time inside the part. This work applies the simulative design method for the optimized placement and heating power on a mold for a three-dimensional part. As the temperature field of the heating coating depends on the contacting, the electro-thermal simulation is analyzed and confirmed as sufficient to establish the optimal heat flux distribution. A process simulation study shows the dimension with the most critical warpage is decreased by 90%.

Keywords: Heating Coating, Injection Molding, Local Heating, Process Simulation, Thermal Mold Design, Warpage

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Introduction

Thermal mold design is a crucial step in creating an injection mold. Its primary objective is to rapidly cool down the molded part, ensuring an efficient manufacturing process. It must simultaneously allow for mold filling under moderate process conditions while preventing premature solidification of the melt. Balancing these conflicting goals, the cooling conditions also impact the optical and geometric properties of the part. Variations in part wall thickness and localized mass accumulation lead to significant differences in temperature, cooling rate, and solidification time. These state variables influence the material's specific volume during cooling. Non-uniform 3D-specific volume states or shrinkage during cooling induce local stress within the part, resulting in warping upon demolding due to unconstrained geometric shrinkage. Properly adjusting the heat balance of the mold through temperature homogenization, cooling rate, and freezing time distribution within the molded part helps reduce discrepancies in locally specific volumes [1].

Conventionally, the part is cooled down by heat transfer into a fluid like water or oil running through cooling channels inside the mold, close to the cavity. Various research is conducted to create methods and design rules on how to design the cooling channel layout for injection molds [2]. The approaches to inverse thermal mold design have the advantage that no initial tempering channel layout is necessary and that the user cannot influence the result by his choice of starting conditions [3,4]. The term "inverse" is derived from the objective: At the end of the cooling phase, a thermally homogeneous molded part is to be produced. The central tool is an objective function, which evaluates the thermal state of the molded part [7,8]. Based on this target definition, the heat balance of the injection mold is iteratively adjusted until an optimality condition is reached. The automized thermal design and cooling channel derivation have shown that the boundary conditions for cooling channels limit the level of detail with which the optimal heat balance can be set. Consequently, the necessary heat flux cannot be supplied locally. One example is the minimum diameter of the cooling channel or minimum distance between the cavity and the cooling channel [5,6].

In order to establish a well-defined heat flux profile, extremely high temperature gradients are necessary. A prior simulation study demonstrated the advantages of applying localized heat input to the edges of an injection-molded part to mitigate warpage [7]. The practical implementation and extent of localized heat input is promising. A newly developed heating coating consisting of two electrically isolating ceramic layers around a electrically contacted ceramic layer was applied on the cavity wall of a plate geometry and practically tested [8-10]. The electric flow creates a heat source according to the joule heating. The coating's low mass ensures a high heating and cooling rate of the wall temperature. An adjustable influence on the part warpage is also validated and, therefore, the use of this technology for higher geometric precision is suggested [8]. The heating power distribution, which is derived by the temperature field on the surface, is homogeneous but depends on the contacting positions of the coating. The position determines the resistance for the electric current between the different contacts and, consequently, the electric current density distribution and direction within the coating.

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An adaptation of the inverse thermal mold design shows the applicability of this methodology for heating coatings on the cavity wall [11]. Heat sources on the cavity wall make it possible to significantly reduce the result of the optimization's objective function. For example, more homogeneous surface temperatures on the part and cooling rates inside the part are achieved. To experimentally validate the effect of the heating coating, a three-dimensional part and the optimal heating coating layout is calculated. A test was performed to determine if a thermo-electrical simulation calculating the joule heating and the resulting heat flow can be used to set up different contacting positions of the coating and whether it predicts the resulting heating power distribution. Finally, a commercial process simulation is conducted to compare the warpage of the part with and without a heating coating to ensure the positive effect before the manufacturing of the mold.

Electric Simulation and Calibration of the Heat Transfer Coefficient

The influence of the electrical contacting and position indicates that it needs to be considered to actually create the optimal heating power distribution. Therefore, an electro-thermal simulation of the experiments in [8] is modelled with Comsol Multiphysics 6.1, Comsol AB, Stockholm, Sweden, and compared to define the unknown boundary conditions with a reverse engineering approach. As the temperature dependent electrical resistance of the coating is known through the measured current and voltage, the remaining parameter is the heat transfer coefficient between the coating and substrate.

The experimental setup is a mold insert with a heating coating which is cooled by the mold's cooling channel [8]. The mold insert is a flat surface usually used for injection molding of plates. Figure 1 shows the temperature distribution of the numerical model and the experimental setup measured with a thermography camera. The temperature level is considered approximately equal and the electric contacts are recognized by the temperature hot spots. However, the simulation shows that the hottest area is between the two contacts at the bottom instead of the two contacts in the middle. Since the contacts are in a parallel connection and are the same distance apart, no path with a lower electrical resistance is expected. However, a reduced heat flow at the bottom or increased heat flow at the top in x-direction would lead to a temperature gradient in x-direction. Thus, the coating's electrical resistance is lower in the hotter area. Further adaptations of the heat flow were tested by increasing the natural convection at the bottom and decreasing the heat transfer coefficient between the top of the insert with the coating and the mold base. Currently no significant improvement of the correspondence of the temperature field's quantitative conformity is achieved.

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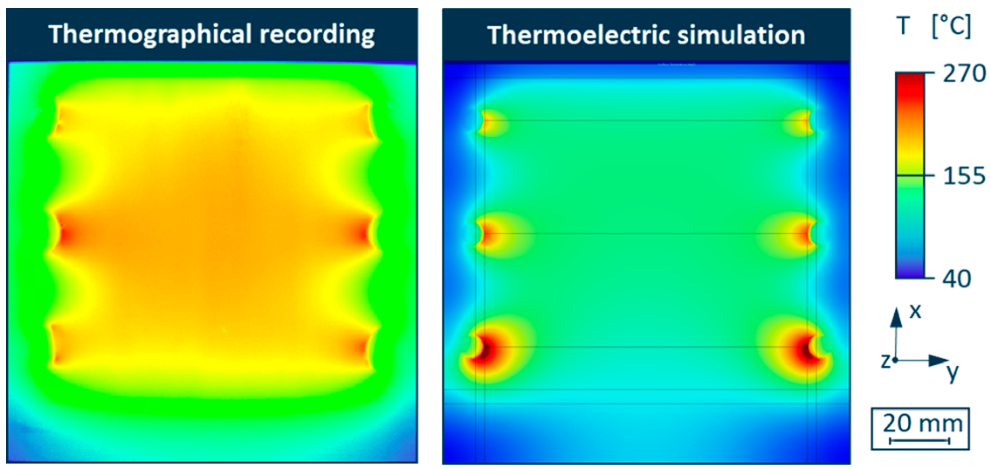

Figure 1. Comparison of the temperature distribution between thermography and simulation.

Optimization of the Heating Coating Position and Power

The design and optimization routine developed in previous works is applied on a three dimensional geometry [11]. The chosen geometry is a simplification of a stacking box (Figure 2). The simplifications are necessary to ensure the access of the thermal spray gun to the whole mold surfaces during the coating process. Additionally, the decreased structural stiffness increases the risk of warpage and therefore poses a more critical case to validate the warpage compensation due to local heating coatings. Figure 2 shows the cooling channel layout designed by professional mold manufacturers. It serves as an industrial example to demonstrate whether additional and more localized control of the cooling of the part brings advantages for the existing conventional mold cooling. The inlet is realized by a cold runner and located in the back of the bottom of the box.

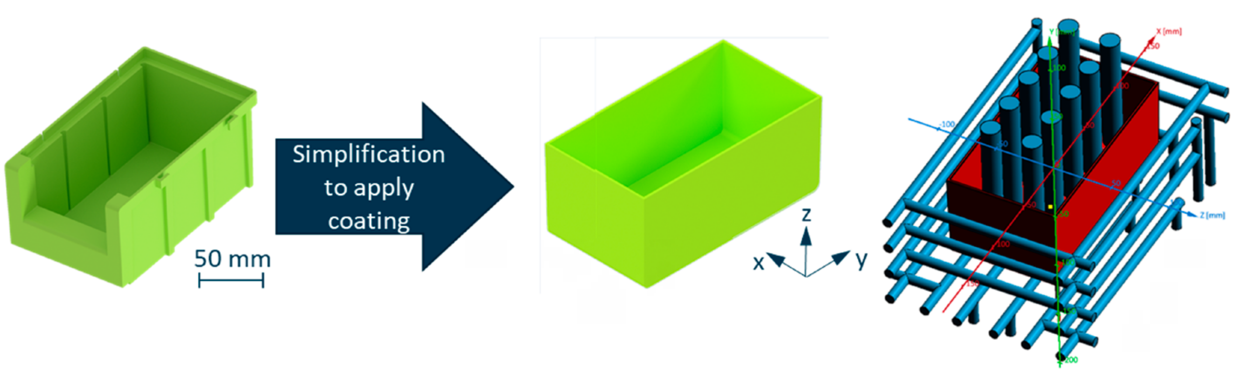

Figure 2. Part geometry and cooling channels for the validation case.

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The material of the mold and part as well as the process parameters are chosen for the design routine to calculate the initial conditions of the part after injection (Table 1). The simulation software, Sigmasoft, Sigma Engineering GmbH, Aachen, Germany, is used to determine and export the temperature and pressure distribution of the mold and melt.

Table 1. Material and process parameter for calculating the initial conditions for the subsequent thermal optimization. An unreinforced polybutylene terephthalate (PBT) is used for the mold design.

Parameter	Value/Name	Unit
Melt material	PBT–Pocan B1305, Envalior GmbH, Düsseldorf, Germany	-
Mold steel	1.2311 / 40CrMnMo7	-
Melt temperature	255	[°C]
Mold temperature	80	[°C]
Injection rate	100	[cm^3/s]
Ejection temperature	98	[°C]
Cooling time	15	[s]

The optimization routine is conducted with the Comsol Multiphysics software. Firstly, the heating power on the cavity surface as the design variable is optimized with a gradient based optimization algorithm. The algorithm minimizes the objective function [11,12] and thus homogenizes the temperature on each part's surface and the cooling rate as well as the freeze time inside the part. The first optimization results in an optimal heating power distribution. Secondly, a non-gradient based optimization algorithm assigns the heating power distribution to either the discrete heating zone or no heating. The optimal result is a heating zone of 6,000 W/m^2 assigned to each position with a value above 3,500 W/m^2 from the first optimization step.

The simulation without a heating coating shows a wide temperature distribution on the surface, with the lowest temperature on the edges and corners and the maximum temperature in the edges inside the box (Figure 3). The area with higher temperatures originates due to the proximity of the inlet and the four surfaces in this area that transport energy to the cooling channel in the middle, whereas the cooling channels withdraw energy from one side of one wall. This area can also not be optimized by applying heating coating, which is why the maximum value in all optimized layouts is similar (Figure 3).

The potential of the heating coating is visible in the area, which is colder than 98°C in simulation result without heating. The optimal heating distribution homogenizes this area to a high degree, (Figure 3). The minimum temperature is a lot closer to the average temperature and half of the temperature values lie within a range of 2.5 K. This is smaller than the range of 6.0 K without heating. The minimum values from the discrete solutions are in-between the optimal distribution and the one without heating, and the temperature distribution is also narrower. Half the values lie within

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a range of 3.4 K. This shows that the discrete optimization focuses on a narrow distribution rather than increasing minimum temperature significantly to achieve the best compromise in terms of the objective function.

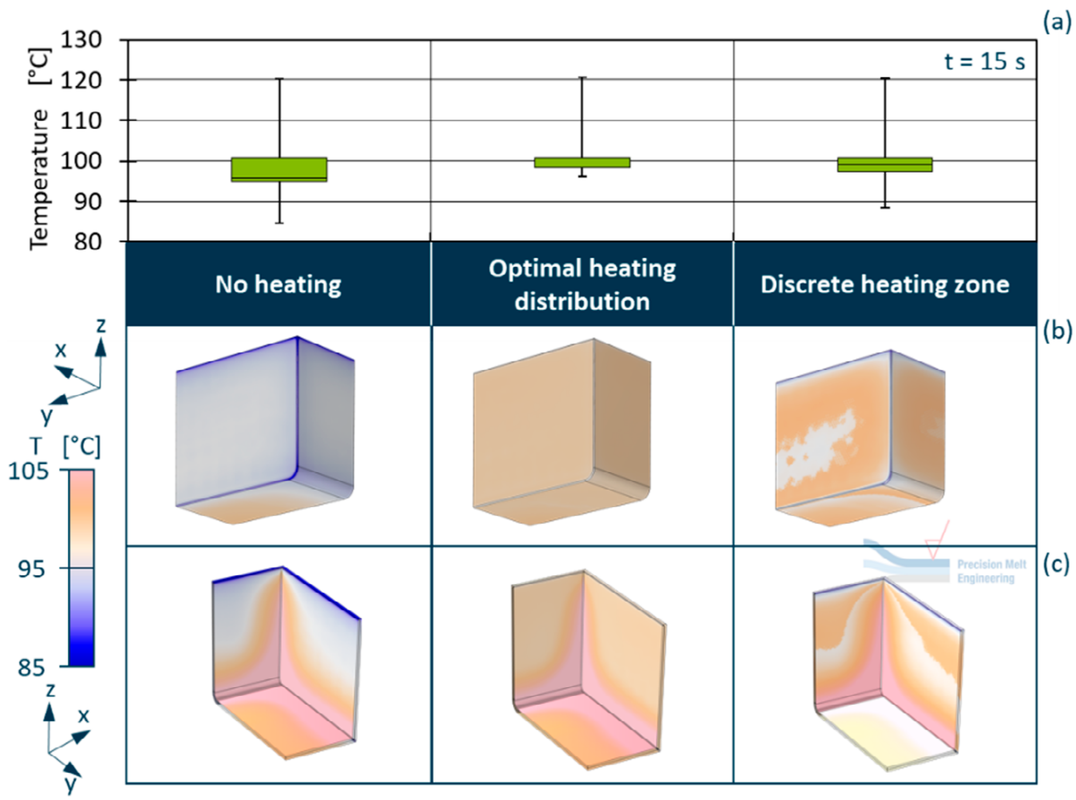

Figure 3. Box plot showing the temperature distribution on the part's surface without a heating coating, with the optimal heating coating distribution and one discrete heating coating zone (a). False color plots displaying the temperature distribution on a quarter model with a view of the outside (b) and inside (c) of the box.

Simulative Validation of the Heating Coating's Warpage Compensation

The process is simulated with and without the developed heating coating, according to the predefined parameters in Moldex3D 2023, CoreTech System Co., Ltd, Taiyuan St. Zhubei City, Taiwan (Table 1). The first comparison in terms of temperature distribution shows a more similar temperature level on the inside and outside of the box with heating coatings (Figure 4). However, the temperature influence of the heating coatings is seen on the outer walls in terms of hot spots. The temperature distribution is less homogenic compared to the simulation in Comsol. This is explained by the differing heat transfer coefficient implemented in all process simulation software.

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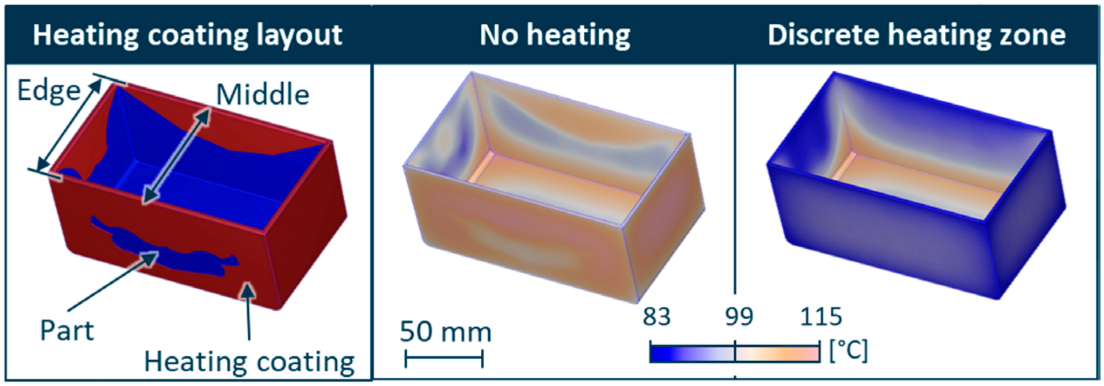

Figure 4. Temperature distribution on the part's surface displayed regarding the Moldex3D model.

An indicator for the geometric precision the typical warpage for box-shaped geometries is the wall collapse. The difference between the width of the part in the middle and the edge is supposed to be the same (Figure 4). Table 2 shows that the wall collapse is 90% lower with -0.15 mm compared to the 1.46 mm without heating coatings.

Table 2. Distances of the part in the middle and edge of the long wall after 15 s cooling.

Measurement	Edge [mm]	Middle [mm]	Wall collapse [mm]
Nominal	94.6	94.6	0
No heating	93.03	91.57	1.46
Discrete heating zone	92.71	92.86	-0.15

Conclusion

The methodology presented in previous works is applied on a three-dimensional part. A discrete heating power is derived and created as a geometry to create a heating layout. The thermo-electrical simulation was established for this heating coating technology and can be used in the future for developing the electrical contacting. The ideal heating power distribution ignoring the influence of the contacting in an injection molding simulation already shows that the warpage is reduced. However, the different heat transfer coefficient model used in the design software and the validation software led to different boundary conditions. A more comparable set of boundary conditions for the different simulations will be used in the future, by defining a constant heat transfer coefficient.

All in all, the result is a significant layout that will be manufactured in the future and iterate design changes of the heating coatings position and size should be reduced.

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Research Data

This work's research data can be accessed here: http://hdl.handle.net/21.11102/ce52d6c9-906e-49ea-a5eb-a600675fd4f1

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