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RESEARCH ARTICLE

Enhancing Thermal Simulations for Prototype Molds

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Abstract

Our goal was the thermal analysis of epoxy acrylate-based prototype molds with numerical simulations, and to compare and analyze the measured values and calculated results. The difference between the thermal calculations and the measured values is significant; the actual temperature of the mold is higher than the calculated values. Based on the numerical simulations, we found that in the case of epoxy acrylate-based mold inserts, temperature results can be made significantly more accurate by changing the heat transfer coefficient between the surface of the mold insert and the melt. We proved that in the case of small-series epoxy acrylate-based molds, the temperature dependence of the thermal properties of the mold material, and the temperature and pressure dependence of the heat transfer coefficient need to be taken into account for accurate temperature results. We proved that the heat transfer coefficient between the mold surface and the melt is considerably lower than in the case of metal molds, due to lower cavity pressure and a lower temperature difference between the mold surface and the melt.

Keywords

injection molding, conformal cooling, prototype molds, injection molding simulation, thermal analysis

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1 Introduction

The plastic industry is continuously developing and plastic products are more and more widely used. In 2016 the industry processed 335 million tons of polymers, which is a 10 % increase compared to 2015 [1]. One of the most important processing technologies of the plastic industry is injection molding, and as a result, more and more modern methods appear on the market, such as the rapid mold heating and cooling method [2, 3], resin transfer molding [4, 5], foam injection molding [6] and conformal cooling circuits [7, 8] etc.

The advantage of conformal cooling is that the cooling circuits follow the geometry of the part; therefore the smaller diameter channels placed closer to the cavity surface can extract heat faster and more uniformly than conventional cooling channels. As a result, the quality of the part improves and its cost is reduced [8-10].

An optimal conformal cooling circuit cannot be designed without injection molding simulation. This way product-specific layouts can be produced, which further improve the quality of the product and reduce the probability of defects [11-13].

Small series products require proper manufacturing technology and mold design since it is a difficult and complex task to produce such products economically. Additive manufacturing technologies provide help with this. With these technologies indirect [14, 15] or direct tools [16-19] can be manufactured.

In spite of the fact that many researchers are researching the development of the material [20-23] and manufacturing technology [24-26] of small series injection molds, few papers have been published on the numerical analysis of these molds, even though the heat load of the molds could be calculated this way. Kovács et al. [27] investigated with numerical simulations the effect of the thermal conductivity, specific heat and the heat transfer coefficient between the mold insert and the melt on the mold temperature of epoxy acrylate-based mold inserts manufactured with additive manufacturing technologies. They claimed that in the case of the investigated mold insert layout the calculated results cannot be made acceptably accurate if only one parameter is modified. The modification of the thermal conductivity can result in the smallest difference between the measured and calculated values (thermal conductivity 0.6 W/mK, specific heat 1700 J/kgK, heat transfer coefficient 20W/m^{2}K), but this thermal conductivity is considerably higher than what was measured. Also, the authors performed the simulations on a model containing beam elements and using simplified cooling calculations, therefore the accuracy of calculated temperatures cannot be as precise as with the CFD (Computational Fluid Dynamics) calculations.

Our goal is the thermal and numerical analysis of prototype mold inserts with conformal cooling circuits, the comparison of measured and calculated results, the investigation of the causes of possible differences between them with numerical methods, and the modification of the initial and boundary conditions so that the calculated results correlate better with the measured data.

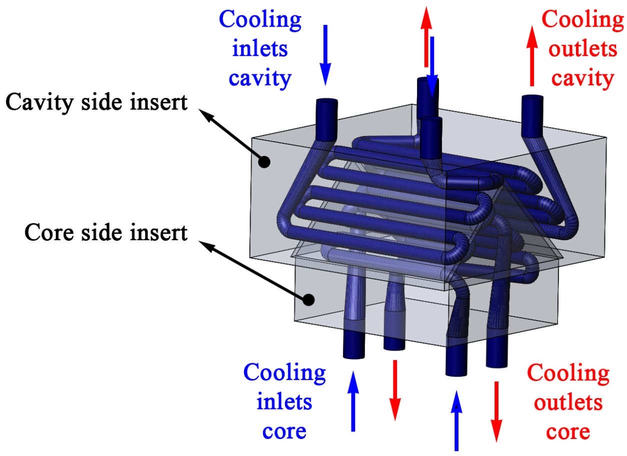

Fig. 2 Conformal cooling channel layout

2 Mold and insert layout

We used a two-plate, two-cavity mold which has an insert in both the stationary and the moving side. The mold can produce two parts, each composed of two 2 mm thick perpendicular plates (Fig. 1).

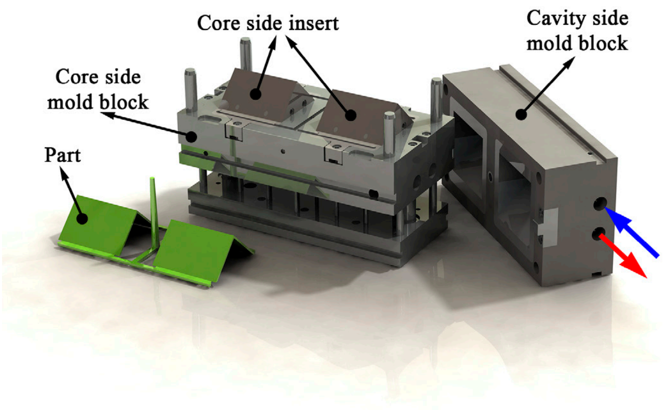

Fig. 1 Injection mold used for the numerical calculations

The mold inserts are cooled by conformal cooling channels. In the case of conformal cooling, the diameter of the channels is smaller and they are closer to the cavity than in the case of conventional cooling. Heat removal is uniform because the channels follow the geometry of the part (Fig. 2). The diameter of the cooling channels decreases to 5 mm from 8 mm as they enter the insert; the cooling channels are 6.5 mm from the cavity surfaces and 8 mm from each other.

3 Injection molding

Small series prototype molds require the use of different processing parameters than large-series metal molds, due to their inferior mechanical and thermal properties (Table 1). For the injection molding tests, we used PP (Tipplen H145F, MOL Petrolkémia Zrt.), because it flows well at lower temperatures and shear rates as well (190 °C, 4500 1/s, 25 Pas). This way the heat and shear load on the mold is smaller, which increases the lifetime of the mold so that the necessary number of tests can be performed. The injection molding experiments were performed on an Arburg 370S 700-290 injection molding machine.

Table 1 Injection molding parameters

Material	PP Tipplen H145F
Melt temperature (°C)	200
Coolant temperature (°C)	25
Flow rate (cm^3/s)	15
Injection pressure (bar)	500
Holding pressure (bar)	300
Holding time (s)	20
Residual cooling time (s)	180
Delay time (s)	260

The mechanical properties of prototype molds are at least one order of magnitude worse than those of metal molds. Also, their mechanical properties are greatly impaired over the glass transition temperature of the material; therefore, melt and mold temperature, filling rate and holding pressure have to be minimized. In addition, residual cooling time should be considerable longer and a delay time is necessary between the cycles. The increased, 180 s residual cooling time ensured that the part cooled under the ejection temperature in the case of every insert. During the delay time of 260 s, the inserts cooled an additional 20-30 °C, which increased their lifetime. Total cycle time was 477 s.

4 Simulation parameters

We built the simulation model and performed the calculations with Autodesk Moldflow Synergy 2018 with the CFD (Computational Fluid Dynamics) module. Average element size was chosen to be 3.5 mm (Table 2), but we decreased the chord error, to improve the modeling accuracy of more complex geometry parts, such as the conformal cooling circuit, the sprue and the runner etc. The thickness of the mold cavity was chosen to be 3 mm; in this thickness we had more elements, therefore close to the surface, where heat can be accumulated, calculations are more accurate (Fig. 3). We used a transient algorithm for the calculation of cooling, with which the temperature distribution of the part, mold inserts etc. can be calculated as a function of cycle time. Technological parameters are identical to the parameters used during injection molding. We used the thermal properties of the Fullcure 720 mold material determined by Kovács et al. [27].

Table 2 Main parameters of the numerical calculations

Global edge length (mm)	3.5
Chord angle (°)	45
Element number (-)	10 million
Minimum number of tetra layers (-)	12
Ambient air temperature (°C)	25
Number of part heat flux time steps (-)	15
Transient mold temperature convergence tolerance (°C)	0.5
Mold insert density [g/cm³]	1.3
Mold insert specific heat [J/kgK]	2000
Mold insert thermal conductivity [W/mK]	0.278

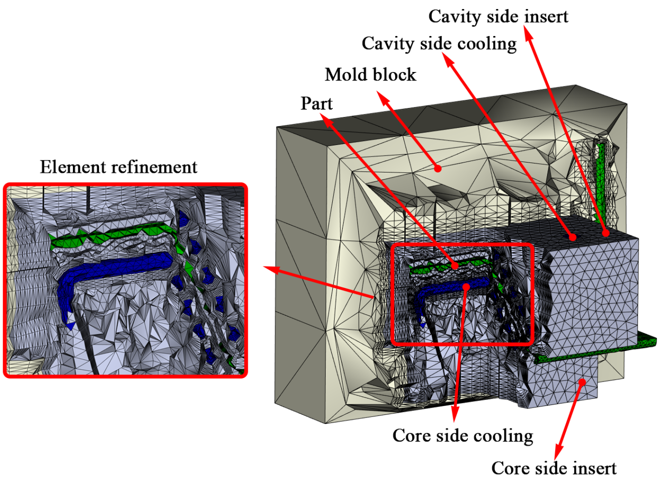

Fig. 3 Numerical model

5 Thermal measurements

We measured mold temperature with thermocouples and collected the measured data with an Ahlborn Almemo 8990-V6 instrument. The sampling rate was set to 3 s and in each case, three measurement series were averaged. In each mold insert, temperature was measured at four points; three in the core side and one in the cavity side (Fig. 4). Two of the three points in the core side (MP2 and MP4) were 4.2 mm from the main edge, while the third point (MP3) was within the mold insert, 32.5 mm from the main edge. On the stationary side, the thermocouple (MP1) was also 4.2 mm from the cavity surface. Starting at ejection, the surface temperature of the mold inserts was monitored with a Flir 325SC thermal imaging camera. Surface temperature was measured on the core side because the main edge is here, which is critical from the aspect of heat removal.

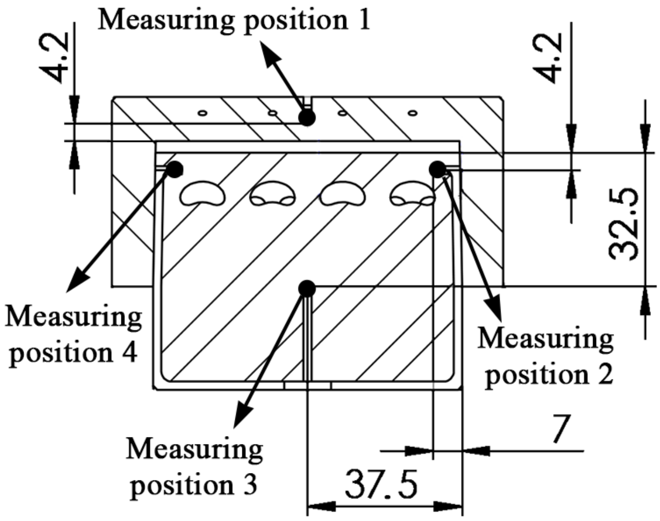

Fig. 4 Thermocouple positioning

6 Results and discussion

The calculated filling patterns correspond well to the filling pattern obtained during injection molding (Fig. 5).

The temperature of each node of the mold inserts can be examined with numerical calculations as a function of cycle time. A great advantage of conformal cooling circuits is that they can be positioned closer to the cavity surface; therefore in this case heat is concentrated in a small volume (Fig. 6).

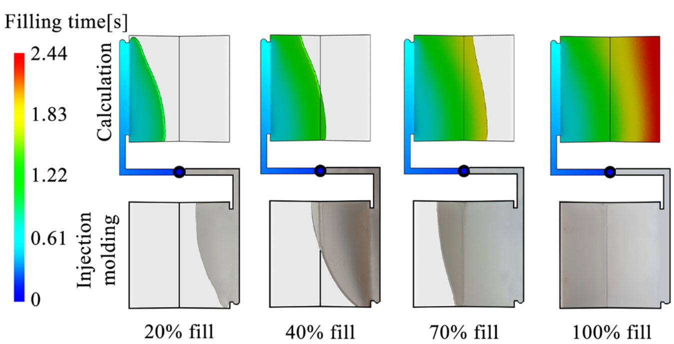

Fig. 5 Calculated and real filling pattern

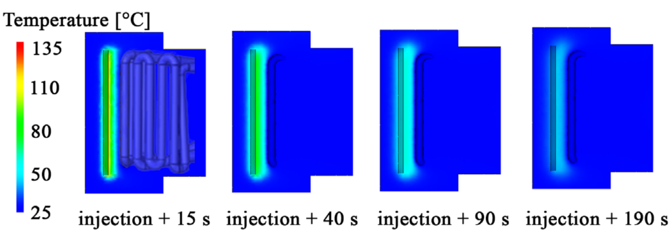

Fig. 6 Calculated temperature in the middle of the insert as a function of time

Between ejection and mold closing, the surface temperature of the mold inserts can be measured, and the measurement results can be compared to the calculated values. Calculated temperatures are 15 °C lower than measured temperatures immediately after ejection (Fig. 7). This difference is due to the fact that the calculation algorithm neglects several factors, including the temperature dependence of the heat transfer coefficient.

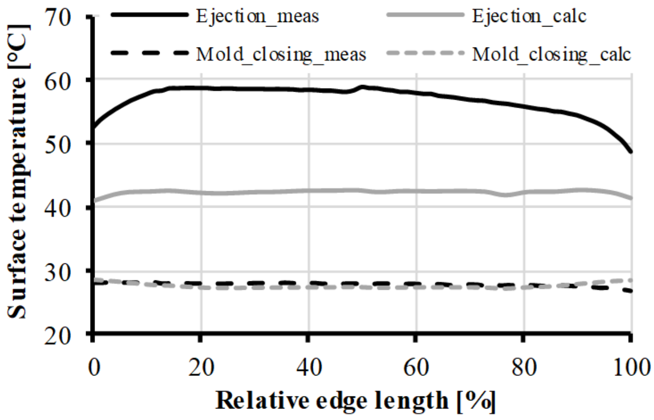

Fig. 7 Calculated and measured surface temperature after ejection and before mold closing

The comparison of the measured and calculated temperatures at the measurement points as a function of cycle time yields a tendency similar to that of surface temperatures (Fig. 8); the calculated temperature curves are different from the measured temperature curves and at measurement point two, calculated temperatures are 10 °C lower than measured temperatures in much of the cycle time.

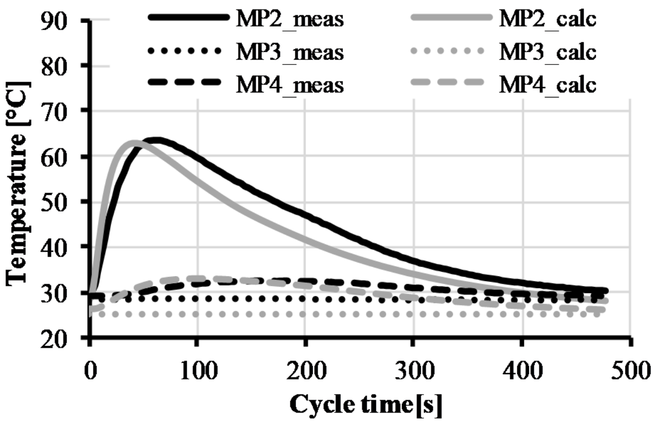

Fig. 8 Measured and calculated temperatures at the measuring points of the insert as a function of cycle time

The measured and calculated temperatures may be different because in the case of thermal parameters, the program neglects several factors. The thermal conductivity coefficient and specific heat capacity of the mold material are temperature-dependent, which the program does not take into consideration. The heat transfer coefficient can be considerably lower in the case of epoxy acrylate-based mold inserts because in the case of resin-based molds, heat accumulates near the cavity due to the bad thermal conductivity of the mold material. The heat transfer coefficient depends on the temperature difference between the mold surface and the melt surface; a smaller difference means lower heat transfer coefficient. The heat transfer coefficient also depends on cavity pressure, which is smaller in the case of epoxy acrylate-based molds, which results in a lower surface heat transfer coefficient. In the case of resin-based mold inserts, cavity pressure cannot be accurately determined with a conventional pressure measurement system. Conventional pressure sensors have a metal casing and the pressure transfer pins are also metal. The thermal conductivity of metals is several orders of magnitude higher than that of the mold material. Consequently, metal parts remove a large amount of heat from the melt locally, therefore it locally freezes and pressure decreases. Since the heat transfer coefficient and cavity pressure are not known, therefore, we examined the difference between calculated and measured values with numerical simulations. The thermal parameters for the simulation were chosen according to the mold material used. Moldflow divides the injection molding cycle into three phases based on the heat transfer process: injection (5000 W/m^{2}K), holding (2500 W/m^{2}K) and residual cooling (1250 W/m^{2}K). We chose lower heat transfer coefficients (Table 3) than those because of the conclusions from Fig. 8.

Table 3 Investigated thermal parameters

Specific heat (J/kgK)	1000	2000	3000			
Thermal conductivity (W/mK)	0.2	0.25	0.278	0.3	0.35	
Heat transfer coefficient (packing phase) (W/m^{2}K)	25	50	100	125	500	2500

The results indicate that the thermal conductivity of the mold material only has a little effect on the calculation results in the investigated range; the maximum and the shape of the temperature curve do not change when this parameter is varied (Fig. 9). The specific heat of the mold material greatly affects the maximum of the temperature curve; the maximum temperature increased by 20 °C as specific heat was reduced from 2000 J/kgK to 1000 J/kgK (Fig. 10). The time of the maximum temperature only changes little as specific heat changes. Reducing the heat transfer coefficient between the wall of the mold and the melt reduces the maximum temperature and extends thermal processes, that is, ejection and the maximum temperature occur later (Fig. 11). This indicates that reducing the heat transfer coefficient may reduce the difference between measured and calculated values.

Based on the tests, if the original heat transfer coefficient of 2500 W/m^{2}K is set to 100 W/m^{2}K, the total difference of the measured and calculated temperatures can be reduced to 2 % from the original value of over 16 % (Fig. 12). This indicates that in the case of resin-based prototype molds, the accuracy of numerical calculations depend most on the accurate determination of the heat transfer coefficient between the wall of the mold and the melt. Also, in the case of prototype molds, the heat transfer coefficient is an order of magnitude lower than in the case of metal molds, which is probably caused by the lower cavity pressure and the smaller temperature difference between mold wall and the melt.

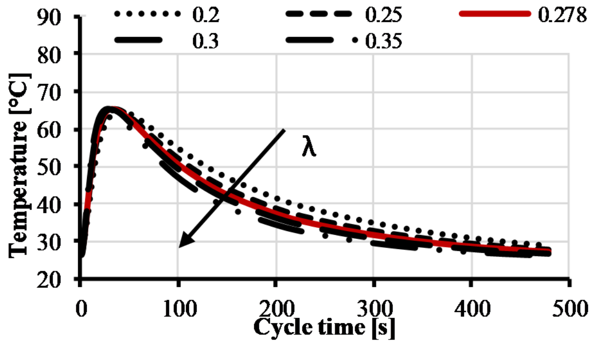

Fig. 9 Calculated temperature at MP2 with 0.2, 0.25, 0.278, 0.3 and 0.35 W/mK mold thermal conductivity, default value marked with red

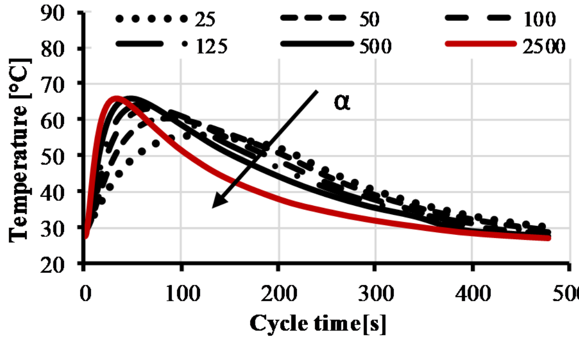

Fig. 11 Calculated temperatures at MP2 with a heat transfer coefficient of 25, 50, 100, 125, 500 and 2500 W/m²K (cooling phase); the default value is marked with red

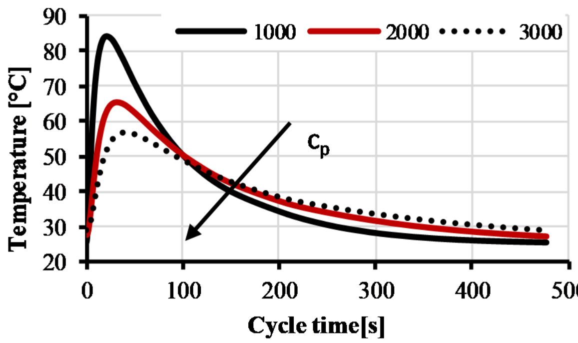

Fig. 10 Calculated temperatures at MP2 with 1000, 2000 and 3000 J/kgK mold specific heat; the default value is marked with red

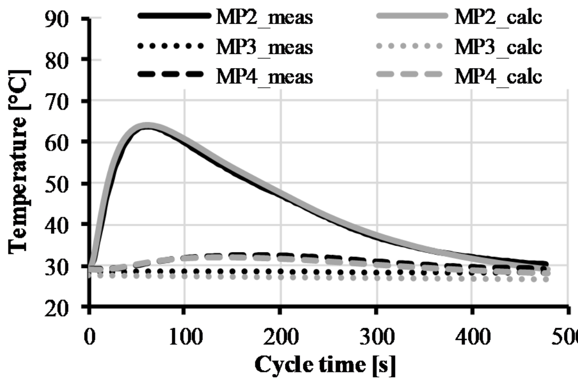

Fig. 12 Calculated temperatures in the middle of the insert as a function of time

7 Conclusion

Our goal was the thermal analysis of epoxy acrylate-based prototype molds with numerical simulation, and the comparison and analysis of the calculated and measured values. The filling results indicate that the calculated and actual filling of the mold are in good agreement. However, there is a considerable difference between the results of thermal simulations and actual, measured temperatures; the measured surface temperature of the mold is nearly 30 % higher at ejection and the temperature within the mold is 20 % higher than the calculated values. These differences can be the results of neglections related to thermal parameters, for example the neglection of temperature dependence or pressure dependence. The numerical simulations indicated that in the case of epoxy acrylate-based mold inserts, temperature results can be made considerably more accurate if the heat transfer coefficient between the surface of the mold insert and the melt is modified. The results show that in the case of small-series, epoxy acrylate-based molds, the temperature dependence of the thermal parameters of the mold material and the temperature and pressure dependence of the heat transfer coefficient need to be taken into account in the simulations for accurate temperature results. It was also found that due to the lower cavity pressure and the smaller temperature dependence between the cavity surface and the melt, the heat transfer coefficient is significantly lower than in the case of metal molds.

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