Thermal simulations and measurements for rapid tool inserts in injection molding applications

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Abstract

Rapid prototyping (RP) is a widely used process in the industry to shorten development time. Another advantage of this technology is the ability to create conformal cooling systems, thus not only cooling time and cycle time can be shortened, but also shrinkage, thus warpage can be decreased. The main disadvantage of Rapid prototyping materials is their low thermal conductivity, which strongly influences cooling properties and warpage.

The research based on a special developed injection mold for novel rapid prototyping based mold inserts with cooling systems. A method has been introduced to determine the most important thermal parameters for injection molding simulations using rapid tools. Those parameters, which can be measured such as the specific heat and thermal conductivity of the mold materials, are directly implemented into the software. The heat transfer coefficient between the polymer melt and the rapid tool insert surface cannot be measured in a reasonable way, thus simulation software was used to determine that based on indirect calculation derived from real measurements. In the paper, the method was proved with Fused Deposition Modeling (FDM) and Polyjet mold inserts.

Keywords: rapid prototyping; FDM; Polyjet; thermal parameter; simulation

1. Introduction

The need for a faster development cycle led to rapid prototyping becoming a common tool in product development [1]. The materials available in these technologies cannot always substitute the materials needed for products; when this is needed, rapid tooling can be used. With rapid tooling, small series of a product can be manufactured, with the same technology and materials as those of the final product [2].

Rapid tooling is the term for either indirectly utilizing a rapid prototype as a tooling pattern for the purposes of molding production materials, or directly producing a tool with a rapid prototyping system [3]. Epoxy or particle (like ceramic [4] or metal [5] particles) filled epoxy molds can be manufactured reasonably faster than machined molds. If the molds are designed properly, they can withstand the injection or the compression pressures with the use of aluminum standoffs or mold boxes. However, cycle time can be several minutes because of poor thermal conductivity [6]. The lifetime of the tool depends on the thermoplastic material, the fillers and the complexity of the part. Some molds can only produce a few dozen parts, while others in excess of a thousand [7].

To decrease the time to market, the rapid tooling and the injection molding simulation is an important tool. The numerical simulation in the conventional injection molding is a well-elaborated area [8]. On the contrary, the numerical simulations for rapid tooling inserts or molds are poorly investigated as far. The typical thermal conductivity of a mold is between 20 and 80 W/mK in the case of conventional tool steel. The warpage of the part between these values is nearly constant, but with rapid tool inserts, it can vary a great deal more. The thermal conductivity of an unfilled polymer resin mold is around 0.5 W/mK, which causes increased warpage of the part [9]. Naturally, the durability and abrasion resistance of rapid tool inserts (soft tools) are worse compared to the conventional molds, but they are worth using if only a small number of parts are needed for testing purposes. Hence, to optimize the part quality and the molding parameters with numerical analysis at the case of rapid tools is an important issue.

The design of cooling system has also a great influence on the quality of the injection molded parts. Many papers deal with cooling systems design, which not only has a vital role in reducing cycle time but also significantly affects the productivity and quality of the final product. Hassan et al. in the work of [10] found that the position of the cooling channels has a major effect on shrinkage rate distribution. In another paper, their results showed that the cooling system layout that results in the shortest cooling time does not necessarily produce optimum temperature distribution throughout the product, therefore the layout of the system must be optimized to achieve both goals [11]. The shape of the cooling channels also has a significant role in the heat transfer process. Simulations made by Hassan el. al. [12] proved that cooling was improved when the cooling channels were rectangular. Several other research projects have focused on the analysis, optimization, and manufacturing of cooling systems. Xiao et al. [13] developed a rapid thermal cycling mold with electric heating and water impingement cooling and proved its efficiency. Agazzi et al [14] introduced a methodology for the design of effective conformal cooling channels of an injection mold. Lin [15] developed a neural network method to optimize the injection mold cooling systems. Li et al. developed [16] and improved [17] an automatic method to design conventional cooling systems. Wang et al. [18] presented an automatic process for designing conformal cooling circuits. Au et al. [19] proposed also an automatic designing method to generate cooling channel for rapid tools. Furthermore they presented a multi-connected porous cooling system [20].

Based on the research done by Hassan et al. [12], it can be concluded that the optimal cooling system can be determined with the thermal analysis of the effect of the cooling system on the heat transfer process in the mold. The measurement of the heat contact resistance between the polymer melt and the mold surface is very difficult, but its correct value is necessary to obtain precise results from numerical simulations. There are some publications to measure these thermal properties, but its correct measurements are still a big challenge. Dawson et al. [21] developed an instrument to measure the thermal contact resistance between the polymer-mold interfaces. They concluded that the thermal resistance of the polymer-steel interface is small compared with the thermal resistance of the polymer itself. Bendada et al. [22] concluded that the thermal contact resistance in the polymer-mold interface is not negligible, changes during the cycle and strongly depends on the process conditions. Le Goff et al. [23] showed that, when the contact developed between the mold and the semi-crystalline polymers melt surface the thermal contact resistance is relatively high then it decreases to reach a minimum value. After that, the resistance starts to increase due to the shrinkage of the part, but after the crystallization process the gradient of the curve decreased. Masse et al. [24] analyzed the contact conditions between the polymer and the injection mold for different mold surface roughness and at different pressures. They noted, that the conductance decreases when the roughness increases. Liu et al. [25] showed through injection molding simulations that the melt temperature and the cavity surface roughness has important role on the conductance.

Although it can be concluded according to the literatures, that the rapid tooling is an important issue in the injection molding, the precise numerical simulation of the process still is a big challenge. In our present paper the Fused Deposition Modeling (FDM) process and Polyjet technology was used to manufacture injection mold inserts. The goal of this research project was to determine the thermal contact resistance between the RP mold surface and the polymer melt during injection molding via comparing the measured and calculated temperature curves. These results can be used for further simulations of molds with Polyjet inserts having conformal cooling systems.

2. Experimental

2.1. The development of a test mold for rapid tooling evaluation

To characterize the influence of mold properties on injection-molded parts, a part with a special geometry was designed. It can be used to measure the effects of mold design, mold materials and various technological parameters on the quality of the part and to estimate the lifetime of rapid mold inserts [26].

To produce the so-called V-top specimens, a special mold was designed with exchangeable and variable inserts (Fig. 1.). The special mold slides into a quick-change frame and has two cavities with a variable runner and gate system.

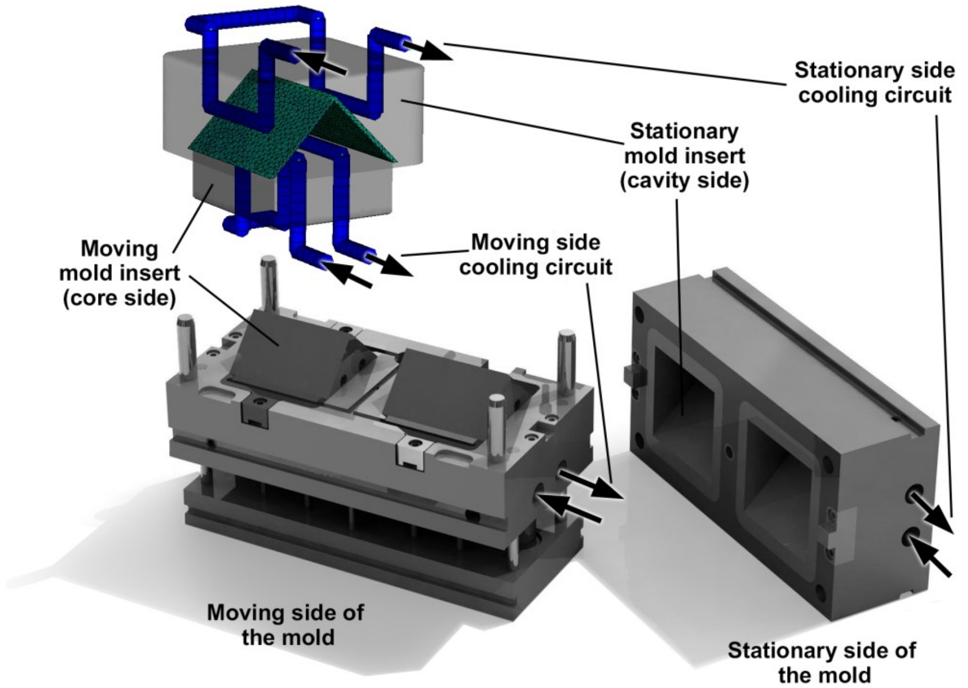


Fig. 1. The moving and stationary sides of the mold with the inserts and cooling channels

Warpage is highly influenced by cooling and is significant at the corners. The core of the mold has to dissipate heat faster than the cavity; otherwise, the internal area of the corner of the part solidifies more slowly and causes a sharpening of the corner itself. To be able to measure the performance of the new rapid tool inserts with a conformal cooling system, first we had to design a conventional cooling system (Fig. 1.) as reference. Using conventional mold making methods, only straight channels can be produced, while rapid tooling could offer freedom in the design.

To ensure the highest control precision, temperature sensors were installed into both the core and the cavity of the mold. With the help of these sensors, the temperature was captured in different locations, which has a fundamental importance in a simulation comparison.

To test and qualify the rapid tool inserts, the conventional mold insert structure was copied and a similar cooling circuit was manufactured. Both FDM and Polyjet technology were tested with conventional cooling circuits, which were similar to drilled cooling circuits. This phase was necessary for the optimization of the simulation models and determining the material properties data for the new rapid tool materials.

2.2. Manufacturing of the test mold by Fused Deposition Modeling

A Stratasys Dimension Elite rapid prototyping machine has been used to produce the mold insert. The FDM process first fuses a solid thermoplastic filament and then extrudes the fused material through a nozzle. The Elite machine has a minimum layer thickness of 0.178 mm. ABS material was used and layer thickness was 0.254 mm.

The support material was removed with Stratasys WaterWorks Soluble liquid. Before installing the inserts into the mold frame, threads were cut into the mold with a screw-tap to hold the inserts in position and the temperature sensors (KISTLER 6192A) were installed with thermal grease (Fig. 2.).

2.3. Manufacturing of the test mold by Polyjet technology

An Objet Alaris 30 rapid prototyping machine was used to produce the mold inserts. The Alaris 30 printer uses thin 28 μm layers with a resolution of 600x600x900 dpi. The mold inserts were printed using FullCure720 as build material and FullCure705 as support material. The support material was removed with 5% NaOH solution and similarly to the FDM inserts, threads were drilled and the temperature sensors (KISTLER 6192A) were installed into them (Fig. 2.).

2.4. Materials and process parameters of the injection molding experiments

An Arburg 370S 700-290 Advance injection molding machine with a screw diameter of 30 mm was used for the tests. Injection volume was 44 cm^3, the injection rate was 50 cm^3/s, the switch-over point was 12 cm^3, clamping force was 50 t, the pressure limit was 400 bar and melt temperature was 220°C. Coolant temperature was 20°C in the case of the Polyjet mold insert, while no cooling could be applied with FDM inserts because of their porous structure.

The applied raw material was Acrylonitrile butadiene styrene (ABS) (BASF, Terluran GP-35), which was dried for 4 hours at a temperature of 80°C before processing, as recommended by the manufacturer.

2.5. *Temperature measurement and control systems*

Two different methods were used to control the temperatures of the mold inserts: temperature sensors were built into the insert block, and a thermal camera was used to check the surface temperature of the inserts.

The temperatures in the mold inserts were measured by Kistler 6192A type temperature sensors (Fig. 2.) with a range of 0°C and 450°C and an accuracy of 0.1°C. The sensors were connected to a Mouldrix data acquisition system, which is similar to the Kistler CoMo system.

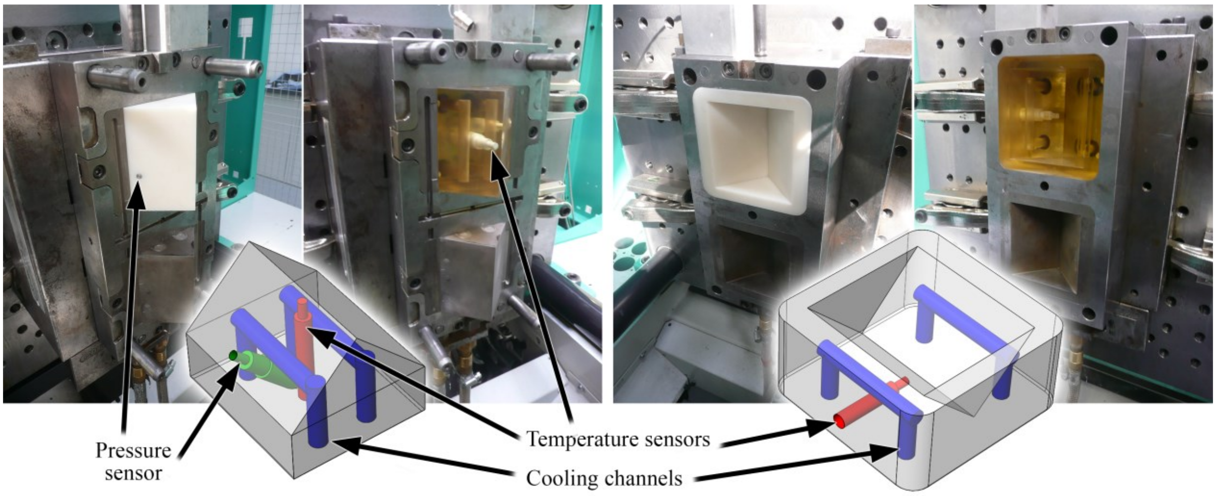


Fig. 2. The Kistler temperature sensor positions in the moving mold inserts (left) and in the stationary mold inserts (right), with the FDM (white) and the Polyjet (yellowish transparent) mold inserts

The temperature of the Polyjet mold surface was measured by a Testo 875 infrared thermal imaging system, and the images were analyzed with Testo IRSoft software. The apparatus has a range -20°C and 280°C and provides an image of temperature distribution in a very short time with an accuracy of 2°C. The emissivity coefficient was set to 0.96.

2.6. *Measurements of thermal conductivity*

The thermal conductivity (TC) of the materials of the prototyped mold material (FullCure720) was measured using the hot plate method [27]. For this purpose, an in-house developed one-specimen hot-plate apparatus was used, presented in previous work [28]. For the measurements, 80x80 mm specimens were printed with thicknesses of 2, 4 and 8 mm. The measurements were performed at 50, 60 and 70°C. The cold side of the apparatus was cooled by four 40x40 mm sized Peltier cells. The hot side was heated with a heating wire. The temperatures were measured by thermistors. To minimize heat loss, the apparatus was thermally insulated with polystyrene foam.

2.7. Measurement of specific heat

The specific heat of the FullCure720 model material was determined with Differential Scanning Calorimetry (DSC) with a Q2000 TA apparatus. The specific heat of the FullCure720 material was analyzed in the range from -10 to 100°C with single heating. The heating rate was 10°C/min and the mass of the sample was 5.78 mg. The thickness of the samples was minimized and the contact area was maximized during measurement to increase accuracy. The samples were printed with the Objet Alaris 30 apparatus with a thickness of 0.5 mm and a diameter of 3.5 mm.

2.8. Simulations for the calculation of thermal parameters

Injection molding simulations were completed with Autodesk Moldflow Insight 2013. 3D Tetra meshes were used for the simulations. The software package also contains a material database, including the BASF Terluran GP-35 type ABS, thus we were able to run simulations with data from the database and use the results in our thermal parameter measurements. In the software a non-steady state flow problem is solved for the cavity filling. The flow process calculation of incompressible melt contains the mass, momentum (in three dimensions) and energy conservation equations. In this method the equations are integrated over a control volume, yielding in a discretized equation in the nodes. The resulting equations are solved using the Algebraic Multi Grid method. The transient heat transfer processes were calculated with the Conduction solver of the software that is based on the Fourier's law. During the filling stage the viscosity of the melt as a function of the shear rate and the temperature was calculated, using the Cross-WLF model. The pressure-specific volume-temperature relationship was determined using the 2-domain Tait equation.

3. Results

3.1. The temperatures of RP inserts

The experiments showed that with the applied sensor positions and cooling layouts the stationary half stabilized faster than the moving half in the case of both inserts. In the experiments, the mold was closed for 2 and 15 minutes (Polyjet insert only) and the mold was not water cooled in the case of either insert. Without any cooling, the FDM inserts resulted in a much slower cycle compared to a steel mold as the temperature stabilized more slowly. When the mold was closed for 15 minutes before ejection, the stationary half did not warm up as much as the moving half and it resulted in a more than 8°C colder insert (Fig. 3.).

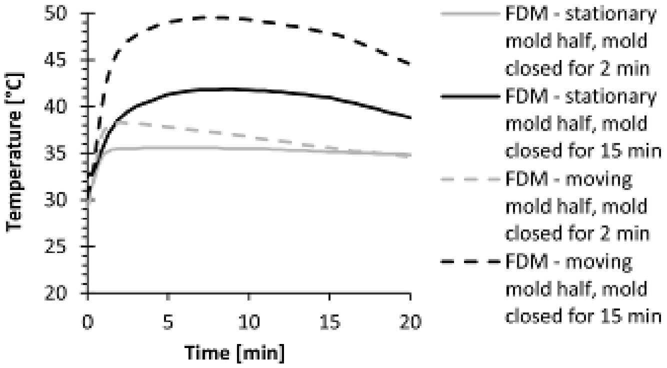


Fig. 3. The temperatures of FDM mold halves shown as a function of time, without cooling. First, the mold was closed for 15 minutes, then the mold was opened after 2 minutes

To increase the productivity of FDM molds and to decrease their heat load, the mold was opened 2 minutes after injection took place. Although much less heat accumulated in the inserts (10°C decrease on the moving part) (Fig. 3.), the part did not solidify as the heat transfer coefficient and the thermal conductivity of the mold were very low. Although the FDM inserts were produced with cooling channels, water cooling could not be applied. FDM products are not suitable for fluid pressure applications due to the porosity of the mold insert. Many papers surface modification, e.g. chemical post-treatment or the infiltration of FDM parts to fill the pores within the part [29]. In addition to environmental and health risks, sealant cost, post-processing costs, possible problems of aesthetics, or, in the case of epoxies, a not negligible change of dimensions also need to be taken into consideration [30].

To increase the efficiency of cooling, pressurized air was blown on the surface of the insert, thus further heat was removed from the mold (Fig. 4.). In spite of this, good parts could not be produced as the ejection temperature of the parts could only have been reached in a much longer time.

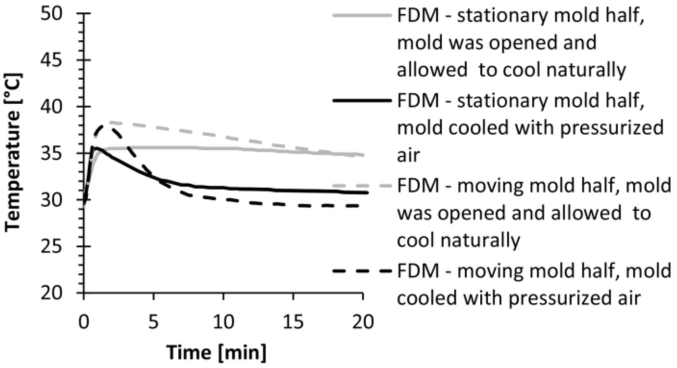


Fig. 4. The temperatures of FDM mold halves shown as a function of time without cooling, with the mold closed for 2 minutes, firstly the mold was opened and allowed to cool naturally, secondly the mold was cooled with pressurized air

It was expected that the Polyjet inserts might offer better quality parts because of their better surface finish and better thermal stability. The insert was suitable for water cooling, as the model was a full-density (non-porous) model as opposed to the FDM models.

Experiments were carried with the mold kept closed for 15 and 2 minutes and with and without water-cooling of the mold. When the mold was closed for 15 minutes, it can be seen that cooling has a strong effect on the temperature distribution in the insert (Fig. 5.). With water cooling, the temperature of the inserts decreases significantly compared to the original cycle without cooling.

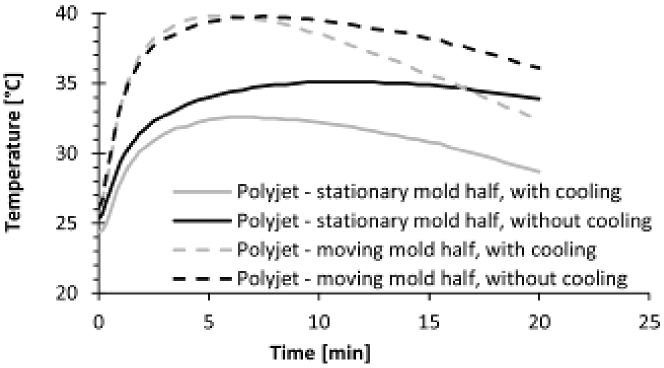


Fig. 5. The temperatures of Polyjet mold halves represented as a function of time, with and without cooling, with the mold kept closed for 15 minutes

Using a shorter period for cooling resulted in less heat dissipated to the insert, thus less heat load generated. Excessive heat load may destroy the insert itself (Fig. 6.).

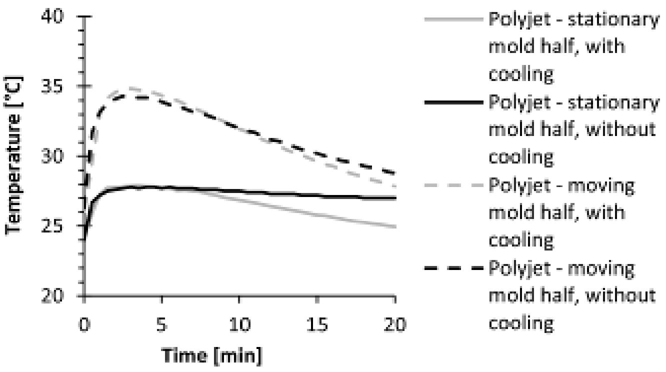


Fig. 6. The temperatures of Polyjet mold halves shown as a function of time, with and without cooling, with the mold closed for 2 minutes

It can be concluded that cooling time – while the mold is closed – can be optimized (minimized) to produce perfect parts and while heat load on the inserts can also be decreased. As optimization is a time-consuming process, simulations should be used for further optimization.

Not only thermocouples, but also a thermal camera was used for the evaluation of temperature distribution in the Polyjet mold inserts. As can be seen, heat accumulated in the corner area (Fig. 7.), which will cause deformations in the produced thermoplastic part. As the thermal camera images show, the difference of the temperatures could be as high as 10°C between the bottom and the corner area of the insert, while the center and the side show only a minor difference (Fig. 7.).

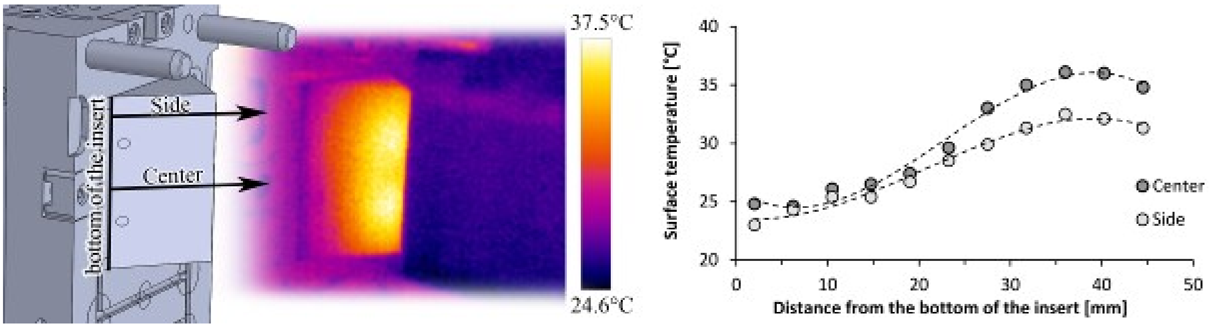


Fig. 7. Thermal camera images of the Polyjet moving mold half surface right after ejection (with the mold closed for 2 minutes, with cooling), and the surface temperature of the Polyjet mold insert shown as a function of the distance from its bottom

In summary, it can be stated that Polyjet has remarkable advantages over FDM technology for rapid tooling applications. The advantages are the surface finish, density and heat removal capability of the models (Fig. 8.).

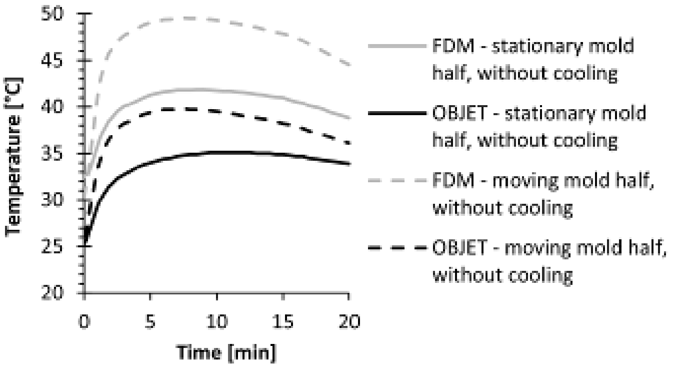


Fig. 8. The comparison of Polyjet and FDM mold inserts (the molds were closed for 15 minutes)

Moreover, as opposed to the FDM technology, good quality parts were produced with Polyjet technology with the mold closed only for two minutes. In this comparison much lower temperatures were measured in the inserts; with a cooling time of 15 minutes, the temperature was 10 and 15°C lower in the stationary and moving mold halves, respectively, than in the FDM halves.

3.2. The thermal parameters for injection molding simulations

The most important characteristics of rapid tool inserts are their thermal parameters as they significantly differ from the thermal parameters of conventional mold insert materials. These parameters have fundamental importance for the accurate simulation and proper development of mold inserts, therefore the thermal conductivity and specific heat of FullCure720 model material were determined.

Thermal conductivity was determined with Fourier's law (Eq. 1.)

$$\lambda = \frac{P}{S} \cdot \frac{L}{T_2 - T_1} \tag{1}$$

where P [W] is the electrical power, S [m^2] is the cross-sectional area and L [m] is the thickness of the specimen. T_1 [K] is the temperature of the cooled side and T_2 [K] is the temperature of the heated side of the sample, which were measured with the one-specimen hot-plate apparatus that we developed.

A series of samples with different thicknesses were used to measure the thermal conductivity of the FullCure720 Polyjet material. The results showed that the average TC is about 0.22 W/mK. It was shown that sample thickness has a minor effect on thermal conductivity but the thicker the sample is, the more precise the results are, which can be proved with the standard deviation of the results. The measured values were used as input parameters in the simulations.

In another series of measurements, 4 and 8 mm thick samples were used to determine thermal conductivity as a function of temperature (Fig. 9.). As can be clearly seen, thermal conductivity doubled as the temperature increased from 50 to 70°C.

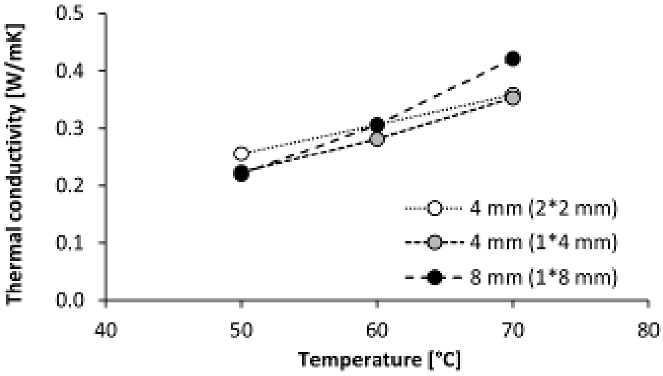


Fig. 9. The results of the thermal conductivity measurements on FullCure720 Polyjet material with different thicknesses, shown as a function of temperature

The other important thermal parameter, specific heat, was obtained with the DSC method. The measured values vary between 1,100 and 1,950 J/kgK depending on the temperature (Fig. 10.). A further observation is that specific heat increased linearly under and above the glass transition temperature (T_g), while the gradients are different.

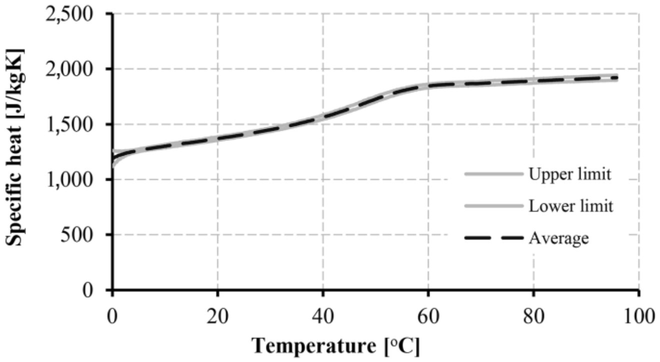


Fig. 10. Specific heat shown as a function of temperature, measured with DSC

3.3. Indirect calculation of thermal parameters with simulation software

The thermal parameters, such as specific heat, heat transfer coefficient and thermal conductivity of the Polyjet material (FullCure 720) were necessary for injection molding simulations. Although some of them had been measured, an indirect calculation method through the simulation software was used to calibrate them. The temperatures of the two mold halves measured in the real injection molding process with thermocouples (Fig. 5.) (with cooling and the mold kept closed for 15 minutes) were used as reference for the simulations.

The temperatures were calculated as a function of time with the simulation software in exactly the same positions as were measured with the thermocouples in the experiments. By varying the input thermal parameters, the time-temperature curves from the simulation software were fitted to the measured curves. With this method specific heat, thermal conductivity and the heat transfer coefficient were determined for further calculations.

In the simulation model – similarly to the real mold – the Polyjet insert was modeled (Fig. 11.). 3D tetrahedral elements have been used for both the parts (~650,000 element with an initial edge length of 1 mm) and for the mold insert (~920,000 element with an initial edge length of 2 mm).

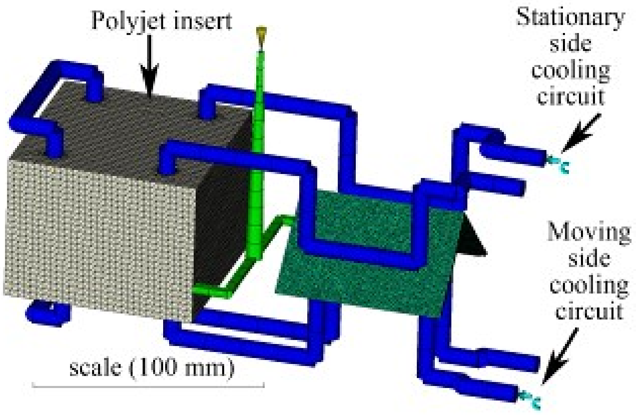
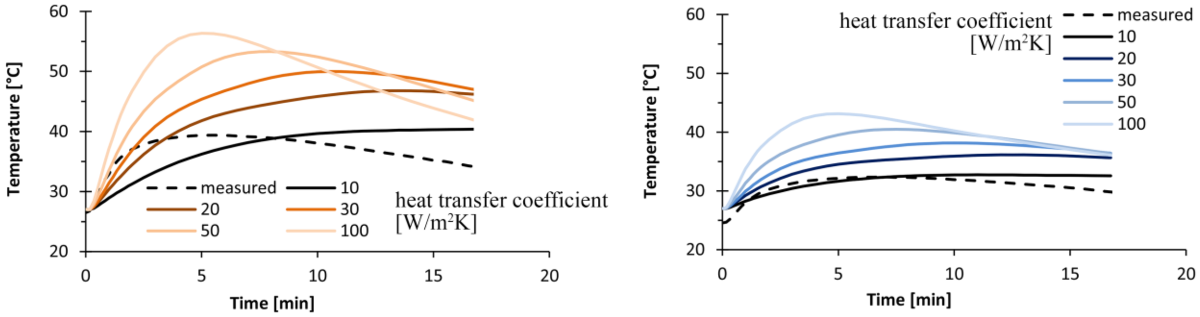
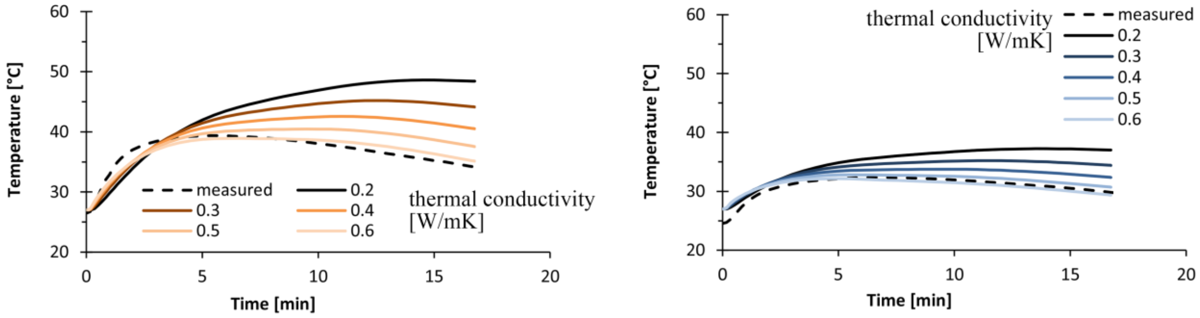


Fig. 11. The simulation model (the cube is the model of the Polyjet insert)

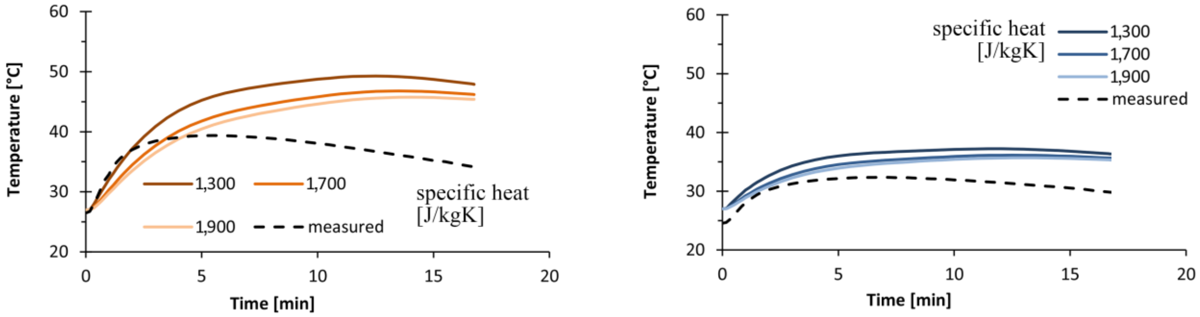
Two series of simulations were carried out using different initial parameters. Based on the first series results, in the second series initial specific heat and the initial heat transfer coefficient in the filling stage were changed to 1,700 J/kgK and 20 W/m^{2}K, respectively. Thermal conductivity was the same (0.25 W/mK). Again, in each simulation series, only one parameter was changed while the two others were fixed. The simulation results were shown in the same graph as the measurements from injection molding (Fig. 12.).



(specific heat: 1,700 J/kgK, thermal conductivity: 0.25 W/mK)



(specific heat: 1,700 J/kgK, heat transfer coefficient: 20 W/m²K)



(thermal conductivity: 0.25 W/mK, heat transfer coefficient: 20 W/m²K)

Fig. 12. Temperature shown as a function of time (with initial parameters of 1,700 J/kgK for specific heat, 0.25 W/mK for thermal conductivity and 20 W/m^{2}K for the estimated heat transfer coefficient in the filling stage; left graphs: moving mold halves, right graphs: stationary mold halves)

The simulation results with the changed parameters in the second series show good correlation with the measured data. Based on the investigations, specific heat varies between 1,300 and 1,900 J/kgK in accordance with DSC measurements. Thermal conductivity is higher than the measured values. Indirect simulation produced values as high as 0.5 to 0.6 W/mK, while the hot plate measurement experiment resulted in around 0.22 W/mK. The higher thermal conductivity obtained from the simulation can be explained by the temperature dependence of thermal conductivity, which was measured and presented earlier in this paper (Fig. 9.). The heat transfer coefficient cannot be measured directly, therefore it was determined using the simulations. The simulations yielded a value of 20 W/m^{2}K, but it could be significantly higher. The heat transfer coefficient is strongly dependent on pressure but the simulation software cannot handle this relationship. The other issue is that the software cannot use temperature-dependent data for specific heat and thermal conductivity for the mold material. This does not cause significant inaccuracy for conventional mold materials, where thermal conductivity is above 20 W/mK and the heat transfer coefficient is higher than 1,000 W/m^{2}K. In the case of rapid tooling materials, however, this simplification may cause significant inaccuracy. The heat transfer coefficient should be pressure-dependent, but the software currently calculates it at three different stages, as it was presented earlier. The first is the filling stage, the second is the holding stage and the last one is the cooling stage, when the part detaches from the mold surface. In the above-mentioned cases, when the heat transfer coefficient is 20 W/m^{2}K, its value typically drops to 10 W/m^{2}K in the holding stage and to 5 W/m^{2}K in the cooling stage.

4. Conclusions

A new method was developed for rapid tool insert tests. With the help of this technique, all types of rapid tooling technology can be tested, including cooling systems. With the application of this method, FDM and Polyjet technologies were studied and the parameters for the simulation programs were determined.

It was concluded that simulation software can be used to determine the thermal and other parameters of rapid tooled mold inserts. A special mold insert was designed and produced by different rapid prototyping methods for comparison. Measurements of the inner and surface temperature of the inserts showed that the Polyjet insert has a remarkable advantage over the FDM insert for rapid tooling applications considering surface finish, the density of the models and their heat removal capability.

The heat transfer coefficient, thermal conductivity and specific heat of the Polyjet material were determined, and the results were verified with hot plate thermal conductivity and DSC-based specific heat measurements. These results can be used for further simulations to make the calculations even more accurate.

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