Thermal analysis based method development for novel rapid tooling applications

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Abstract.

The use of soft molds manufactured by additive manufacturing is gaining popularity in small-series production, thanks to the development of additive technologies and their materials. The thermal properties of soft molds, however, differ considerably from those of conventional, metal molds, and this greatly affects the conditions in the mold during manufacturing. We investigated the thermal properties and cooling conditions of epoxy acrylate-based, directly manufactured soft prototype molds. We used four different mold inserts, two with conformal cooling, one with conventional cooling and one without cooling. We found that due to the poor thermal properties of the mold material, the thermal conditions in the insert with conventional cooling and the insert without cooling were almost identical, this proves that in this case, conventional cooling cannot remove heat effectively. The use of conformal cooling, however, can reduce the cyclic heat load of mold inserts by about 70 %, which increases the lifetime of the mold.

1. Introduction

Thanks to the continuous development of materials plastic parts are used for more and more new applications [1], [2]. Injection molding is the most used technology to produce plastic parts, so it is also continuously developing [3]. Injection molding can also be used to produce small series parts, but it is a complex task to do it efficiently, because conventional, steel molds are costly to manufacture so product costs rise. By additive manufacturing, products can be manufactured cost effectively and low-cost molds can be produced in a short time [4]. However, the mechanical, tribological and thermal properties [5], [6] of the materials used for small series injection molds are several orders of magnitude poorer than those of metals, therefore failure occurs much faster. Worse thermal properties result in an increase in cycle time as heat is concentrated in a volume close to the surface, from where it can only be extracted slowly. The thermal and mechanical properties of molds can be improved with fillers and reinforcements, such as aluminum, carbon nanotubes, glass fiber etc., and improved properties result in shorter cycle times and longer lifespan.

Tomori et al. [6] manufactured small series mold inserts from epoxy filled with SiC particles. They found that adding 40 μm SiC to the epoxy increased the tensile strength and thermal conductivity of epoxy-based mold materials but impaired the surface roughness of the injection-molded parts. Hopkinson and Dickens [7] compared uncooled injection mold inserts made by stereolithography (SLA) to aluminum inserts. The surface temperature of the SLA core reached 100 °C, which is double that of the aluminum insert. The internal and surface temperature of the SLA insert is higher than the heat deflection temperature of the insert material in almost the whole injection cycle, which decreases the mechanical properties considerably. Fused Deposition Modeling (FDM) can also be used for manufacturing prototype molds. The materials used for the process can easily be filled with particles e.g. iron particles, which enhance thermal conductivity and mechanical properties [10]. The modulus of elasticity decreased as filler fraction was increased and particles size decreased but strain at break increased as particle size decreased.

Cyclic thermal and mechanical load can lead to fast mold failure in the case of prototype molds. Rahmati et al. [8] investigated the failure and thermal conditions of epoxy-based molds made by stereolithography. They found that the failure of the mold was most likely caused by the flexural load during the injection molding phase. Flexural stress can cause fatigue fracture in stress concentration points, and in addition, according to Hertzberg et al [9], cracks can start in the polymerization defects of the resin, which can also contribute to the fatigue fracture of the mold. Failure caused by shear stress, however, is not characteristic to small series molds because the shear stress during the injection cycle is considerably lower than the shear strength of the mold.

Based on Kovács et al. [11], it can be stated that the Polyjet technology is more suitable for the production of RT molds than the FDM technology. They also stated that thermal parameters cause considerable uncertainty in the numerical simulation of small series molds because we cannot specify these parameters accurately enough. The parameters that have the greatest influence on thermal calculations are the thermal conductivity of the mold material and the heat transfer coefficient between the melt and the mold. Several papers focus on the development of the materials of small series molds with fillers [12]-[14]. Based on these, it can be stated that the mechanical and thermal properties of the mold material can be improved with the use of various reinforcements and fillers but the thermal conductivity and mechanical properties of these filled and reinforced materials are still a great deal worse than those of metals, which considerably limits the use of these materials as mold materials.

Another way to decrease cycle time and increase the lifetime of the mold is cooling. In the case of small series molds, however, it is not clear yet how much cooling circuits can improve the quality of parts and mold lifetime because it is not fully known how much heat can be removed with cooling circuits, due to the poor thermal conductivity of the mold material. The longest phase of injection molding is cooling, which greatly influences the quality of the injection-molded part as well. Molds or mold inserts manufactured with additive manufacturing technologies can be made with conformal cooling circuits, which have a more complex geometry than conventional drilled cooling circuits but also have far higher cooling efficiency. This way the quality of the product can be improved and the length of the injection molding cycle can be reduced. According to Michaeli and Schönfeld [15], the use of conformal cooling improves cooling efficiency less in the case of cylindrical mold inserts than in the case of angular inserts. They stated that conformal cooling offers considerable advantages compared to conventional cooling systems in the case of cold-water cooling and complex geometry products. Wang et al. used numerical methods to examine conformal cooling systems using the centroidal Voronoi tessellation [16] and boundary-distance map [17] procedures. They performed calculations on parts of complex geometries. The cooling system generated with Voronoi tessellation resulted in a 26% decrease in cooling time and a 47% decrease in the maximum temperature of the mold insert, compared to conventional cooling. It has to be noted that the authors used beam elements for the flow investigations. However, flow conditions at branches cannot be determined with beam elements. The boundary-distance map procedure yields a further 10% reduction in temperature compared to the Voronoi method. Ilyas et al. [18] found that the use of conformal cooling resulted in a nearly 25% increase in productivity and an 11% saving in energy if the part was big or had a complex geometry. Numerous other papers focus on the designing of conformal cooling [19]-[24] and its advantages [25]-[27], and the results are always the same as the above-mentioned findings. Some authors suggested the use of conformal cooling in the case of other technologies, such as extrusion and [28] and metal machining [29], [30].

Our goal is to investigate the thermal conditions of small series resin-based cooled and uncooled mold inserts, with which the advantages and limits of the use of conventional and special cooling circuits can be determined in the case of prototype molds. We paid special attention to how cooling circuits affect the service life of molds.

2. Materials and Methods

In the following sections the thermal differences between resin-based and metal mold inserts, the materials used, and the injection molding technology used are presented.

2.1. Mold and mold insert design

The mold used has two cavities. The temperature of the stationary and the moving side can be controlled separately (Fig. 1/a). The product is made up of two flat 2 mm thick plates at an angle of 90° to each other. On the core side, near the main edge, where the two flat sheets meet, the heat entering with the melt accumulates because of the corner effect. We used mold inserts of four different designs, manufactured with the Polyjet technology. Three of the four inserts were cooled. One of them had conventional drilled cooling channels, and the other two had conformal cooling. The conventional cooling channels (*Conventional insert*) (Fig. 1/a) had a diameter of Ø8 mm. They were 13 mm from the cavity surface on the cavity side and 12 mm from the surface on the core side. The difference between the two conformal cooling circuits is that one has cooling channels perpendicular to the main edge (*Perpendicular insert*) (Fig. 1/b), and the other has cooling channels parallel to the main edge (*Parallel insert*) (Fig. 1/c). In both cases the diameter of the cooling channels is 5 mm, and they are 6.5 mm from the surface an both the cavity and the core side. The fourth insert was not cooled (*Insert without cooling*) (Fig. 1/d).

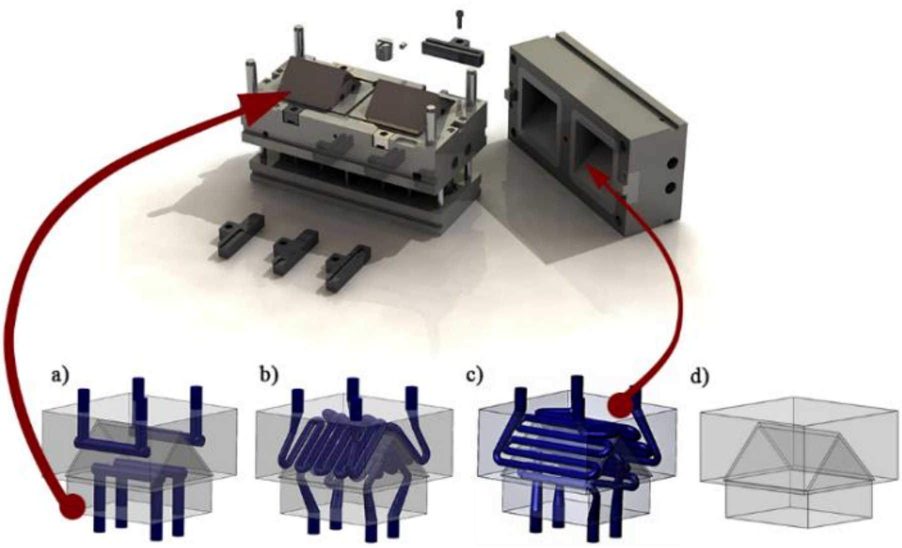


Fig. 1. Mold and cooling circuit designs: conventional (a), perpendicular conformal (b), parallel conformal (c) and without cooling (d)

2.2. Materials used

We used two epoxy-based resins for the inserts: Fullcure 720 (RGD720) and Digital ABS Plus (RGD5160-DM). The two materials have similar properties (Table 1), the biggest difference is that RGD 5160-DM is tougher and its heat deflection temperature (HDT) is higher.

	RGD 720	RGD 5160-DM

Density after polymerization (g/cm^3)	1.18-1.19	1.17-1.18
Tensile strength (MPa)	50-60	55-60
Strain at break (%)	15-25	25-40
Tensile modulus of elasticity (GPa)	2.6-3	2-3
Flexural strength (MPa)	80-110	65-75
Flexural modulus of elasticity (GPa)	2.7-3.3	1.7-2.2
Heat deflection temperature (0,45 MPa) (°C)	45-50	58-68
Glass transition temperature range (°C)	48-50	47-53
Shore hardness (type D) (Scale D)	83-86	85-87

Table 1. The mold materials used in the tests

We used polypropylene (PP) (TIPPLEN H 145 F, MOL Nyrt.) and polylactic acid (PLA) (Ingeo 3100HP, NatureWorks LLC) for the injection molding tests. The two materials are similar concerning processing parameters (Table 2), so thermal loads on the inserts are almost the same during processing.

	TIPPLEN H 145 F (PP)	Ingeo 3100HP (PLA)
Viscosity (200 °C, 4500 1/s) (Pas)	22.5	60
Tensile strength (MPa)	89	112
Tensile elongation (%)	8	3,4
Tensile modulus of elasticity (GPa)	1.75	3.59

Table 2. The PP and PLA used for the tests

2.3. Injection molding parameters

Small series prototype molds require different processing parameters than large series metal molds, due to the worse mechanical and thermal properties of the mold material (Table 3).

Material	PP	PLA
Melt temperature (°C)	200	200
Injection rate (cm^3/s)	15	15
Injection pressure (bar)	500	750
Holding pressure (bar)	300	450
Holding time (s)	20.2	20.2
Residual cooling time (s)	180	180
Delay time (s)	260	260

Table 3. Main injection parameters

The mechanical properties of prototype molds are far worse than those of metals and are also greatly impaired above the glass transition temperature (T_g), therefore injection temperature, mold temperature, flow rate, injection pressure and holding pressure have to be minimized. In addition, a residual cooling time considerably longer than average has to be set and a delay time is necessary between the injection molding cycles (Fig. 2). The long residual cooling time of 180 s ensured that the part cooled below the ejection temperature in the case of each insert. During the delay time of 260 s the temperature of the inserts decreased a further 20-30 °C, which increases the lifetime of the inserts. We calculated delay time to ensure that the plasticized material does not degrade even during the long residence time. The whole cycle time was 477 s.

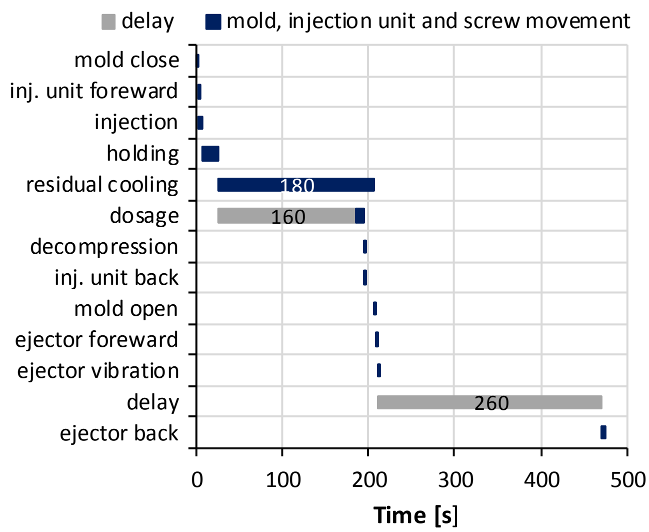


Fig. 2. The injection molding process

The degradation of polymer chains decreases the viscosity of the material, which can be shown better in the case of low shear rates; therefore we checked the degradation of the material with a capillary plastometer. The results (Table 4) showed that the delay time set did not result in considerable degradation in either the PLA or the PP.

	Melt Flow Index (200 °C, 2.16 kg) (g/10 min)		
	0 min residence	5 min residence	30 min residence
PP	19.9±1.8	22.7±0.8	20.9±1.5
PLA	22.3±0.7	25.2±0.8	43.8±1.3

Table 4. Melt flow indices of PP and PLA in the case of various residence times

2.4. Temperature measurement

We measured the volume temperature of the inserts with NiCr-Ni T 190-0 thermocouples and registered the measured values with an Ahlborn Almemo 8990-V6 data logger. The wires used had a diameter of 0.5 mm, a measuring accuracy of 2.5 °C (Class 2), and sampling frequency was set to 3 s. Temperatures were measured in each insert at four points, three of which were in the core side and one in the cavity side (Fig. 3). Two of the three core-side points were 4.2 mm from the main edge and the third was inside the insert, 32.5 mm from the main edge. The thermocouple in the stationary side was 4.2 mm from the cavity surface. After ejection, it was possible to measure the surface temperature of the inserts, which we did with a Flir 325SC thermal imaging camera. Surface temperature was measured on the core side because the main edge (which is critical from the point of view of heat removal) can be found here.

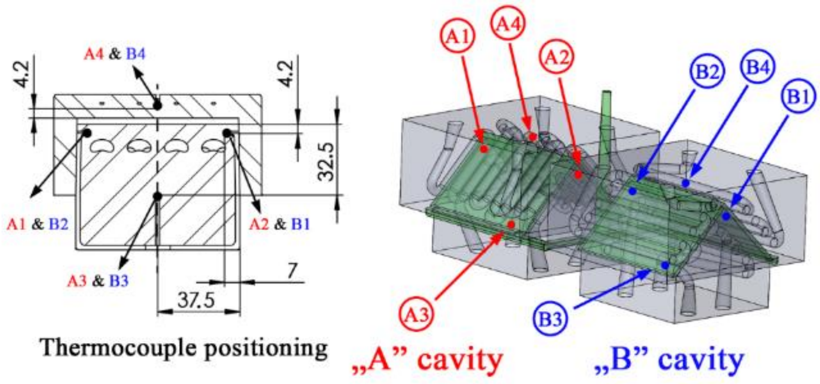


Fig. 3. The location and designation of the thermocouples

3. Results and discussion

In the following sections the measurement results and the conclusions are presented.

Nomenclature			
C_1	mold dependent heat input constant, 1/s	C_2	mold dependent fitting parameter, s
C_3	mold dependent fitting parameter, K/s^2	C_4	mold dependent fitting parameter, K/s
C_5	mold dependent fitting parameter, K/s	C_6	mold dependent cooling constant, 1/s
τ	time, s	τ_0	time when the heat input ends, s
τ_{ej}	ejection time, s	$T(\tau,z)$	location and time dependent temperature, K
T_{ej}	mold temperature at ejection, K	T_{env}	environmental temperature, K
T_{max}	maximal mold temperature, K		

3.1. Volume temperature in a steady state condition

From a thermal point of view, the technology of injection molding starts with injection, which can be modeled well with the relatively fast change of the surface temperature of the mold insert because the melt fills the cavity in 3 seconds. Heat is transmitted to the inside of the insert from its surface via conduction. The temperature of the insert increases in each cycle until a steady state condition is reached, which requires about 10 cycles. We only took into account results measured after the steady state condition was reached (Fig. 4). In each insert, thermocouple B1 and B2 measured the highest temperature. They are in the same position on the core side insert; this is why the temperatures are identical. Thermocouple four (4.2 mm from the cavity surface on the stationary side) measured a temperature more than 30 °C lower in the case of each insert. This is because thermocouple four is in the cavity side insert, where the cooling channels can be made more uniform and closer to the main edge of the insert, therefore cooling is more intensive and uniform. In the case of thermocouple three (deep inside the moving inserts) in cooled inserts (*Parallel*, *Perpendicular* and *Conventional insert*) no temperature change can be observed, the measured temperature is constant and identical with ambient temperature. In the case of the *Insert without cooling*, the temperature of the fourth thermocouple increased to nearly 50 °C during the cycles.

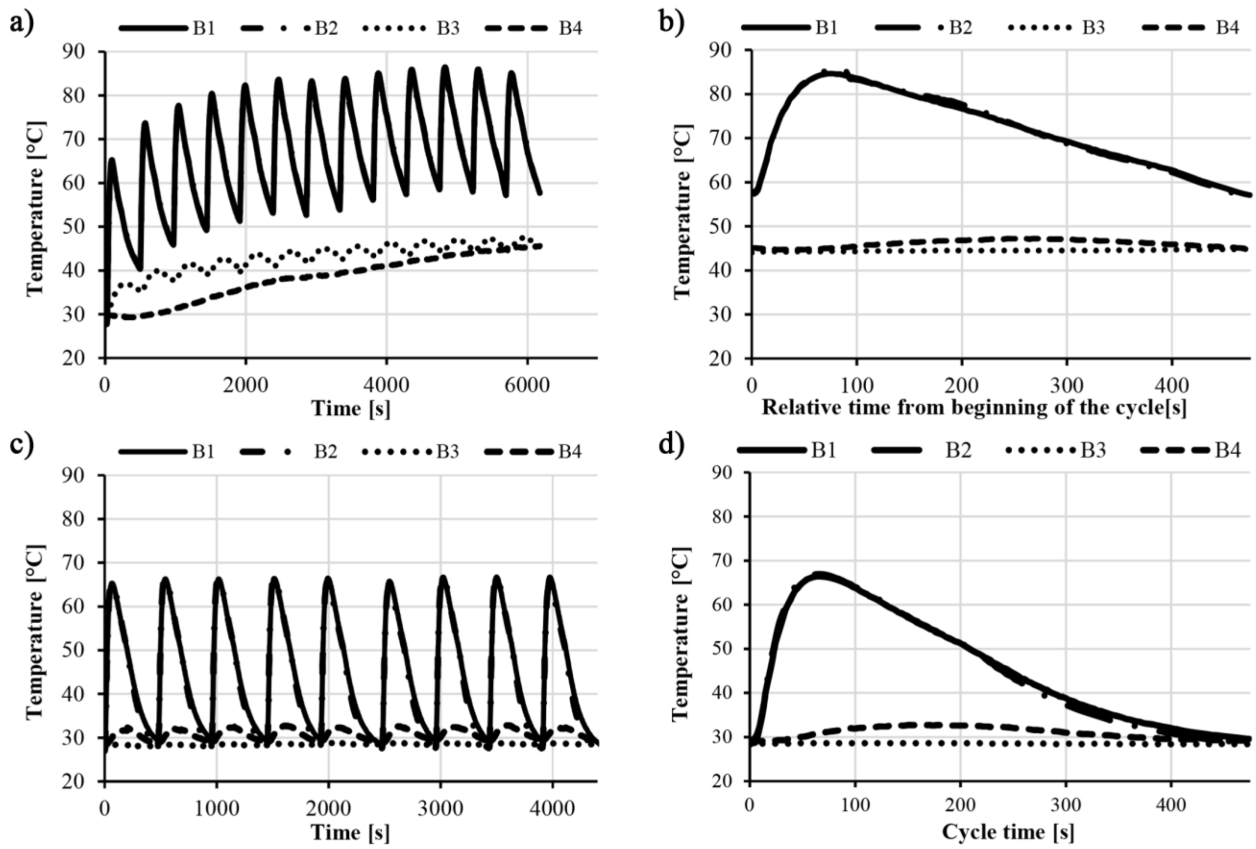


Fig. 4. Temperature curves of the *Parallel insert* (a) and the *Insert without cooling* (c) from the beginning of manufacturing, and the temperature curve in a single cycle in the case of the *Parallel insert* (b) and the *Insert without cooling* (d)

The individual elements of the injection molding cycle can be observed on the volume temperature curves of the inserts, which makes the detailed evaluation of the curves possible (Fig. 5). The curve can be divided into three main parts: the first section of the temperature curve (section I) starts with injection and lasts until the temperature of the whole volume of the melt and the surface of the mold becomes the same. In this section the temperature of the mold increases monotonously until the maximum temperature is reached. After the maximum of the temperature curve is reached, the mold and the melt cool together. Heat extraction in section II is a nearly straight section on the temperature curve, if heat extraction is steady and greater than heat input, heat does not accumulate and the derivative of the heat flux according to time is nearly constant. If heat extraction is inadequate, the heat transmitted to the mold accumulates in the immediate vicinity of the cavity due to the poor heat conductivity of the resin, and the slope of the curve continuously decreases. After mold opening and ejection (section III), the mold can transmit heat to the environment as well, by convection and radiation. As a result of the continuous decrease in the difference of the temperature of the cavity surface and ambient temperature, this heat removal decreases as a function of time.

section I $\quad 0 \le \tau \le \tau_0 \quad T(\tau, z) = \frac{T_{max}(\tau,z)}{1+e^{-C_1(\tau-C_2)}},$ (1)

section II $\quad \tau_0 \le \tau \le \tau_{ej} \quad T(\tau, z) = \frac{T_{max}(\tau,z)}{1+e^{-C_1(\tau-C_2)}} - C_3 \cdot (\tau - \tau_0),$ (2)

section III $\quad \tau_{ej} \le \tau \quad$ with cooling $\quad T(\tau, z) = T_{ej}(z) + \tau \cdot (C_4 \cdot \tau - C_5),$ (3)

no cooling $\quad \mathrm{T}(\tau, z) = T_{env} + (T_{ej}(z) - T_{env}) \cdot e^{C_6 \tau}$ (4)

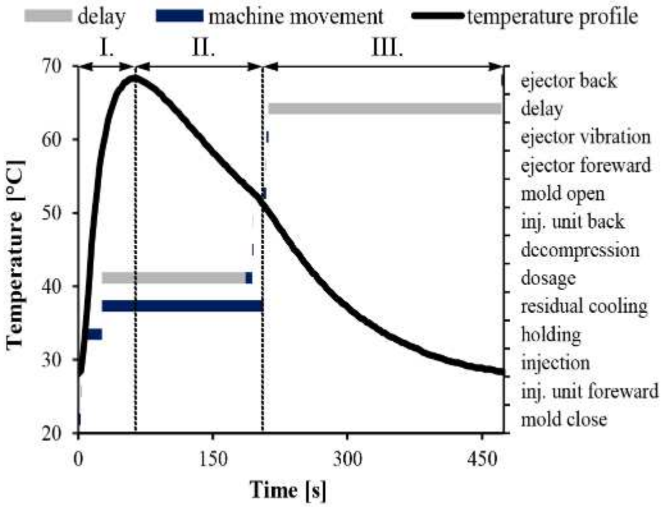


Fig. 5. The volume temperature curve of the mold insert as a function of time during an injection molding cycle

Fig. 6 shows the temperature curves for each mold insert in the case of PLA and PP, in measurement points A2 and B2. Measurement points one and two are closest to the cavity, therefore these measurement points provide the most information about the thermal state of the insert. The two inserts with conformal cooling have the same temperature when the cycle is started, section I is also identical, but when the mold is closed the *Parallel insert* extracts more heat form the melt than the *Perpendicular insert*. The mold opens at 200 seconds, by that time the *Parallel insert* is 5 °C cooler than the *Perpendicular insert*, but this difference is reduced to a negligible amount by the end of the cycle, when the temperature of both inserts is about 30 °C. The maximum temperatures of the *Conventional insert* and the *Insert without cooling* are nearly 25 °C more than the temperature of the inserts with conformal cooling. The temperature curves of the three inserts with cooling are not exponential after mold opening because heat is not only removed by the cooling channels, but by convection and radiation, too.

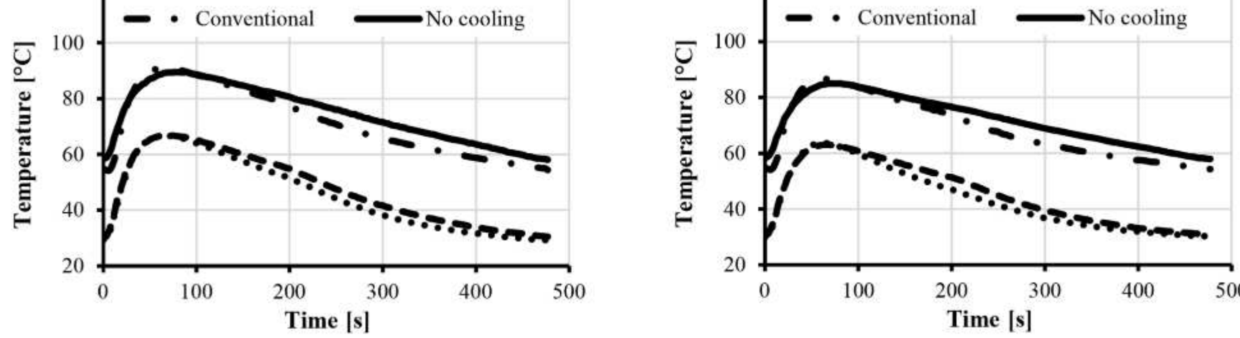


Fig. 6. Temperature curves measured in a steady-state condition in points B2-A2 of the *Parallel*, *Perpendicular* and *Conventional inserts*, and the *Insert without cooling*, in the case of PLA (a) and PP (b)

The temperature of the inserts has to be kept below the glass transition temperature of the mold material because the glass transition temperature affects the applicability of PolyJet mold inserts most, as above the glass transition temperature the mechanical properties of the material are impaired as a function of temperature (Fig. 7). The injected melt puts a considerable shear, flexural and compression load during injection on the surface of the insert, and pins and ribs on it. During the holding phase, the viscosity of the melt increases as a result of heat extraction, the extra melt forced into the cavity forces the higher viscosity melt to move and thus puts further compression and flexural load on the insert. During the injection and holding phases, the mold cavity exerts a pressure of several hundred bar on the mold, which results in a further compression load on the cavity surface. During the residual cooling time, the temperature and pressure of the melt decreases, the material in the mold shrinks considerably, which exerts a compression load on parts standing out from the surface of the cavity. When the mold is opened, removing the part shrunk on the core side exerts a further tensile and flexural load on the insert. These loads can lead to failure quickly as mechanical properties worsen above the glass transition temperature. In the case of *Conventional insert* and the insert *without cooling,* the temperature of the immediate vicinity of the cavity surface of the mold was above the glass transition temperature of the Fullcure 720 and the Digital ABS Plus during the whole injection molding cycle. In the case of the two inserts with conformal cooling, the temperature near the cavity was over the glass transition temperature of the materials for nearly 150 seconds. This is during residual cooling time, when the characteristic load is compression and bending, resulting from the shrinkage of the part. There is a great difference in the maximum temperatures of the inserts; the maximum temperature of the inserts with conformal cooling is 25 °C lower, therefore the storage modulus of the mold is almost an order of magnitude higher, and so it withstands loads better.

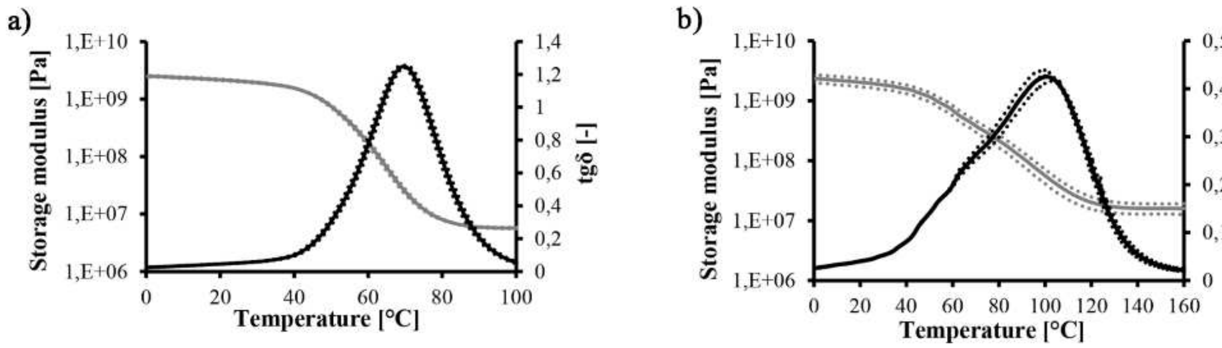


Fig 7. The storage modulus and loss factor of the FullCure 720 (a) and the Digital ABS (b) material, and the corresponding standard deviations as a function of temperature

3.2. Surface temperature

We examined the distribution of surface temperature with a thermal imaging camera, from ejection to mold closing. At ejection, the surface temperature of the inserts with conformal cooling was close to identical (Table 5), 60 °C, while in the case of the *Conventional insert* and the *Insert without cooling*, the maximum surface temperature was above 90 °C.

	Parallel	*Perpendicular*	*Conventional*	*Without cooling*
Maximum surface temperature at ejection (°C)	56	60	91	98
The maximum of the difference of surface temperature at ejection (°C)	11	20	30	35
Maximum surface temperature at mold closing (°C)	29	31.5	62	65.5
The maximum of the difference of surface temperature at mold closing (°C)	1.5	4	27.5	23

Table 5. The surface temperatures of the inserts at ejection and just before mold closing (ejection+260 s)

During the delay time, the inserts cool at approximately the same rate (Fig. 8), only the *Parallel insert* cools a bit faster, thus the delay time could be shorter in the case of the *Parallel insert*. At the end of the cycle, the maximum temperatures of the *Parallel* and *Perpendicular inserts* are about the same.

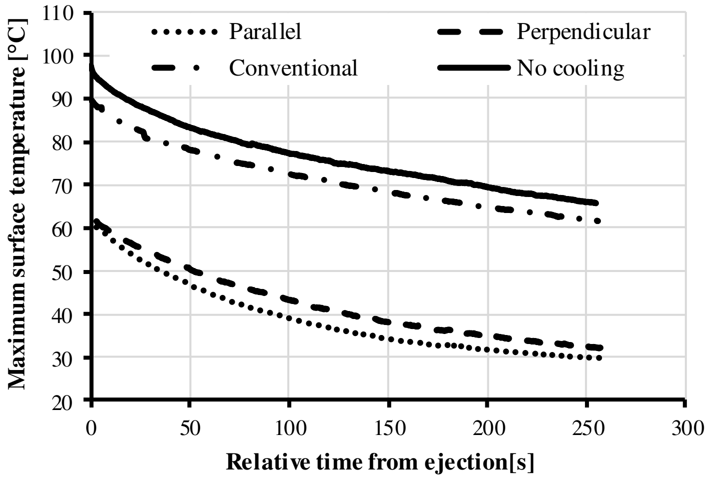
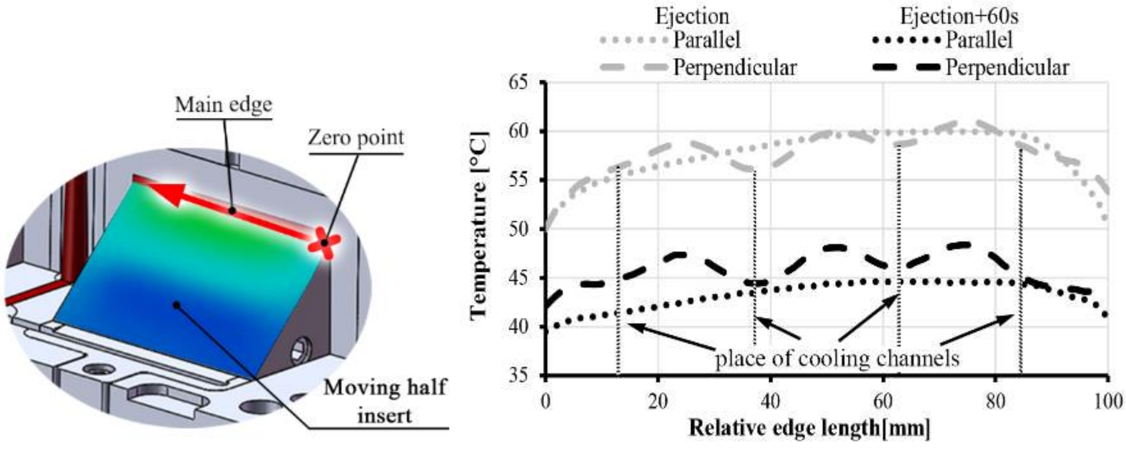


Fig. 8. The surface temperature distribution of the various mold inserts as a function of time

The surface temperature distribution in the case of the *Perpendicular insert* shows the contour of the cooling channels, in spite of the poor thermal conductivity of the materials. (Fig. 9). In the case of the *Perpendicular insert*, heat accumulates near the main edge, from where cooling cannot remove it (Fig. 10).



a) b)

Fig. 9. The main edge used for the evaluation of the surface temperature (a), and the temperature distribution of the *Parallel* and *Perpendicular inserts* measured with the thermal imaging camera along the main edge immediately after ejection and 60 seconds after ejection (b)

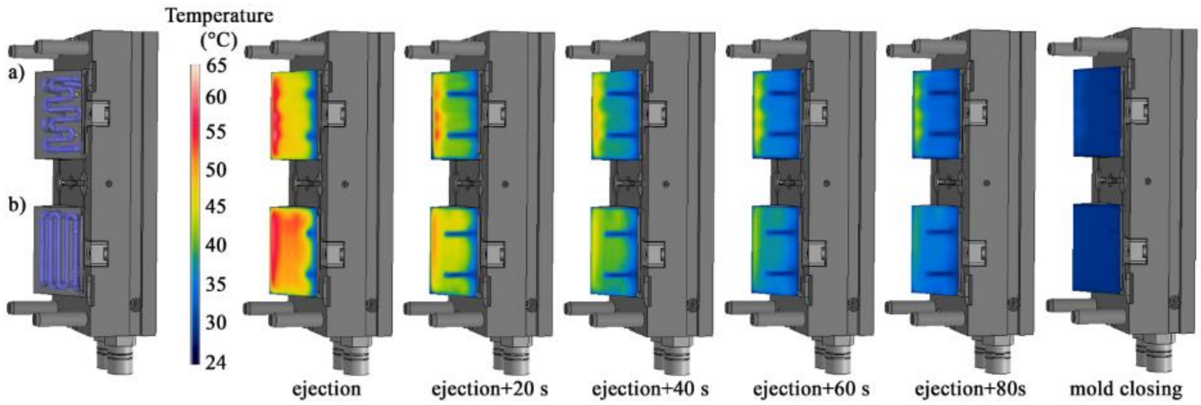


Fig. 10. The temperature distribution measured with infrared camera of the P*erpendicular insert* (a) and the *Parallel insert* (b) as a function of time

The temperature distributions of the *Conventional insert* and the *Insert without cooling* are also identical; the maximum temperature of both inserts is over 90 °C. During the delay time between the two cycles, conventional cooling does not influence the maximum temperature of the insert considerably compared to the *Insert without cooling* (Table 5 and Fig. 8). The temperature distribution of the *Conventional insert* shows (Fig. 11), that in 260 seconds, cooling was able to extract heat from the part of the insert nearer to the mold block; this is the reason for the greater temperature difference at mold closing.

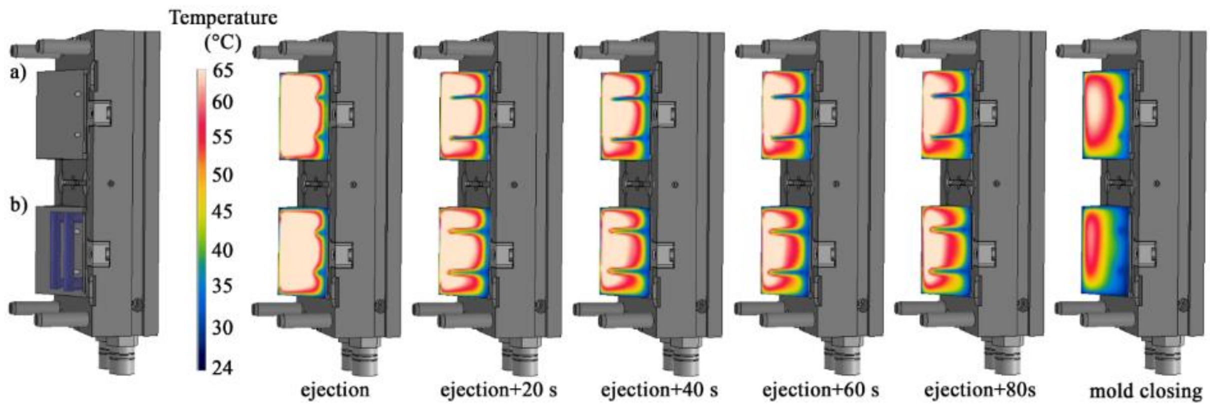


Fig. 11. The surface temperature distribution measured with infrared camera of the *Insert without cooling* (a) and the *Conventional insert* (b) as a function of time

3.3. Measuring cooling efficiency

When measuring cooling efficiency, we set the boundary conditions of the measurement to the same values in the case of each insert, therefore the cooling performance of the inserts can be compared. We chose the *Parallel insert* as reference, so temperature was 30 °C at the beginning and at the end of the injection molding cycle for all inserts. The ejection temperature was set to 47 °C in all cases. The results (Fig. 12) correlate with the results in the steady state condition well; cycle time in the case of the *Perpendicular insert* increases by about 10% compared to the *Parallel insert*. The difference between the *Conventional insert* and the *Insert without cooling* is 15% but they both produce a cycle time increase of nearly 150%. The maximum temperature of the inserts with conformal cooling is a few degrees higher than the maximum temperature of the other two inserts, which is due to the fact that in the case of conformal cooling, the location of the temperature sensor is between the surface and the cooling channels, where, according to Fourier's law, heat flux density is higher due to the higher temperature difference (between the cavity surface and the surface of the cooling channels). Also, the mass of the inserts with conformal cooling is lower than the mass of the other two inserts. In section II, the slope of the temperature curve in the case of the *Conventional insert* and the *Insert without cooling* decreases continuously after 200 s, which means that heat accumulates due to inadequate cooling and the extent of heat removal decreases (Fig. 12/c and d).

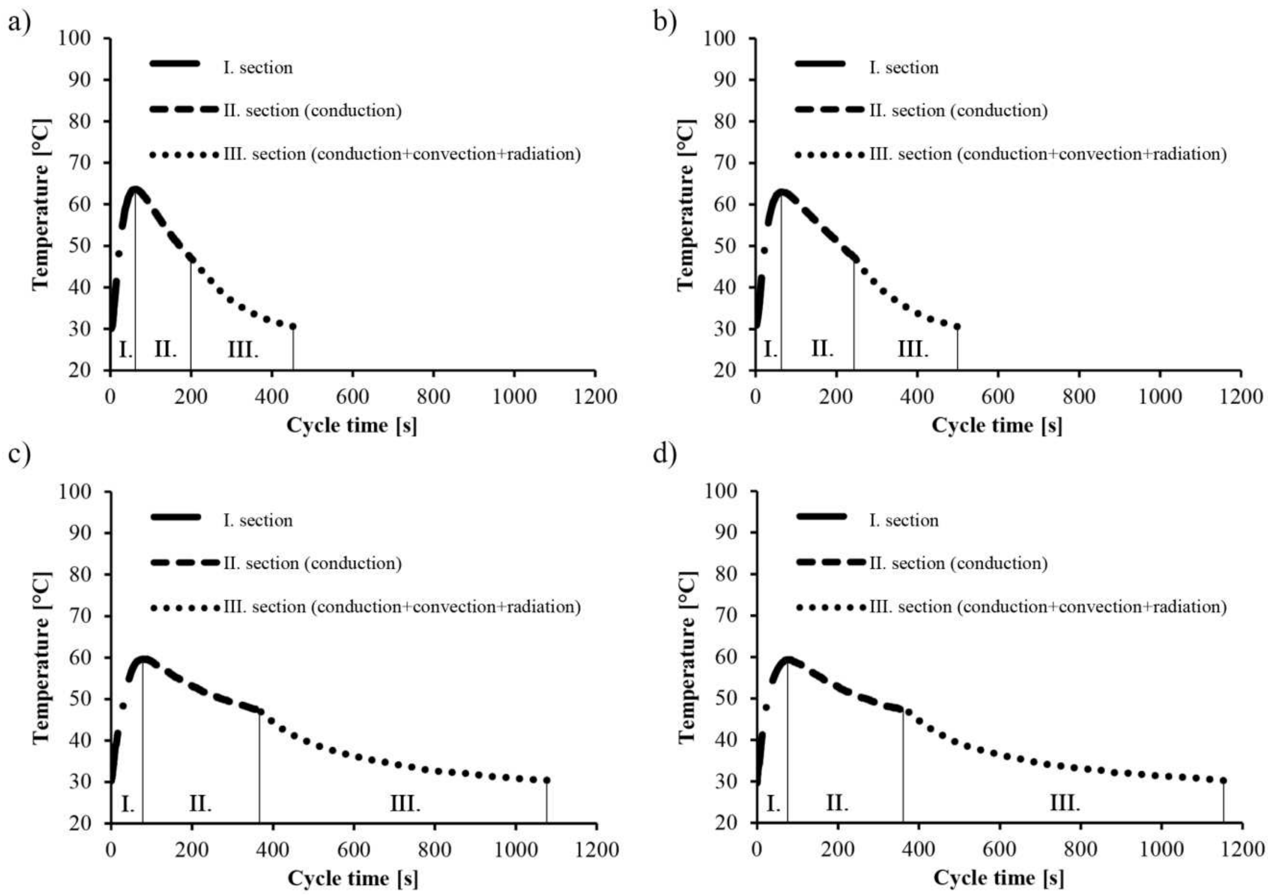


Fig. 12. The temperature curve measured by thermocouple one as a function of cycle time when PP was injection molded, in the case of the *Parallel insert* (a), *Perpendicular insert* (b), *Conventional insert* (c) and *Insert without cooling* (d)

We further evaluated the curves by integrating them. Integrating quantifies the area of the three sections of the temperature curve, therefore they can be compared better; the smaller the area under the curve, the more intensive heat input or heat extraction is. The difference between the two inserts with conformal cooling (Fig. 13) forms in section II, where the melt and the mold cool together with the mold closed. In the case of the *Conventional insert* and the *Insert without cooling,* heat input and heat removal is slower in all three sections. If the sections are added, relative efficiency compared to the *Parallel insert* can be calculated from the whole areas under the curve. Compared to the *Parallel insert*, the efficiency of *Perpendicular insert* is 82.5%, and the efficiencies of the *Conventional insert* and the *Insert without cooling* are similar, 53.9% and 52.7%, respectively.

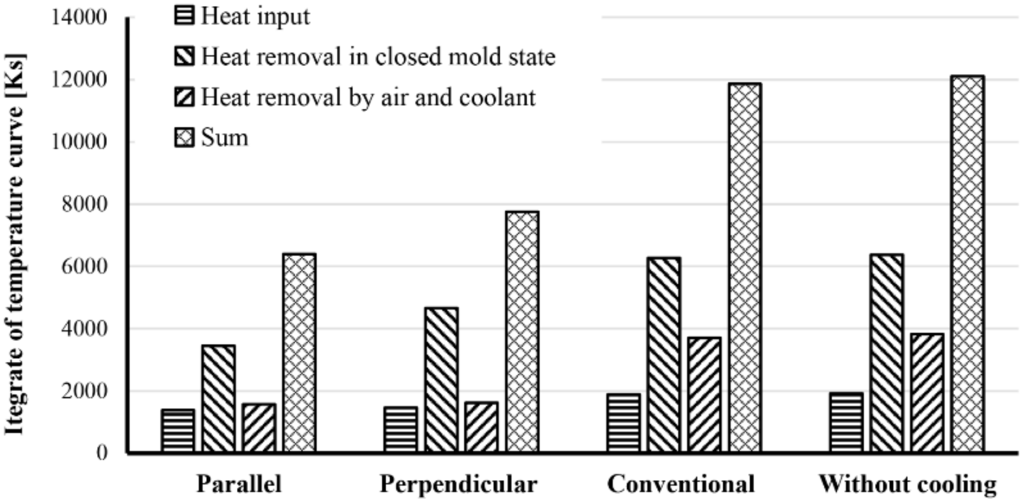


Fig. 13. Areas under the temperature curves in the case of PP, for the *Parallel*, *Perpendicular* and *Conventional insert*, and the *Insert without cooling*

4. Summary

Based on the results, in mold inserts manufactured directly by rapid prototyping, the temperature of the volume immediately next to the cavity surface is higher than the glass transition temperature of the mold material during the whole injection molding cycle in the case of conventional cooling of the insert or no cooling. Conformal cooling reduced the time the surface of the mold inserts was above T_g by 70%. This is during residual cooling time, when the characteristic load is compression and bending, resulting from the shrinkage of the part. It can be stated that in the case of inserts manufactured by rapid prototyping, conventional cooling circuits do not increase cooling efficiency considerably compared to no cooling, therefore the use of conventional cooling in this case is not recommended. The injection molding cycle of prototype molds can be divided into three sections. In the first section, heat input is greater than heat removal, therefore the temperature of the mold increases fast until the temperature of the mold and the temperature of the melt become the same. In the next phase, if cooling efficiency is adequate, heat does not accumulate in the mold and heat removal is close to constant, therefore the given section of the temperature curve is close to linear in the case of mold inserts with conformal cooling. Conventional cooling circuits cannot remove the heat input and the slope of the measured temperature curves decreases. In the first two sections, when the mold is closed, the dominant way of heat transmission is heat transfer between the wall of the mold and the melt, and heat conduction within the mold insert. In the last section, when the mold is open, this is supplemented by convection, but its effect gets smaller and smaller as surface temperature decreases. Of the materials that can be used for the PolyJet technology, RGD525 has the highest glass transition temperature, which is 62-65 °C. With the use of this material, mold inserts with conformal cooling can be manufactured in which the immediate vicinity of the cavity can be kept under the glass transition temperature with higher probability.

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