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Resin molds to improve thermal energy consumption in injection molding process

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Abstract. The injection molding process is one of the most widely used in industry to produce plastic parts. To optimize overall energy consumption, controlling thermal energy is a key factor. This can be achieved through smart modifications to the mold design. In this study, two molds made from different materials are compared, focusing on thermal analysis using numerical models. Examined materials for the mold base parts are mold steel and High Temp Resin (Formlabs), while an insert made in steel is used for both cases. The aim is to optimize the thermal energy management inside the mold. The software used is COMSOL Multiphysics for thermal characterization to evaluate thermal behaviour within the mold. Numerical models are calibrated by experimental testing. The results demonstrated that the resin's capacity to retain heat within the steel insert is superior, requiring less thermal energy to maintain the desired temperature and for thermal transients.

Introduction

Injection molding is the most widely used process for high-volume plastic product manufacturing due to its versatility in accommodating various materials and product geometries [1]. Considering all process phases, thermal energy plays a critical role, directly influencing efficiency, product quality, and cost-effectiveness. A global assessment of energy consumption in injection molding reveals that total cycle time is the primary factor affecting overall energy use, with cooling time representing the most significant component [2,3]. Therefore, reducing cooling time leads to a reduction of cycle time and energy consumption. Although the highest power peaks occur during the filling stage, extended cooling times can make cooling phase a significant energy consumer [4]. It becomes central to manage cooling phase in proper mode to reduce energy consumption. A key strategy to this purpose is to optimize the thermal energy distribution within the mold.

Mold design has to take into account this aspect considering geometry, material and channel layout. Traditionally, cooling channels are created by drilling several straight holes within the mold core and cavity. This approach results in variable distances between the cooling channels and mold cavity, leading to non-uniform heat extraction from the cooler.

To address this limitation, it is possible to apply localized cooling by using mold inserts with conformal cooling lines, made using additive manufacturing technologies [5,6]. These technologies are economically sustainable when used in a "hybrid construction" approach,

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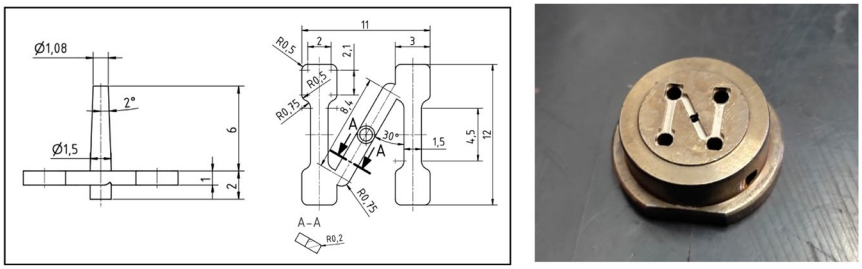
combining conventionally pre-manufactured base workpieces, as a build platform, with additively generated functional geometries of minimized volume [7,8].

Alongside cooling system design, the thermal conductivity of the mold is one of the primary factors influencing the thermal energy behavior. Typically, high-strength steels are used for mold and mold insert fabrication. With the advent of additive manufacturing (AM), different scenarios are now available [9-11]. Among these, the state-of-the-art presents several studies of soft mold inserts (or plates) with cavities made of polymers or composites via AM technologies, but maintaining a conventional steel mold base to guarantee the required mechanical stiffness and strength [11–14]. Leveraging previous results, in this work the research approach is inverted. Assuming the limitations of polymers and composites for mold inserts with cavities, it is possible to conceive a new structure of mold with steel mold inserts and polymeric/composite mold base components (i.e., support plates). These hybrid molds limit the possible drawbacks of thermal and mechanical weaknesses, by exploiting, instead, advantages from the material properties of polymers and composites (i.e., lightweight and thermal insulation). This is an original approach since no previous works were found in the literature. Maintaining a steel mold core with the cavity made by AM technologies allows us to achieve the advantages of conformal cooling and reduced cycle times without limitations compared to conventional steel molds. At the same time, polymeric/composite mold base components change the thermal behavior of the mold and the process, since they do not participate in thermal conduction and heat transfer. Finally, the use of polymer and composite for mold components allows to design of lightweight molds with additional advantages in terms of mechanical energy committed for mold motion (close/open) during the production and in the turnover phases. This approach enables the conception of a more sustainable injection molding process.

In this context, this study aims to test a new mold design by using unconventional materials to optimize thermal energy commitment. The experimental campaign was conducted with a micro-injection molding press by designing and testing hybrid molds consisting of polymeric bases and steel inserts. The comparison with the conventional fully steel system allowed us to preliminary indagate the heat transfer regimes, the thermal transients' evolution as well as the benefits in the use of proposed hybrid solution. For transient numerical analysis, the simulation software COMSOL Multiphysics has been used to model the heat exchanges during the entire injection molding process and then evaluate thermal behaviour inside the mold. COMSOL software is based on finite element method (FEM), used often as a tool to analyze complex multi-physics processes [15,16]. Experimental-numerical comparison was performed to calibrate the numerical model and ensure the numerical approach's goodness as a powerful tool to optimize and reduce the design phase of the mold systems and the entire process.

Experimental procedure

The aim of the experimental activity is to acquire thermal transient data on the molds (traditional and innovative), such as mold temperature variations during the injection molding cycles, from transient to steady state regime. The tested specimen was a mini dog bone tensile sample with a part thickness of 1 mm, length of 12 mm, and width of 1.5 mm in the narrow region and 3 mm in the larger one (Figure 1) [17]. The overall molded mass is about 78mg, comprehensive of sprue, cold runner channels and cavities.



(a) (b)

Figure 1 Specimen design (a) [17] and mold insert, ejection side (b)

Each mold side (injection and ejection) is composed of a mold plate and a mold insert. Mold inserts were fabricated in X33CrS16 steel (Werkstoff nr.1.2085) with traditional cutting (milling and grinding) technologies. By maintaining the same steel inserts, traditional steel mold (TM) and hybrid steel - resin mold (HM) were tested (Figure 2). In TM, mold plates were realized as mold inserts, (i.e., same material and manufacturing technologies). In HM, mold plates were fabricated of photopolymer (Formlabs High-Temp V02) specifically engineered for high-temperature applications via Stereolithography (SLA). The polymer mold plates were designed with a bulk structure in close proximity to bushes and columns required for guiding and alignment of the mold parts and a hexagonal lattice structure in low-stress regions. A Formlabs Form3 machine was used for the mold plates fabrication, by setting the following process parameters: layer thickness of 25µm, part orientation flat on the build platform (XY plane) on base and supports, support density of 1, support attach size of 0.6mm, base thickness of 2mm, part distance from the base of 5mm. Part post-processing consisted of three phases: 1) washing in high purity (99%) isopropyl alcohol (IPA) for 20 minutes; 2) UV-curing in a Formlabs Cure machine for 120 minutes at 80°C; 3) Annealing for 180 minutes at 160°C. Postprocessing operations 2 and 3 allow to achieve an increase in the mechanical properties of the part. Particularly, the annealing allows for reaching a heat deflection temperature of 238°C (HDT at 0.45 MPa, ASTM D648-16), which is a relevant parameter to guarantee the required mechanical performance (stiffness and stability) at the temperatures of injection molding.

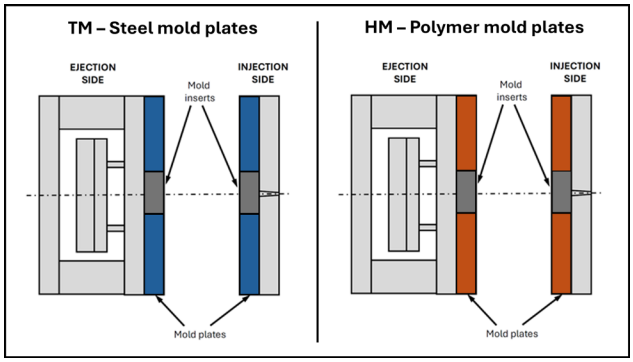


Figure 2 Schematic section of two setups: TM with steel mold plates; HM with polymer mold plates.

Molds are mounted on the injection molding machine Formica Plast 1K by DesmaTec, available in the CNR-STIIMA Lab (maximum injected volume 150 mm^3, maximum injection pressure 300 MPa and maximum injection rate 3.5 cm^3/s).

The polymer used for injection was Polyoxymethylene (POM, Ultraform N2320 003, BASF Engineering Plastics), due to his diffusion for mechanical parts manufacturing, without using coolant during the cooling stage, to analyse the mold's thermal transitory and demonstrate the

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feasibility of polymer molds to store the heat committed during the process. Indeed, in the context of sustainable injection molding process, this heat energy can be subsequently extracted with efficient cooling systems of the mold core, thus without heat dispersion into the environment. Process conditions are reported in Table 1.

Table 1 Process parameters settings.

Symbol	Description	Units	Value
T_m	Melt Temperature	°C	230
T_{mo}	Mold Temperature (ambient)	°C	18
V_{inj}	Injection speed	mm/s	150
t_f	Filling Time	s	0.4
t_h	Holding time	s	4
P_h	Holding Pressure	bar	500
S	Piston stroke	mm	10
t_c	Average total cycle time (without coolant)	s	12

The machine has been equipped with sensors to acquire temperature information. The system was designed to acquire the values from two K-types thermocouples every 400ms, thus with a sampling frequency of 2.5 Hz. This enabled a temperature acquisition inside the molding cycle. In detail, thermocouples named T1 and T2 were placed into the holes made in the movable and fixed insert, respectively, which were close to the mold cavity. Data were acquired for 134 cycle, starting from cold mold at room temperature up to the steady-state temperature. This survey permitted to acquire data during heating process of molds for each setup.

Numerical Modeling

The experimental data were used to calibrate the boundary conditions applied in the process simulations for both TM and HM. Consistent with the experimental configuration all process parameters, excluding the mold material properties, were identical for both TM and HM. Numerical simulations were conducted using COMSOL Multiphysics 6.1. To reduce computational time, the 3D model of mold block used for the simulation was simplified compared to the original one. In detail, the injection and the extractor units were modeled as plates, to consider the heat exchanges with the injector and the extractor systems. The complete simulation model, as implemented in COMSOL Multiphysics, is illustrated in Figure 3.

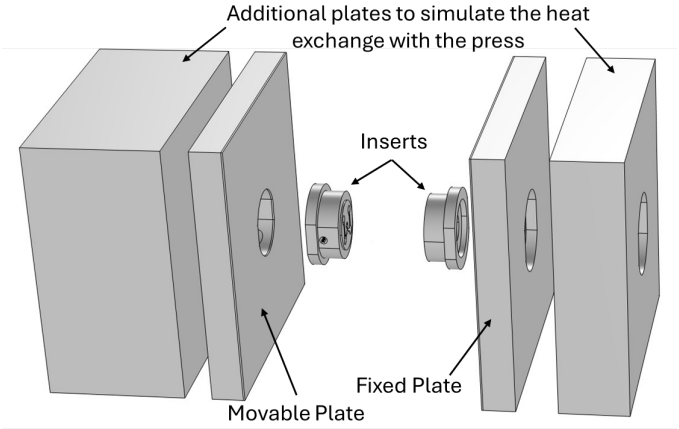


Figure 3 Model used in COMSOL Multiphysics

After importing modified 3D model inside the software all the boundaries were set as shown in Figure 4, considering the injection process dynamics.

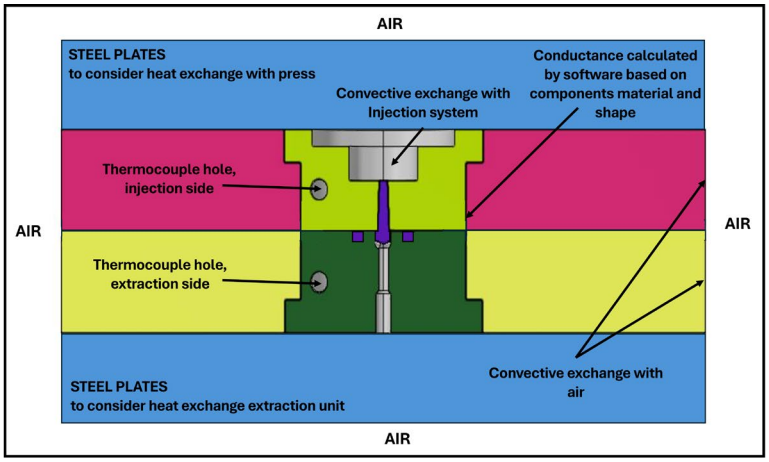


Figure 4 Boundaries setted in COMSOL Multiphysics

Since the model was focused on predicting the thermal field during the process, to strongly reduce the computational time, the fluid dynamic of the injection was simplified with a variable heat source, which increased the POM temperature within the cavity during the filling stage. In addition to heat exchange with air, two boundary conditions were calibrated: the heat exchange with the injector and the heat exchange with the extractors. In this way, the numerical prediction can be accurate at reduced computational time, by avoiding modeling the press in all its complexity. Injection molding process time parameters, such as holding time, filling time, and cooling time (without coolant), were managed within COMSOL by events interface module to replicate the actual experimental process evolution. Three-dimensional mesh consisting of 406.670 tetrahedral elements (maximum element size of 1 mm for cavities and insert, 5 mm for other components), ensuring accurate representation of the geometry. Process parameters used are reported in Table 2, while Table 3 reports material properties taken from material datasheets.

Table 2 Process parameters and boundary conditions set within the numerical model.

Process parameters	**Units**	**Value**
Melt temperature	°C	230
Filling time	s	0.4
Holding time	s	4
Cooling time (no coolant)	s	4
Mold open/close time	s	3.6
Initial molds temperature	°C	18
Air (ambient) temperature	°C	18
Injector temperature	°C	200
HTC with air	$W/(m^2 * K)$	15
HTC with injector	$W/(m^2 * K)$	500 (filling+holding), 150 (cooling)
HTC with extractors	$W/(m^2 * K)$	Linear decrease from 500 to 100 in 500s

Table 3 Material properties implemented within the numerical model

Material properties	**Units**	**POM**	**X33CrS16 Stainless steel**	**High-Temp resin V02**
Density	g/cm^3	1.4	7.8	1.3
Thermal conductivity	W/(m*K)	0.14	17	0.31
Heat capacity at constant pressure	J/(kg*K)	f(T), 2137 at 230°	460	2900

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Results and Discussion

Data acquired during the experimental campaign were compared to results from numerical simulation. As a remarkable result, the hybrid system was not damaged during the whole campaign of 134 cycles, confirming its reliability in terms of mechanical resistance. The numerical-experimental comparison has been made based on thermocouples within the inserts, considering an overall molding time of 1600s, as reported in Figure 5.

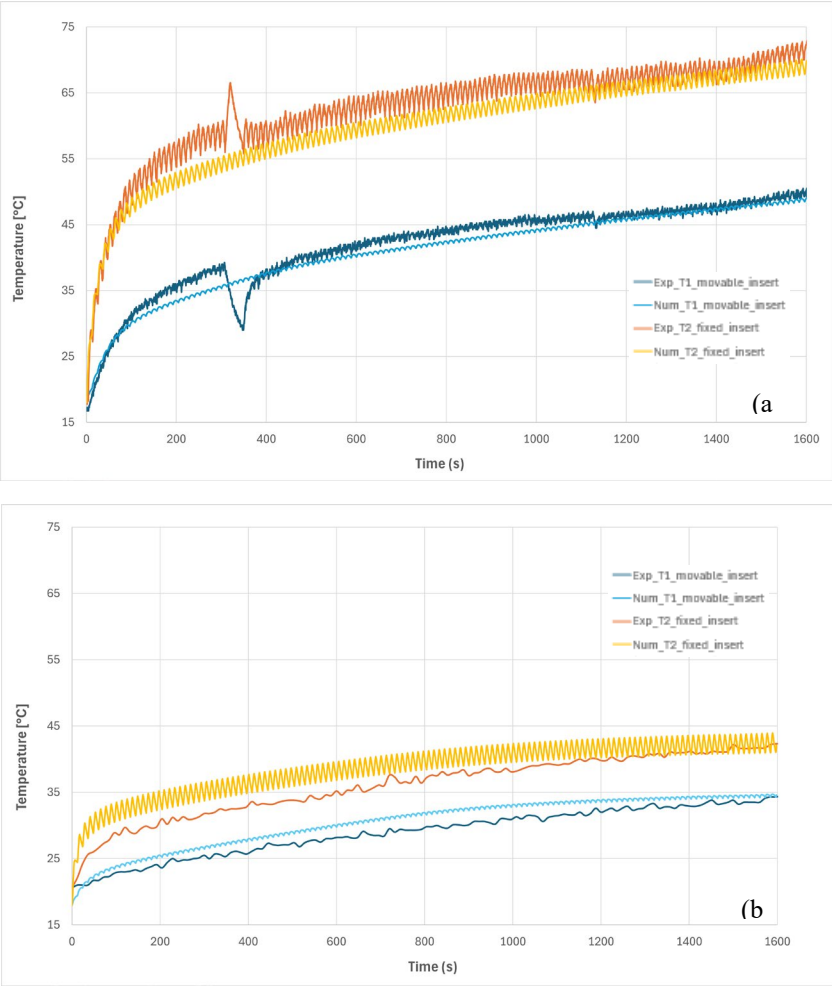


Figure 5 Experimental-numerical comparison of temperature transients acquired by the thermocouples located within the mold inserts, (a) HM, polymer mold plates (b) TM, steel mold plates

It is worth noting that the temperature spike with the subsequent stabilizing transient that occurred on the HM about at time t=300s was due to a part ejection failure, which required the operator's intervention to manually remove the part from the mold cavity. This perturbation was not simulated with the numerical model. The ripple of measurements is due to actual temperature oscillations during the mold opening/closing phases, when the molded part is ejected. Indeed, data temperatures are acquired with a sampling frequency of 2.5 Hz (i.e., one measure every 0.4s), while the part ejection phase requires 3.6 seconds. Therefore, the data acquisition system is capable of acquiring the cooling transients during the opening/closing phase.

Despite the model simplification, the calibration of the simulations was good, thus demonstrating the potentiality of numerical tools in terms of thermal field prediction. At steady-state condition the numerical-experimental error is under 1% for steel plates and under 4,5% for

resin plates. This error can be reduced performing a thermal characterization of used resin, to refine model calibration. The graphs reported above evidence how in both setup the injection side is typically warmer than the ejection side. Moreover, the thermal transient phase of the mold core on the hybrid innovative solution was much faster than the traditional steel mold. This is due to the lower conductive mass and to thermal insulation of the hybrid mold.

Comparing the internal temperatures HM always presented higher values, with an average difference on injection side of 30°C respect TM. The temperature difference between the injection and ejection sides was about 20°C in the HM and about 5°C in the traditional one. HM acted, indeed, as insulating support for the steel insert, resulting in higher core temperatures and thermal sensitivity but lower thermal energy dispersion. The thermal transient of internal components of the TM was characterized by a fast exponential rise followed by a quasi-linear trend, while in the HM, only the linear trend was present. The slopes of the linear trend were almost equal (i.e., about 2-3°C/200s). In continuous long-term molding, the regime temperatures tend to stabilize at higher temperatures in HM due to its low thermal inertia.

Summary

This work indagated an innovative mold design for injection molding process to optimize thermal energy consumption. The designed mold was composed by a steel insert with conformal cooling channel and a base plate realized with high temperature resin. This hybrid mold has been tasted on a micro-injection machine, without cooling activation. The same tests were done using a classical steel plate in substitution of the polymeric one, to compare behaviours.

The experimental results evidenced the potentiality of polymer molds in terms of heat accumulation and fast thermal transients. Indeed, due to the low thermal conductivity of polymer plates, the inserts were better isolated from external heat exchanges: their temperature is higher by more than 50% with respect to the configuration with steel plates (maximum insert temperature 73°C vs 42°C). The thermal conductive mass reduction on the mold promoted faster and more efficient cooling, also in consideration of the implementation of conformal cooling.

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