ORIGINAL ARTICLE

Finite element cooling simulations of conformal cooling hybrid injection molding tools manufactured by selective laser melting

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Abstract

This paper presents an application of additive manufacturing (AM) technology that is suitable for manufacturing injection molding tools with conformal cooling channels to increase productivity. The design and the manufacturing of a hybrid injection molding insert by combining machining and selective laser melting (SLM) technologies was analyzed. A simplified finite element cooling analysis was used to compare conventional and hybrid solutions for the design of cooling channels to decrease the injection cycle time of an automotive plastic part. The simulation results showed that, by using a hybrid steel/high-conductivity copper alloy with conventional cooling for the design of the mold insert, the injection cycle time can be reduced by 50.3%, and by using hybrid steel/steel with conformal cooling, the injection cycle time can be reduced by 65.6%. The hybrid injection molding insert with conformal cooling made by selective laser melting (SLM) technology was successfully tested under real production conditions confirming the significant reduction of the injection cycle time.

Keywords Selective laser melting (SLM) · Additive manufacturing (AM) · Finite element simulation · Conformal cooling · Injection molding

1 Introduction

Injection molding is the most common modern method of manufacturing plastic parts by injecting molten thermoplastic polymers into a mold. The injection molding cycle consists of injection, packing, cooling, and ejection phases. The cooling stage takes up to 50 to 70% of the total time in injection molding process [1]. This cooling duration is dramatically reduced by the use of cooling line–circulating water or oil from an external temperature controller. The standard method of cooling is passing a coolant through a series of holes drilled through the mold plates and connected by hoses to form a continuous pathway. However, only linear and cylindrical channels can be manufactured. Thus, a nonhomogeneous heat transfer occurs in most of cases, leading to the alteration

of the process and the final product [2]. The emergence of additive manufacturing systems offered mold designers a new way to tackle the problems related to the cooling system design. Effective cooling has been proved by using conformal cooling system [3–5]. The additive manufacturing technology such as the selective laser melting (SLM) allowed the manufacture of complex conformal cooling channels that follow the free-form geometry inside the mold. There are no established rules for conformal cooling design [2]. Wang et al. [6] proposed an algorithm to design series spiral cooling pattern for high-curved surfaces. Marques et al. [7] obtained better results for series circuit conformal cooling than the parallel one. Marin et al. [8] showed that a combination of both patterns can reach better results. Kuo and Xu [9] highly recommend the series conformal cooling channel as a solution to enhance the productivity of a new product in the injection molding process. Dang and Park [10] proposed the design optimization process in order to obtain an optimal cooling channels' configuration and target mold temperature by combining different methods: analytical method, design of experiment with 2D simulation, and 3D CAE simulation. Mazur et al. [11] evaluated mechanical properties of a conformally cooled H13 steel

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injection mold manufactured with SLM and used commercial injection molding numerical simulation software to predict mold temperature and plastic part warpage. However, because of the high costs of additive manufacturing [12], a hybrid approach can be used to reduce these costs. This technique combines additive manufacturing and computer numerical control (CNC) machining technologies [13, 14].

This work addresses this issue by constructing and analyzing a conformal cooling injection mold insert produced by hybrid manufacturing for an automotive industrial plastic part. Cooling simulations have been performed, comparing conventional and proposed cooling methodology. For the design of the initial mold, a complete rheological study was carried out using CAE simulation (SolidWorks Plastics Premium software) before the mold was made by a mold maker; this study is not presented in this paper. The initial mold design included a steel insert with machined cooling channels around the rectangular base of the insert leading to high injection cycle time. The CAE simulation showed that the hot spots are located in the insert whose cooling was not optimal. Part production started while waiting for a more efficient solution. The cycle time was experimentally verified, and the produced parts complied with the specifications of the automotive manufacturer. However, the cycle time has a high impact on the final cost of the part. Instead of repeating the full rheological study, we propose a simple and fast method by focusing only on heat exchanges around the insert.

2 Materials and methods

In the injection molding of plastic pedal system for vehicles (Fig. 1), a mold tool insert is designed around a hot runner system with a cylindrical plug (Fig. 2). Due to limitations of machining processes, the cooling channels have to be straight. Besides the cooling problem, the tool insert is sensitive to wear caused by the injected material that is a general purpose,
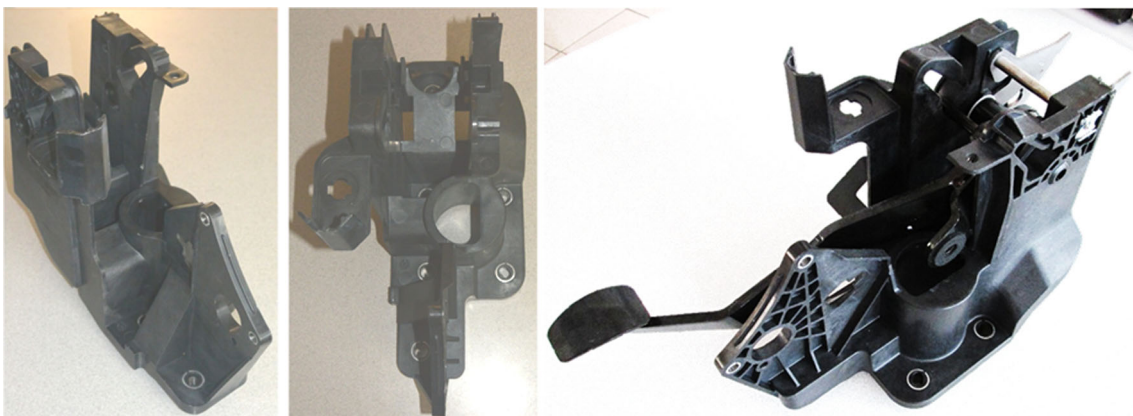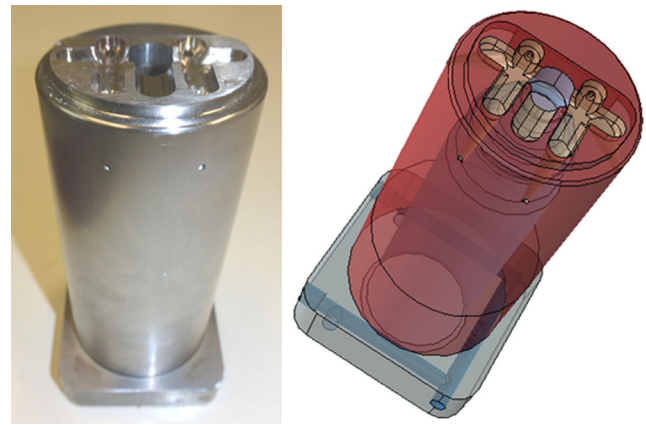

Fig. 2 Injection molding tool insert for the pedal system

40% glass filled, chemically coupled, heat stabilized homopolymer polypropylene compound (PPCOMPOUND G3240A–SABIC).

In this study, different mold tool materials were combined to manufacture hybrid inserts: C45 (XC48) steel and a high-conductivity copper alloy Ampcoloy 83 (Ampco Metal) for milled parts and a maraging steel X3NiCoMoTi 18-9-5 for the SLM processed parts. The maraging steel is supplied as a spherical powder with an average particle size of 34 μm and a particle size distributions of 54 μm with D90. Figure 3 shows a SEM image of the maraging steel powder.

The AM machine used to produce the 3D printed parts is the Selective Laser Melting Machine SLM 280 HL (SLM Solutions) providing a $280 \times 280 \times 365$ mm^3 build envelope, with a build rate up to 35 cm^3/h and a scan speed of 10 m/s.

3 Results and discussion

Cooling simulations of four mold insert configurations were performed. The initial configuration is a machined C5 (XC48) steel mold insert. The shape of cooling channels is very simple consisting of channels running around the rectangular base of the insert. This solution was quickly abandoned because the
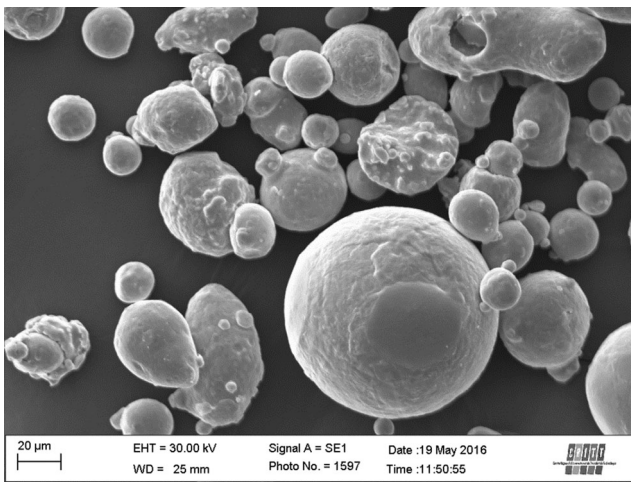

Fig. 1 Plastic pedal system for vehicles

Fig. 3 SEM image of the maraging steel powder

cooling time was too high as confirmed by subsequent cooling simulation. The first solution to improve the cooling consists in using a high-conductivity copper alloy Ampcoloy 83 (Ampco Metal) instead of steel. The cooling is better; however, the insert is subject to wear (Fig. 4) and should be changed periodically. The second solution is a hybrid mold insert consisting in two machined parts. The part around the injection gate subject of wear is made of C5 (XC48) steel, and the remaining part is made of Ampcoloy 83. This solution combines the wear resistance of the steel and the high thermal conductivity of the copper alloy. The last solution is a hybrid mold insert consisting in one machined part and one 3D printed part. The part around the injection gate is made of C5 (XC48) steel and the remaining part is designed with conformal cooling channels made of maraging steel.

For the cooling simulations, a steady-state calculation is performed to determine the average temperature distribution during the quasi-stationary regime. The filling stage of the injection molding process was not simulated, and the thermal effect of the molten polymer in contact with the mold insert is approximated by a flux density calculated from the ratio of the amount of heat produced

during the injection molding process and the contact surface between the insert and the polymer [15].

3.1 Cooling simulation of the initial steel mold insert

Cooling simulation of the initial steel mold insert was performed with ABAQUS software (Version 6.13). Unstructured mesh of 4-node linear tetrahedrons (DC3D4 elements) consisting of 72,649 elements was generated. The insert was made of C5 (XC48) steel with density 7800 kg/m^3, specific heat 450 J/kg/K, and thermal conductivity 50 W/m/K. Governing equation describing the steady-state heat transfer was solved in ABAQUS. Four boundary conditions were set at the mold insert surfaces (Fig. 5).

- Heat exchange with the polymer is the heat flux density generated by the polymer during the injection molding process defined as [15]:

$$q_P = \frac{Q_P}{t_{cycle}S_P} \tag{1}$$

with:

$$Q_P = \left(\left(T_{inject}-T_{eject}\right)C_p + Q_{solid}\right)\rho_P V_P$$
$$t_{cycle} = t_{inject} + t_{hold} + t_{cool} \tag{2}$$

The parameters in Eqs. (1) and (2) are defined in Table 1.

- Heat exchange with the hot runner system: the hot runner at T_{run} = 250 °C and the insert are separated by an air vein. The insert exchange heat with the air by convection:

$$q_{run} = h_{air}\left(T-T_{run}\right) \tag{3}$$

where h_{air} = 25 W/m^2/K is the convective heat transfer coefficient for air [16].

- Heat exchange with the fixed side of the mold: a thermal contact condition is applied on the surface of the insert as:

$$q_{mold} = \frac{1}{R}\left(T-T_{mold}\right) \tag{4}$$

Fig. 4 Wear of the Ampcoloy 83 mold insert at the injection gate

Heat exchange with the polymer
Heat exchange with the hot runner system
Heat exchange with the fixed side of the mold
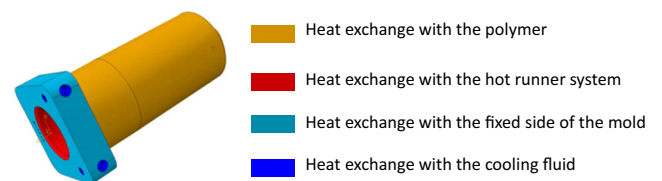Heat exchange with the cooling fluid

Fig. 5 Thermal boundary conditions on the mold insert

Table 1 Parameters for evaluation of the flux density generated by the polymer

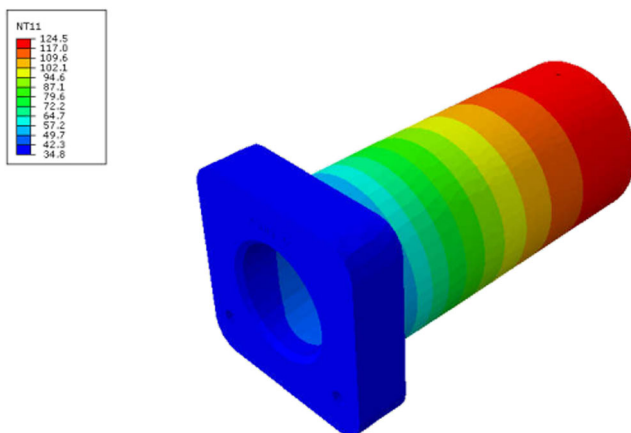| Parameter	Definition	Value
T_{inject}	Injection temperature	250 °C
T_{eject}	Ejection temperature	80 °C
Q_{solid}	Heat quantity provided by the polymer solidification	2000 J/kg
S_P	Surface in contact with the polymer	29,100 mm^2
ρ_P	Polymer density	1220 kg/m^3
V_P	Volume of polymer in contact with the mold insert	29,100 mm^3
t_{inject}	Injection time	6 s
t_{hold}	Pressure holding time	14 s
t_{cool}	Cooling time	145 s

where $T_{mold} = 40$ °C is the temperature of the fixed part of the mold, and $R = 10^{-5}$ m^{2}K/W is the thermal contact conductance.

- Heat exchange with the cooling fluid: a convective heat exchange with the coolant is defined as:

$$q_{cool} = h_{cool}(T - T_{cool}) \tag{5}$$

where $T_{cool} = 30$ °C is the temperature of the cooling fluid, and $h_{cool} = 7016$ W/m^2/K is the convective heat transfer coefficient for the coolant estimated by the Colburn correlation [17].

Figure 6 shows the distribution of temperature on the surface of the tool insert made of C5 (XC48) steel with a cooling time $t_{cool} = 145$ s. The maximum temperature $T_{max} = 124.5$ °C is obtained at the injection gate of mold insert. This temperature is sufficient to eject the part; however, the cooling time represents 83% of the total injection cycle time. To reduce the cooling time, three different solutions were analyzed.

3.2 Cooling simulation of the high-conductivity copper alloy mold insert

The first solution was to replace the C5 (XC48) steel with a high-conductivity copper alloy (Ampcoloy 83). The cooling simulation was performed under same conditions as the previous simulation, except for the cooling time which has been reduced to $t_{cool} = 37$ s. The Ampcoloy 83 properties are density 8260 kg/m^3, specific heat 380 J/kg/K, and thermal conductivity 106 W/m/K.

Figure 7 shows the distribution of temperature on the surface of the tool insert made of Ampcoloy 83 with a cooling time $t_{cool} = 37$ s. The maximum temperature $T_{max} = 123$ °C is obtained at the injection gate of the mold insert. The cooling time represents only 51.4% of the total cycle time. By using a high-conductivity copper alloy as a material for the mold insert, the injection cycle time was reduced by 50.3%; however, the insert was subject to wear because of its lower hardness compared with that of steel. In mass production, the mold insert must be replaced every 6 months.

Fig. 6 Temperature distribution on the surface of steel tool insert at the end of the injection cycle
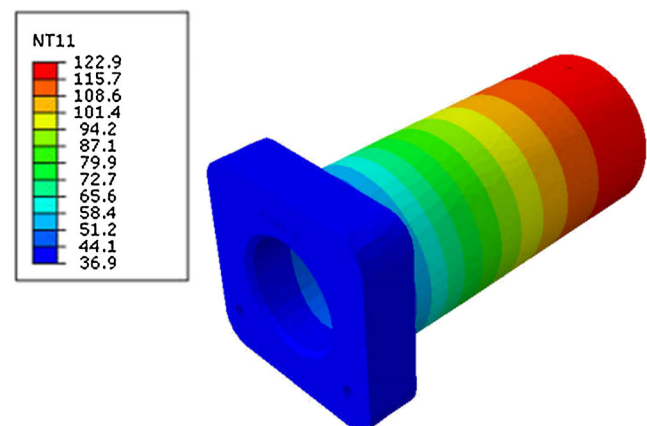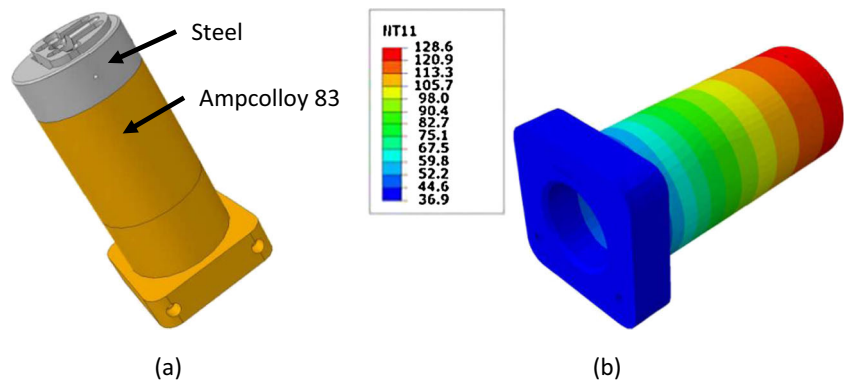

Fig. 7 Temperature distribution on the surface of Ampcoloy 83 tool insert at the end of the injection cycle

Fig. 8 Hybrid tool insert: **a** hybrid geometry; **b** temperature distribution on the surface of hybrid tool insert at the end of the injection cycle

(a)

(b)

3.3 Cooling simulation of the hybrid steel–copper alloy mold insert

To prevent the wearing of the mold insert, a hybrid solution was proposed (Fig. 8a): the part around the injection gate subject to wear was replaced by C5 (XC48) steel and the remaining part was made of Ampcoloy 83. Cooling simulation of this hybrid mold insert was performed under same conditions as the previous simulation with cooling time $t_{cool} = 37$ s.

Figure 8 b shows the distribution of temperature on the surface of the hybrid tool insert with a cooling time $t_{cool} = 37$ s. The maximum temperature $T_{max} = 128.6$ °C is obtained at the injection gate of the mold insert. This hybrid solution was industrially tested, and no wear was observed after more than 1 year mass production.

3.4 Cooling simulation of the hybrid conformal cooling mold insert

To further reduce injection cycle time, we created a hybrid mold consisting of two machined parts made of C5

(XC48) steel and an SLM manufactured part made of maraging steel. Figure 9 a shows the design of the hybrid conformal cooling mold insert with the cooling channels and the two machined parts made of C5 (XC48) steel connected to the SLM manufactured part by screws. Figure 9 b shows SLM parts during the manufacturing process. The parts orientations on the built platform for SLM process were chosen by the following three rules: (1) spread the massiveness of the parts to ensure a good powder supply for each layer; (2) arrange the parts in staggered rows to spread the massiveness and avoid smoke pollution; (3) slightly tilt the parts so that the recoater engages gradually giving better repartition of the recoater force.

Cooling simulation of this hybrid conformal cooling mold insert was performed under same conditions as the previous simulation but with cooling time $t_{cool} = 27$ s. The maraging steel properties are density 8100 kg/m³, specific heat 813 J/kg/K, and thermal conductivity 25.5 W/m/K.

Figure 10 shows the distribution of temperature on the surface of the hybrid conformal cooling tool insert with a

Fig. 9 Hybrid conformal cooling mold insert: **a** mold insert design; **b** SLM parts during printing
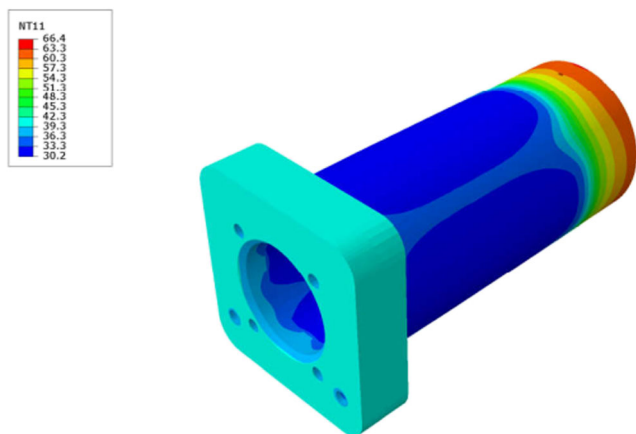

(a)

(b)
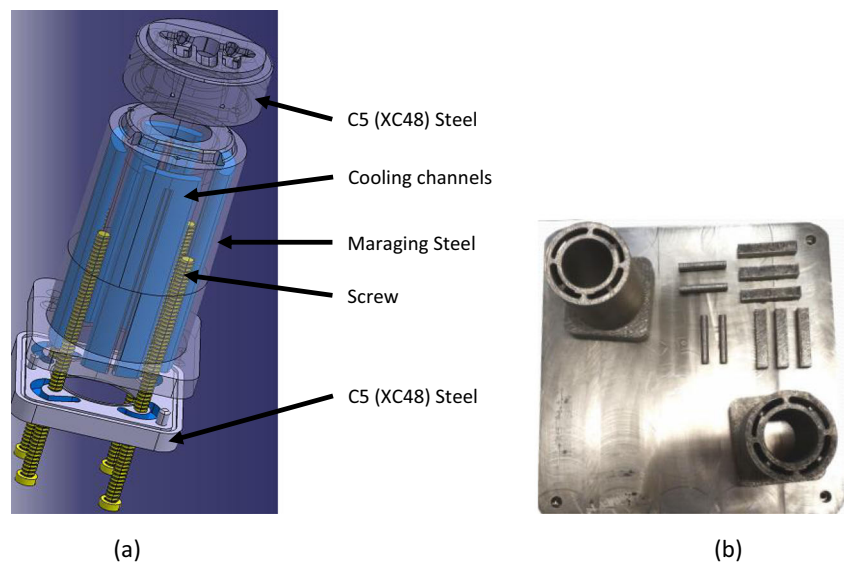
Fig. 10 Temperature distribution on the surface of the hybrid conformal cooling mold insert at the end of the injection cycle

cooling time $t_{cool} = 27$ s. The maximum temperature $T_{max} = 66.4$ °C is obtained at the injection gate of the mold insert. It is clearly shown that the temperature distribution of the hybrid mold insert is more uniform around the conformal cooling design and reaches the temperature of the coolant (30 °C). In this case, the cooling time represents only 43.5% of the total cycle time. By using hybrid conformal cooling mold insert, the injection cycle time is reduced by 13.9% compared with Ampcoloy 83 and hybrid steel–Ampcoloy 83 mold inserts and by 65.6% compared with initial steel mold insert. The maximum temperature has been much reduced, which normally allows us to further reduce the cooling time. However, another mold zone remains hot and requires a higher cooling time. This solution is actually used under real production conditions with the proposed cooling time. The plastic pedal system parts obtained with the proposed hybrid solution are in accordance with the specifications and the productivity increased.
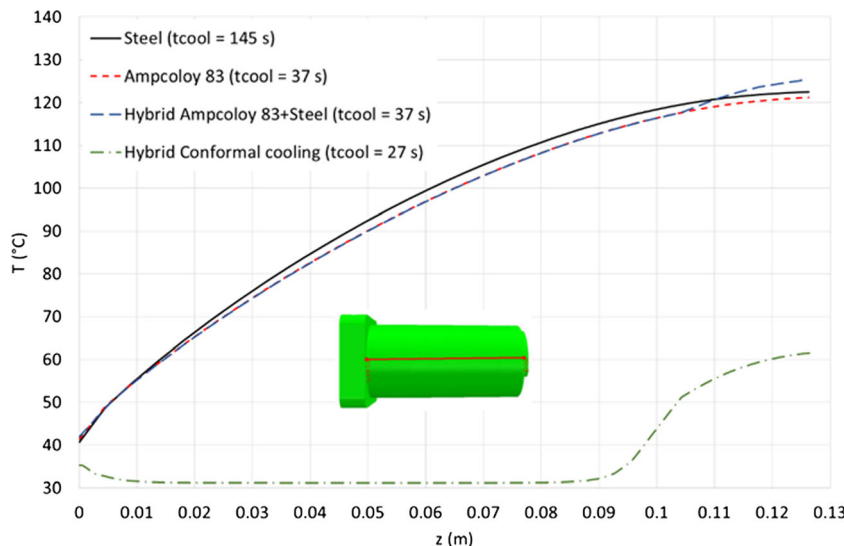
Figure 11 shows a comparison of the temperature profiles following a path along the tool insert. It is clear that the hybrid conformal cooling solution is by far the most efficient. The Ampcoloy 83 and the hybrid Ampcoloy 83/steel machined mold inserts show equivalent behaviors. One can notice the temperature jump near the injection gate for the hybrid Ampcoloy 83/steel mold inserts due to the difference of thermal properties between both materials. A higher jump near the injection gate is seen for the hybrid conformal cooling mold insert because of the design of the cooling channels (Fig. 9a).

3.5 Quality of the finished parts

The quality of the finished parts (plastic pedal system) is strongly related to the mold thermal environment. To investigate the cooling channel layout, we have carried out microscopic observations and mechanical testing on the finished parts obtained with the mold fabricated by conventional way and with the optimized one containing SLM conformal cooling channels.

The injection process of the pedal system with 40% glass-filled polypropylene produces porosity defects. The critical areas of the parts must be checked regularly by sampling to verify if there is a worsening compared to an admitted initial state. Figure 12 shows microscopic observations of a critical section of the pedal system injected in the mold fabricated by conventional way and in the optimized one containing SLM conformal cooling channels. The observed porosities for both parts represent at most 20% of the total wall thickness of the observed section. This value is an indicatively authorized limit in the specifications of the automotive manufacturer. No worsening of molding defects was observed between the two trials.

Fig. 11 Temperature profiles along the mold insert

Fig. 12 Microscopic observations of a critical section of the pedal system injected in mold fabricated by conventional way (left) and optimized mold (right)
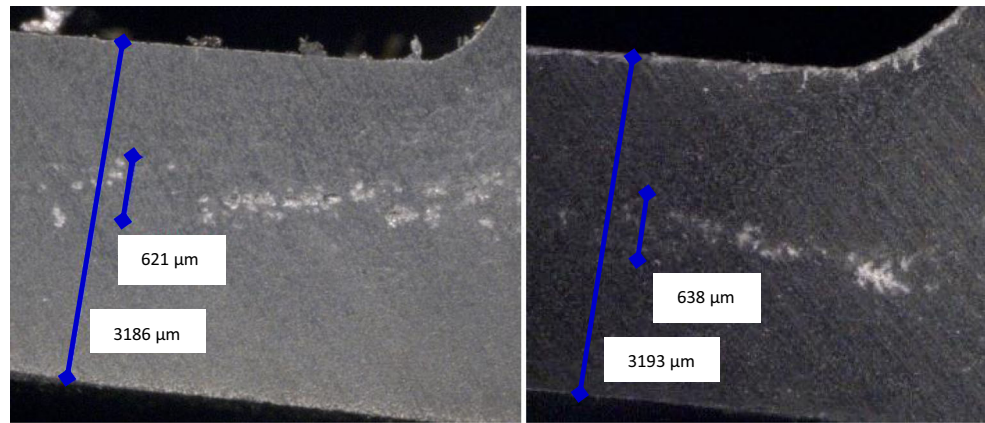
However, these observations must be coupled with mechanical strength testing on the injected parts. According to the specifications of the automotive manufacturer, the pedal system must withstand a load of 250 daN applied by a piston on the pedal. The experimental results of these tests are shown in Fig. 13. These results show no significant change in mechanical behavior between the parts injected in the initial mold and the optimized one.

4 Conclusions

Injection molding is one of the frequently used processing technologies to manufacture automotive parts with high productivity. In order to improve productivity and part quality, optimal thermal management of injection mold is an essential step in the mold design. However, given the increasing complexity of geometries of molds with inserts, designing cooling circuits is challenging. A conformal cooling system is the best solution to uniformly cool a mold insert and reduce the injection cycle time. In this paper, we presented a simply applicable finite element simulation to analyze the thermal efficiency of hybrid mold insert designs. The cooling of injection mold inserts was significantly improved with hybrid conformal
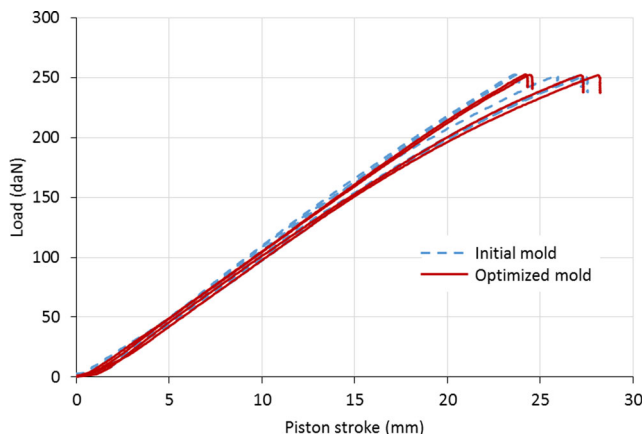
cooling channels. With the hybrid optimal cooling of the mold insert, the injection cycle time was reduced by 65.6%. The hybrid CNC and SLM fabricated mold insert was successfully used in mass production of automotive pedal system parts. The proposed method can be easily applied on any other tool made by SLM process in order to optimize the conformal cooling system.

Fig. 13 Temperature profiles along the mold insert

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