ORIGINAL ARTICLE

A new hybrid process combining machining and selective laser melting to manufacture an advanced concept of conformal cooling channels for plastic injection molds

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Abstract

Firstly, this work investigates a new design of a conformal cooling channel for injection molding tools containing serial and parallel circuits. Secondly, a hybrid-manufacturing process, combining machining and metal powder additive manufacturing, was also evaluated to manufacture molds. Specimens were manufactured by selective laser melting (SLM) using stainless steel (Corrax®) powder, which was deposited on a pre-machined PH13-8Mo stainless steel substrate. The melting zone interface (MZI) between the two materials were assessed. The results showed that the laser-melted and machined surfaces were successfully melted and bonded. Thus, an injection mold was designed and manufactured. A pair of inserts containing the conformal cooling channels were manufactured by the hybrid process and another equivalent pair of inserts containing a conventional cooling system were produced only by machining. Injection molding was carried out alternating the two types of inserts. The results showed that the mold with the conformal cooling channels reduced the warpage of the injected plastic parts by a factor of ~7. The difference in temperature along the insert was reduced by a factor of ~10 and the molding cycle time was around 36% shorter compared with that of the conventional mold. Overall, the proposed hybrid manufacture of the inserts reduced the manufacturing costs and time by 53% and 60%, respectively. The results indicate the benefits of using the proposed conformal cooling design and the hybrid-manufacturing approach, which combines machining with additive manufacturing for injection mold production.

1 Introduction

Currently, injection molding is the process most used to manufacture plastic components. The plastic molding cycle phases are (a) injection (filling and compression), (b) packing, (c) cooling, and (d) part extraction. During the molding cycle, the molds are cooled by a cooling system consisting of internal channels, through which coolant fluid flows. The cooling phase has a dramatic effect on productivity since it consumes more than two-thirds of production time [1]. The efficiency of

the cooling system in the injection molding process influences both the cycle time and plastic product quality. This step must be as short as possible and able to achieve a homogeneous heat exchange between the plastic part and the mold. Currently, drilling is the conventional way to manufacture the cooling channels and so only straight channels are possible. However, for plastic parts with complex freeform surfaces, straight channel cooling lines can cause non-uniform heat exchange between the plastic and the mold. This decreases the product quality and mold productivity.

To overcome this issue, additive manufacturing by selective laser melting (SLM) has been considered to produce molds containing cooling channels that follow the mold cavity freeform surfaces. This approach is known as conformal cooling.

Because of the high costs of SLM, most studies on conformal cooling have been carried out with the use of numerical simulations. The result obtained shows the benefits of the conformal cooling either from the productivity point of view, as reported by Zheng et al. [2], who reduced the cooling time

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by up to 72%, or by improving the quality of the plastic parts, as described by Mohamed et al. [3], who reduced the shrinkage by up to 17%.

However, few experimental scientific studies on molds with the conformal cooling channels manufactured by SLM can be found in the literature. Mazur et al. [4] conducted an investigation of a real mold with the conformal cooling channels in a serial design manufactured by SLM, using H13 steel to mold a plastic box. The results showed that a lower and more homogeneous temperature of the conformal cooling inserts resulted in better plastic parts and reduced the cycle time. This study was performed using a simple plastic box with symmetric geometry (i.e., without geometric complexity) as the workpiece.

Abbès et al. [5] investigated the molding process using a mold with conformal cooling to produce parts of a real automotive component with more complex geometry. However, the design of the cooling channels is simpler, using linear circuits without bifurcations, arranged in a serial design. The authors applied the concept of hybrid molds by assembling parts manufactured by SLM along with parts manufactured by machining. Even though the SLM part was manufactured using maraging steel, which has a lower thermal conductivity, the mold with conformal cooling presented a reduction of 65% in the molding cycle time.

Park and Dang [6] performed an investigation using a mold with conformal cooling for an automotive part with complex geometry. The channels were designed in a spiral and also arranged in a serial design without bifurcations. The authors used P21 steel to manufacture the mold insert by SLM. In this case, the molding cycle time was reduced by 23%.

Based on a review of the literature, it can be noted that more than two decades of research have been carried out in the field of conformal cooling and additive manufacturing for injection molding. Most analyses involve simulation using commercial software or alternative proposed methods. Although some authors investigated the performance of the conformal cooling system experimentally, most of them studied plastic parts with simple geometries, such as plates, boxes, and shell bodies, and the inserts of the molds were manufactures entirely by the SLM process. The hybrid-manufacturing approach (machining and SLM) has not been investigated and is not well understood.

The hybrid-manufacturing concept, combining machining (regions with simple shapes) and SLM (regions with complex shapes), could be a promising alternative to reduce SLM costs and the time required to manufacture injection molds. The results reported herein lend support to a new trend in relation to machine conception, with both manufacturing techniques (machining and SLM) applied in a single machine structure, as described by Liu et al. [7].

Herein, a new design of conformal cooling, mixing serial and parallel cooling circuits, using bifurcated channels, is proposed and investigated. An injection mold was manufactured applying the hybrid-manufacturing concept. The efficiency of the proposed conformal cooling system is compared to a conventional baffle cooling system when applied to inject a complex automotive part. The injection process and the plastic parts are investigated as well as the main mechanical properties of the metal parts manufactured by the hybrid process.

2 Background

2.1 Design of molds with conformal cooling

The design of conformal cooling systems involves the definition of channel dimension, position, and the layout of the feed systems (parallel or serial). Figure 1 shows the geometrical parameters that need to be considered for a circular cross-sectional channel.

Based on the parameters in Fig. 1, Table 1 shows the values used by different authors to design cooling channels.

The parameters presented in Table 1 are some suggestion guides for designing cooling channels. Depending on the part's geometry, it might be not convenient to follow these parameters, because of either the dimension limits or the geometric shape. Thus, some alterations can be necessary.

With regard to the design of conformal cooling systems, Marques et al. [12] used commercial simulation software to evaluate the design of either serial or parallel circuits. The results showed that serial circuits had better heat exchange and a more uniform coolant flow rate when compared to parallel circuits, which presented uneven turbulence and regions with lower heat exchange. Wang, Yu, and Wang [13] showed that serial conformal cooling was more efficient than parallel circuits because of the higher flow rate. Marin, Miranda, and Souza [8] investigated the combination of serial and parallel circuits by numerical simulation where the parallel circuit was applied in critical areas and serial circuits elsewhere, keeping the coolant flow rate as constant as possible and improving the heat exchange, without evaluations of cost and the manufacturing process.

2.2 Thermal analysis of molds with conformal cooling

A general background about the heat transfer process and the conditions that drive the injection molding is presented ahead. It is convenient to understand the co-relations among the parameters to better understand the process and the design of a mold.

According to Xu et al. [14], Eq. (1) can be considered to evaluate the heat transfer between the coolant, mold, and hot plastic and to determine the balance of energy at the advancing front of the polymer, considering an adiabatic boundary.

Fig. 1 Geometrical parameters for conformal cooling
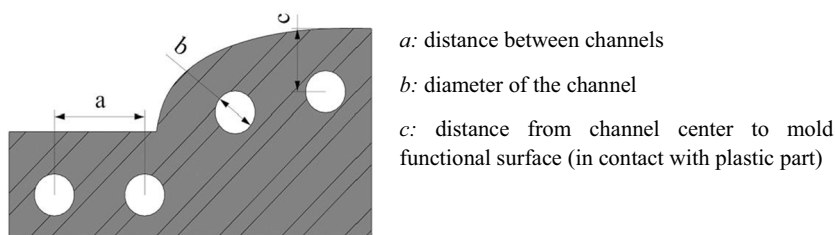
a: distance between channels

b: diameter of the channel

c: distance from channel center to mold functional surface (in contact with plastic part)

$$\Delta E = E_{in} - E_{out} + E_g \tag{1}$$

where ΔE is the energy variation, E_{in} is the energy entering, E_{out} is the energy exiting, and E_g is the energy generated in the control volume. According to Park and Dang [6], when the heat balance is established, the heat flux supplied from the plastic part to the mold and the heat flux removed from the mold by the coolant are in equilibrium. Thus, the heat balance can be expressed by Eq. (2) as,

$$Q_m + Q_c + Q_e = 0 \tag{2}$$

where Q_m is the heat flux related to the melted polymer, Q_c is the heat flux provided by the coolant, and Q_e is the external exchange with the surrounding environment. From the balance of energy, the thermal conditions at the advancing front of the polymer can be analyzed using the equivalent thermal circuit shown in Fig. 2. Thus, considering the thermal circuit representation (Fig. 2), the influence of the distance from the coolant channel to the mold surface (dimension l) is expressed by Eq. (3),

$$q''_{cond} = -k \frac{(T_2 - T_1)}{l} \tag{3}$$

where q''_{cond} is the heat flux, k is the thermal constant, and $T_2 - T_1$ is the temperature difference between the mold functional surface and the cooling channel.

Equation (3) shows that the heat exchange increases when l decreases. However, it also implies a reduction in the mold

wall thickness, which would reduce the mold strength. The transient evaluation can be performed based on the thermal diffusivity in polymers. On analyzing heat losses from the sample surfaces using the finite difference scheme, the thermal diffusivity is governed by Eq. (4) [15],

$$\left(\frac{\partial T}{\partial t}\right) = a \left(\frac{\partial^2 T}{\partial x^2}\right) \tag{4}$$

where t is the time, a is the thermal diffusivity, x is the distance, and T is the temperature.

Correlating Eqs. (1), (2), (3), and (4) and Fig. 2, it is possible to note the behavior of the heat flux and the mold wall temperature against the distance between the cooling channels and the mold wall, so it can help designers to go forward with the parameters presented in Table 1, taking into account the limitations of the material`s properties of the mold (i.e., wall thickness − parameter c on Table 1).

In the flow analysis of the bifurcated conformal cooling channels arranged as parallel circuits, the effect of the flow bifurcations must be taken into account even considering the fluid as incompressible. Thus, the mass, momentum, and energy conservation are considered, as described by Eqs. (5), (6), and (7), respectively [16, 17].
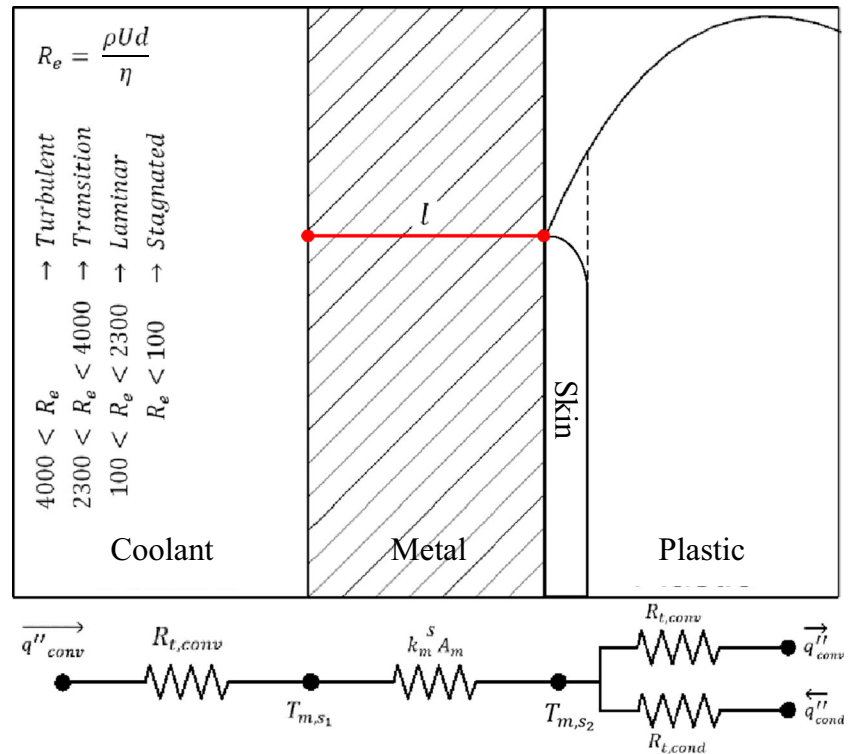
$$\text{Mass } \frac{\partial \rho}{\partial t} + (\nabla.\rho v) = 0 \tag{5}$$

$$\text{Momentum } \rho \frac{\partial v}{\partial t} = -\nabla.\rho + \left[\nabla.\eta \dot{\gamma}\right] - \rho\left[v.\nabla v\right] \tag{6}$$

Table 1 Dimensions used by some researchers to design cooling channels [8]

Author	Wall thickness (mm)	Channel diameter (mm) - b	Distance between channels (mm) - a	Channel left to mold surface (mm) - c
Dang and Park [9]	2	8–10	$c = 0.7a + 1.6b$	
	2–4	10–12		
	4–6	10–14		
Mayer [10]	0–2	4–8	$2b \le a \le 3b$	$1.5b \le a \le 2b$
	2–4	8–12		
	4–6	12–14		
Park and Pham [11]	-	6-12	$2b \le a \le 5b$	$b \le c \le 5b$

Fig. 2 Equivalent thermal circuit analysis

Energy $\rho . C_{\mathrm{p}} \left(\dfrac{\partial T}{\partial t} + v . \nabla T \right) = \beta T \left(\dfrac{\partial p}{\partial t} + v . \nabla p \right) + \eta \dot{\gamma}^2 + \nabla(k \nabla T)$ (7)

Clemente and Panão [18] proposed a mathematical method that considers the minimization of the flow resistance when designing a conformal cooling circuit containing bifurcated channels. Using Eqs. (5), (6), and (7), and the Lagrange multipliers method, the authors proposed an equation to minimize the flow resistance for multiple circular cooling channels according to the relation between the primary channel (D_1) and the bifurcated secondary channel (D_2) described as:

$$\frac{D_1}{D_2} = n^{1/3} \qquad (8)$$

where n is the number of bifurcated channels. Equation (9) gives the maximum number of channels that maximizes the heat transfer, respecting a minimum distance between the secondary channels (D_2),

$$n_{\max} = \text{floor} \left[\frac{\pi L_1 \tan(\alpha)}{D_2} \right] \qquad (9)$$

where floor[x] is set to the nearest integer value less than or equal to x, L_1 is the segment of the channel, and α is the angle between the primary and bifurcated channels [18]. Increasing the number of secondary channels increases internal

turbulence. The Reynolds number (Re) quantifies the flow turbulence, that is, an increase in Re means that there is an increase in the circuit efficiency [12]. The control of Re in conventional straight drilled cooling channels is easier than in circuits with several bifurcations, as is the case of parallel circuits that require more volume of coolant [11]. The proposed conformal cooling design developed in the current work follows the Clemente and Panão [18] constraints.

2.3 Manufacture of molds with conformal cooling

Firstly, considering simple geometries of the plastic parts, such as planar shapes, it is possible to manufacture the conformal cooling channels only by machining. The mold inserts
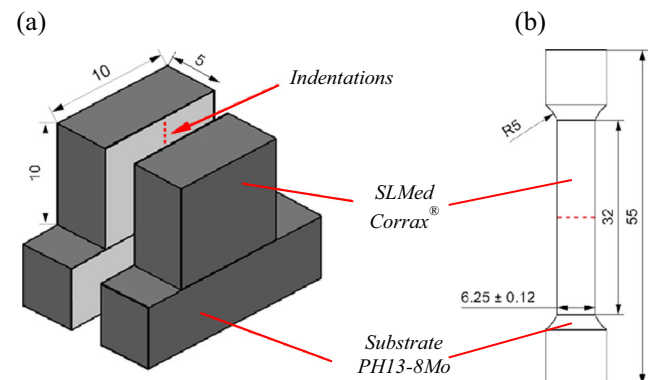
Fig. 3 Specimens manufactured applying the hybrid concept. **a** Prismatic geometry used to analyze the hardness, density, and the melted zone. **b** ASTM 370 specimen used for tensile tests

Table 2 SLM parameters for Corrax®

SLM process	
Atmosphere	Nitrogen
Laser power	400 W
Layer thickness	45 μm
Overlap	30%
Hatch	105 μm
Laser speed	1240 mm/s
Volumetric energy density	68.27 J/mm^3

must be divided into two sections, each one containing half of the cooling channel path. These sections are then assembled and sealed with O-rings [19]. This is a low-cost solution to reach good heat exchange in the mold. However, this method is extremely limited for most real applications.

Another concept involves the use of hybrid molds, where the inserts of the molds are manufactured by different processes, as in the studies mentioned in Section 1, where some components of the mold were manufactured by machining and others by additive manufacturing [5, 6, 20, and].

In conventional SLM manufacturing, the part is built on a substrate plate. After manufacturing, the part is removed from the substrate by cutting.

Today, mold cavities can be manufactured by means of SLM in high hardness materials with low porosity and high mechanical properties [21]. In SLM, energy density is an important factor, along with the laser power, scanning speed, layer thickness, powder quality, and printing direction, all of which are related to the final material porosity and mechanical properties [22]. The effect of porosity and internal voids on the mechanical properties is clear, but porosity also affects the thermal properties of the mold [23]. The thermal heat transfer is

probably lower, due to the anisotropy nature of the additive manufacturing process in comparison with material produced by cold rolling or forging [24].

Laser-based processes produce a melted zone interface (MZI) between the substrate/layer and deposited material, which results in a heat-affected zone that can influence the mechanical performance of the manufactured part. Since high-temperature gradients are involved, residual stresses and cracks can occur, which creates problems for the manufacture of high-quality parts [25]. At the beginning of the SLM process, considering the substrate at room temperature, there is a large temperature difference between the first layers of the SLM and the substrate.

The study reported herein introduces a new concept of hybrid manufacturing of the inserts. Initially, the region of the inserts with a simple geometry is manufactured by machining. The complex regions of the inserts (with the conformal cooling channels) are then manufactured by SLM, using the machined part as the substrate. Thus, the volume produced by SLM can be reduced, as well as costs and manufacturing time. However, two constraints must be considered: (i) It is difficult to ensure efficient bonding in the powder bed fusion with the substrate (which is a fraction of the desired part in the proposed process). This creates an interface zone with a high-temperature gradient (substrate at room temperature and high temperature of first layers of the SLM); and (ii) the characteristics of the ordinary SLM process after building the first layers, with a low gradient but with high temperature.
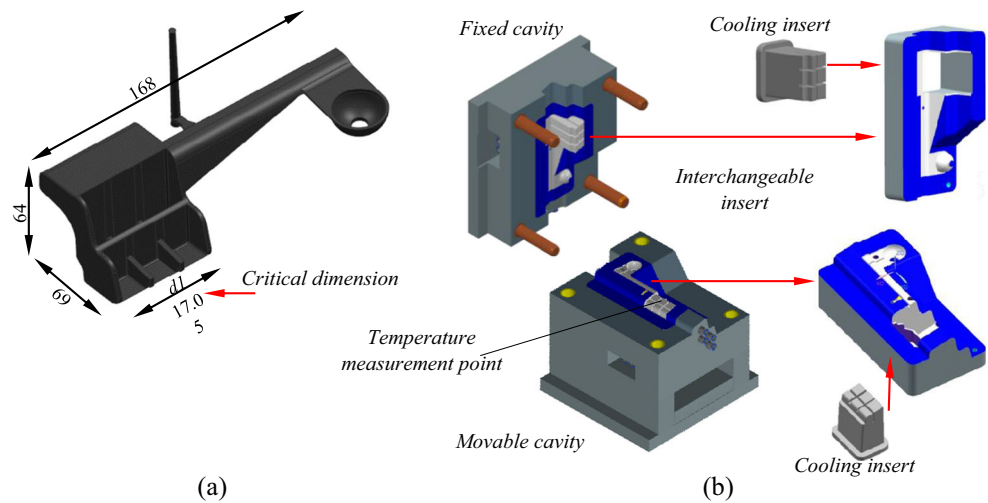
3 Experimental procedure

This study was focused on two objectives. Firstly, the hybrid-manufacturing process, combining machining and metal powder additive manufacturing, was explored with the

Fig. 4 **a** Corrax® powder particles. **b** Powder particle size distribution

(a)

(b)
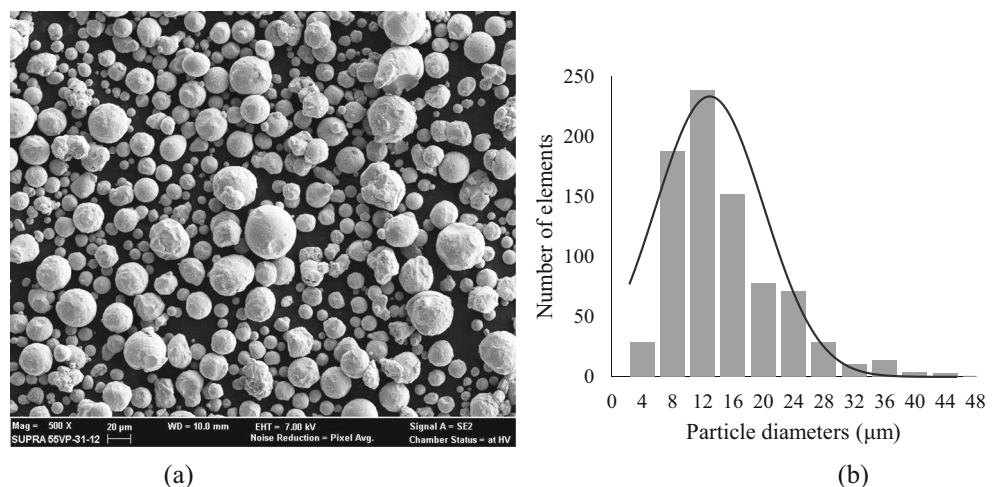
Fig. 5 CAD designs for **a** workpiece and critical dimension d_1 and **b** modular mold and inserts

(a)

(b)

manufacturing of inserts for injection molds. Secondly, a new design of the conformal cooling channels for injection molding, containing serial, parallel, and bifurcated circuits, was proposed and investigated.

Initially, the mechanical properties of specimens produced by the hybrid-manufacturing process were evaluated. An injection mold was then designed and manufactured. The designed mold contains a pair of exchangeable inserts (for the fixed and movable parts of the mold). Thus, one pair was manufactured applying the new hybrid concept (with conformal cooling) and another pair of inserts with the conventional cooling system (baffle) was manufactured by conventional machining. Evaluations were conducted through CAE simulations and by the experimental plastic injection process, first using the conformal cooling inserts and then using their counterparts with the conventional cooling system. The plastic parts and the molding process were analyzed.

3.1 Evaluating the mechanical properties of the specimens manufactured by the hybrid process

Specimens with two different geometries (prismatic and cylindrical) were manufactured by the hybrid process. In each case, half of the specimen was manufactured by machining and the other half by SLM. The quality of the MZI between SLMed and machined parts was investigated.

An SLM Concept Laser® machine (model CL50WS) with a YAG fiber laser (400 W), a spot size of 100 μm and a laser wavelength of 1064–1070 nm, was used to manufacture all of the SLM parts. Corrax® stainless steel (C 0.03%, Cr 12%, and Ni 9.2%) powder was used in the SLM process and fused onto a pre-machined substrate. Because of commercial restrictions, it was not possible to acquire solid blocks of Corrax® stainless steel processed by conventional rolling.

Fig. 6 Sketches of the exchangeable inserts. **a** Insert with the new bifurcated conformal cooling approach. **b** Insert with a baffle
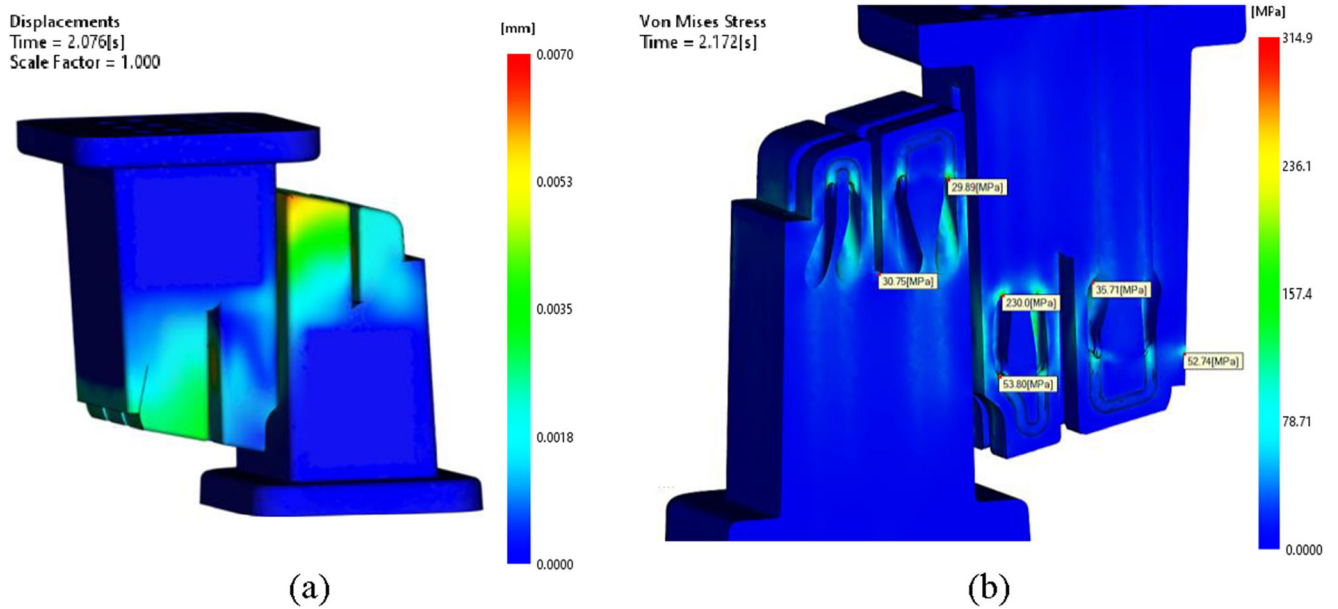

(a)

(b)
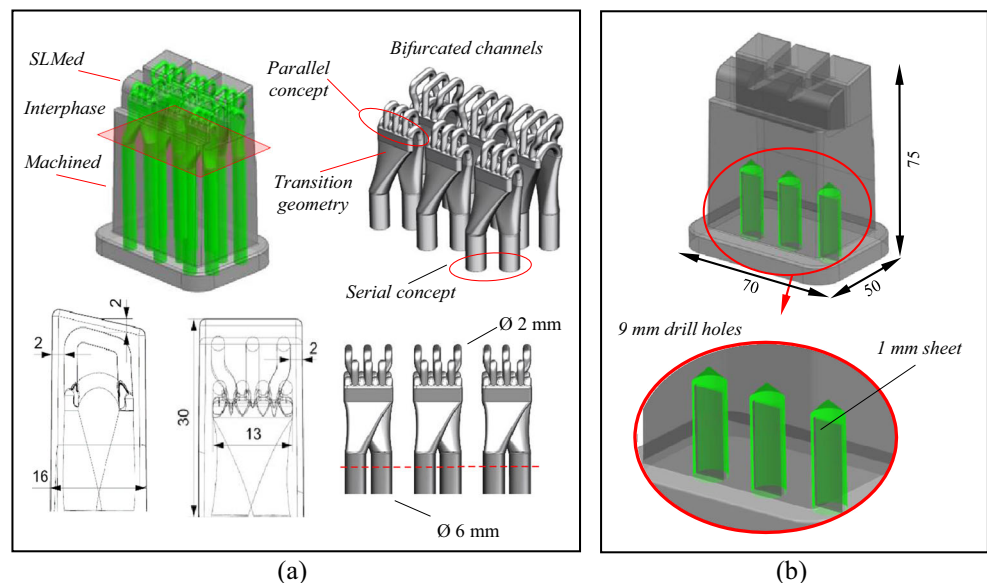
Fig. 7 Simulated **a** maximum displacement and **b** Von Mises Stress at the packing stage

Therefore, solid blocks of martensitic stainless steel PH13-8Mo (13Cr-8Ni-2Mo-1Al-UNS S13800/WNr. 1.4534) produced by the cold rolling process were used as the substrate.

The prismatic specimens (Fig. 3a) and a replica were manufactured by the hybrid process. The porosity was evaluated using metallographic images and the software Multiphase Grains Graphite. The images were taken within 50 μm from the border of the specimens (total of 28 images randomly).

The distribution of the pores was evaluated using a Zeiss® X-ray tomograph (METROTOM 1500) aided by the software Volume Graphics GmbH 3.2. To ensure sufficient penetration of the X-rays, the specimens were cut into four parts.

The hardness was analyzed along the cross section of the specimens with a Wilson Instruments® testing machine (402MVD) according to ISO 6507-1:2008. The hardness profiles of the SLMed and machined portions were accessed, as well as the melted zone. This zone was also investigated based on images obtained from a Carl Zeiss® stereoscope (Discovery V8).

A cylindrical specimen and one replica were manufactured applying the hybrid process for the tensile testing following the standard ASTM 370 (Fig. 3b) using an Instron® universal testing machine (model 5988).

The SLM parameters applied were recommended by the SLM machine supplier and are shown in Table 2.

The geometry and diameter of the powder particles used were evaluated by scanning electron microscopy (SEM) on a Zeiss® SUPRA 55-VP microscope, with ×500 magnification. Figure 4 shows the particle shape and the distribution of particle diameters. It can be observed that the particle sizes ranged from 5 to 50 μm (Fig. 4a), and the Gaussian curve (Fig. 4b) shows an appropriate distribution for powder packing during the SLM process.

Fig. 8 Manufacture of hybrid mold inserts. **a** Substrates on the SLM table. **b** SLM process. **c** Insert after SLM process
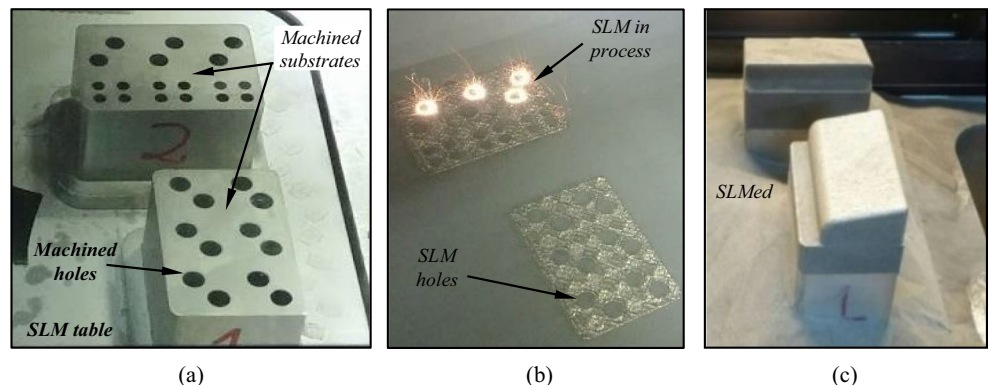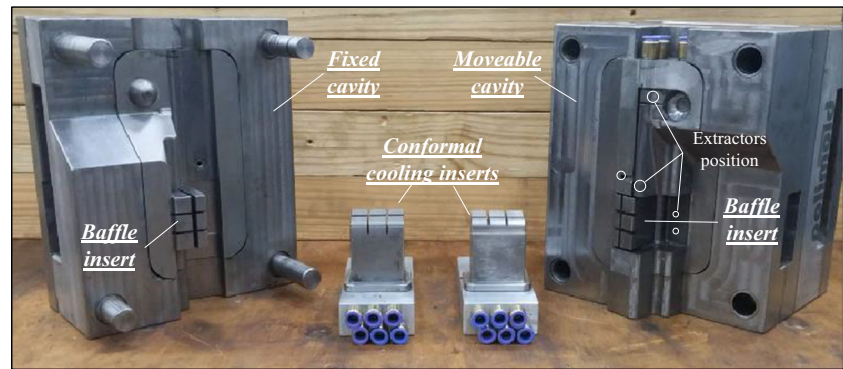
3.2 New approach for conformal cooling design

3.2.1 Design, simulation, and manufacturing of the inserts of the mold

To achieve the objectives of this study, an automotive plastic part was chosen as the workpiece (Fig. 5a). The plastic part was designed with draft angles and ribs considering movable and fixed cavities. It was intended to propitiate more interference with the movable cavity of the mold during the solidification of the part. Thus, when the mold was opened, the part moved together to the movable cavity. After that, the extractors on the movable cavity removed the plastic part from the cavity to finish the injection cycle.

The injection mold was designed with two exchangeable inserts, one for each side of the mold cavity (one fixed and the other moveable), as detailed in Fig. 5b.

One pair of inserts had a conventional cooling system (baffle concept) and was manufactured by machining. The other pair of inserts containing the conformal cooling channels was manufactured by the hybrid-manufacturing approach (machining and SLM). The bottom portion of these inserts has only straight-line holes, which were manufactured by machining (around 2/3 of the insert volume). The top portion of the inserts containing the conformal cooling channels was

manufactured by SLM using the machined portion as the substrate (where the conformal cooling was designed). The same raw materials were used for the hybrid insert and the build parameters are shown in Table 2.

The proposed design for the new conformal cooling system includes a combination of serial and parallel cooling channels, connected by a transition geometry to form a bifurcated circuit. Based on the recommendations in Fig. 1 and Table 1 and taking into account the geometrical constraints of the plastic workpiece, the conformal cooling system was designed using 12 cylindrical channels (6 coolant input and 6 coolant output, the serial component) with a diameter of 6 mm at the bottom of the inserts. Due to the restriction of space at the inserts, each of these channels was split into 5 small channels with diameters of 2 mm (parallel component) using a suave swept with a constant section, as seen in Fig. 6a. The criteria of minimum flow resistance detailed by Clemente and Panão [18] were considered.

Taking into account Table 1 and aided by CAE simulations, the dimensions a, b, and c were established as 2.1 mm, 2 mm, and 3 mm, respectively. These values were established considering the following aspects:

i)   The dimension a affects the heat transfer homogeneity and it was defined to be the maximum value. But it is

Table 3 Parameters used in simulation and real process

Injection parameters	
Material	Polypropylene Braskem® grade H 105
Initial mold temperature	25°C
Injection temperature	240°C
Cycle time	28 s
Open-close time	5 s
Filling time	0.4 s
Switchover	95% filling
Packing	50% injection pressure decreasing to 0 linearly in 2s
Coolant fluid	Water
Coolant temperature	25°C (simulation)

Fig. 10 Density of the SLMed region analyzed by optical images
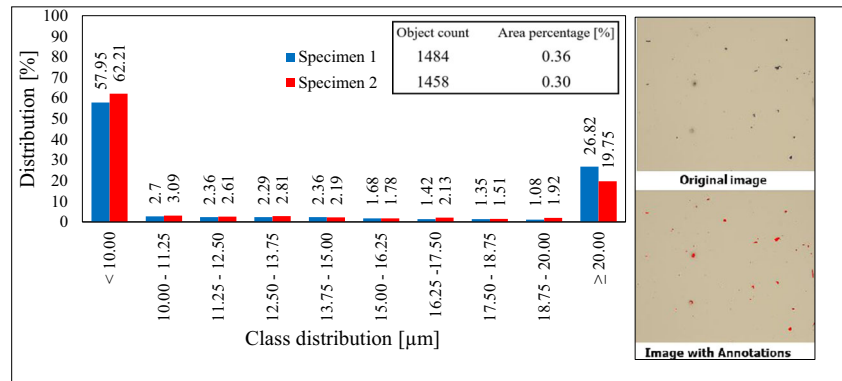
limited by the plastic part geometry. And together with the parameter *c*, both can affect the resistance of the insert.

ii) The dimension *b* was selected based on work presented by Manzur et al. [4], which considers the maximum diameter of cylindrical channels manufactured by SLM.

iii) The dimension *c* was selected to maintain a minimum distance from the wall the ensure its mechanical resistance.

The baffle inserts had three channels (diameter 9 mm and length 31 mm) manufactured by drilling (Fig. 6b). One sheet of metal with a thickness of 1 mm was used in each baffle channel.

The baffle and conformal cooling inserts were designed to have the same volume of coolant entering. Both mold configurations were simulated using the CAE software Sigmasoft® 5.1.

The mechanical resistance of the conformal cooling inserts was evaluated. To determine the dimension *c* (resistance of the inserts), simple estimation analyses were carried out by CAE simulation. First, the injection pressure was obtained (about 32 MPa). Then, the mechanical resistance of the conformal cooling inserts was estimated, considering *c* = 2 mm of wall thickness, Corrax® (material of the inserts), and the geometry of the channels. The results show the maximum displacement of the inserts was 0.007 mm, estimated by the CAE (Von Mises Stress was 314.8 MPa). It is 3 times lower than the maximum resistance of the Uddeholm Corrax® (1100 MPa). Therefore, the inserts were considered to be manufactured. Figure 7 presents the simulations of these displacements and mechanical stress in the packing phase.

Figure 8 details the manufacturing process of the hybrid insert. During the execution of the experimental procedure,

Fig. 11 X-ray tomography images of samples showing porosity
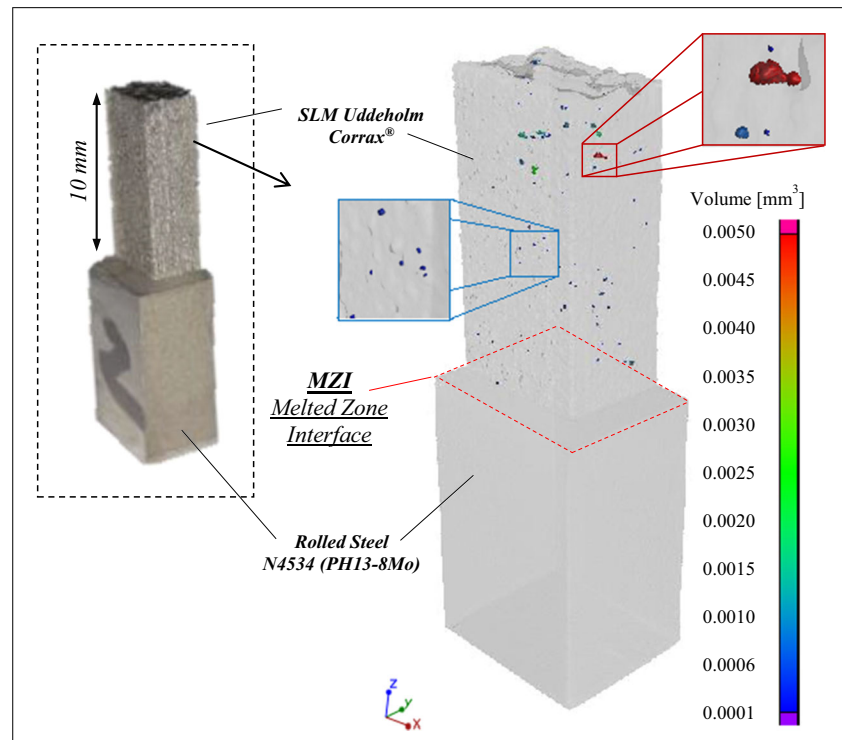
Fig. 12 Depth of MZI and hardness indentations on the machined and SLMed surfaces and at the interface
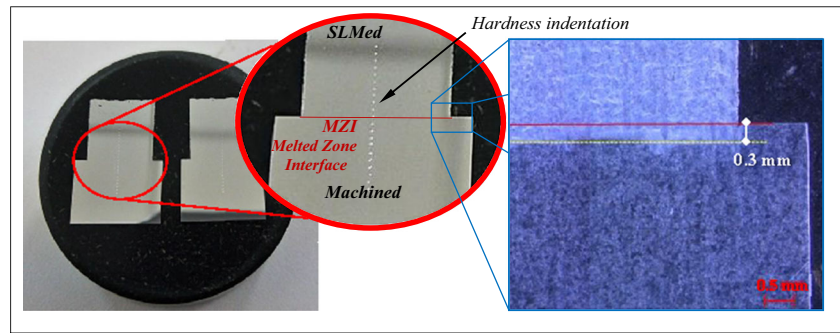
one important point noted is that the reference coordinate system used for machining the bottom part of the insert and the coordinate system used for the SLM machine to build the top portion of the insert must be accurately aligned. Otherwise, in the SLM process, the channels previously manufactured by machining (Fig. 8a) may be obstructed.
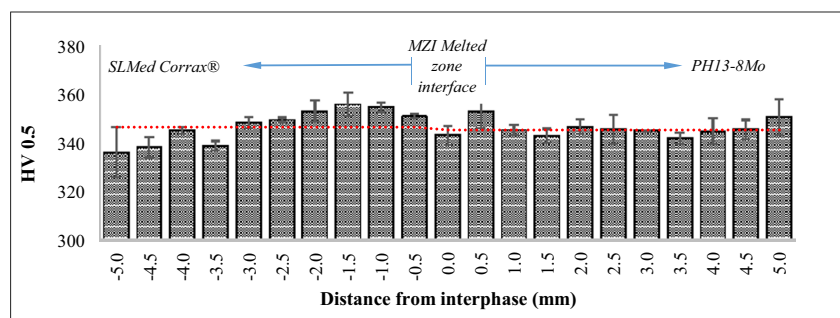
After the SLM, the inserts were finished by milling to achieve accurate surface and roughness according to the end-use requirements. Figure 9 shows the mold cavities manufactured, the interchangeable inserts (baffle assembled and proposed conformal cooling), and also the positions of the extractors of the mold (A-type extractors, two with 9 mm, two with 4 mm, and one with 5 mm of diameter).

3.2.2 Injection molding process and evaluations

Firstly, a batch of plastic parts was produced using conventional inserts with baffle cooling channels. The inserts were then changed to those with the conformal cooling system and the second batch of plastic parts was produced. More than 50 parts were obtained in each batch. The temperature of the mold was verified after each injection cycle using a digital infrared thermometer (KKmoon® GM300), at 300 mm from the top of the movable insert (the temperature measurement point is shown in Fig. 5). A Haitian® MA 2500 injection molding machine cooled with water at 26.1°C (± 2) flowing at 9 l/min was used for the experiments.

The plastic injection molding parameters were obtained from preliminary studies using the CAE software Sigmasoft® 5.1 and are given in Table 3.

The quality of the polypropylene (PP) plastic parts was evaluated by means of warpage and form error analysis. An ATOS® (Core 300) scanner and the software ATOS® Professional 2017 were used to compare the scanned and CAD geometries. The critical dimension (d_1) of the injected parts was the focus of the evaluation (Fig. 5a).

4 Results and discussion

4.1 Mechanical properties of specimens manufactured by the hybrid process

The density of the SLMed region was analyzed using a total of 28 optical images (ten of each specimen) and the software Multiphase Grains Graphite. Figure 10 shows one example of the results obtained.

The density of the specimens considering only the SLM portion reached around 99.7% with a higher concentration of pores with sizes < 10 μm (~60%). The highest percentage of pores (around 60%) were < 10 μm and around 22% were > 20 μm. However, an important factor is the distribution of these pores in the specimen.

Thus, X-ray tomography analysis was carried out and the results in Fig. 11 confirm a low number of pores with most of them being < 0.001 mm^3. This reflects the behavior of both constraints of the proposed hybrid manufacturing: (i) the melted interface zone where the powder bed fuses with the substrate, and (ii) the properties of the ordinary SLM process after building the first layers.

Fig. 13 Hardness profile of the hybrid specimens around the melted zone

Fig. 14 Tensile test results for the hybrid specimens. **a** Stress-strain curve. **b** Local necking in the SLM region
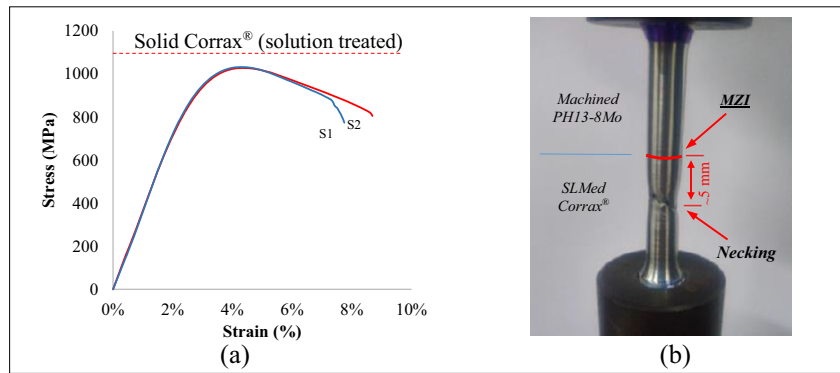
In hybrid manufacturing, the MZI is the region with the highest temperature gradient and this can result in the formation of cracks due to accumulated stress [25]. However, in the current case, Fig. 11 shows that this temperature gradient did not interfere with the quality of the MZI. The first layers of the SLM (corresponding to the melted zone) and the vicinity presented a lower number of pores and no cracks can be observed. This could be because both materials used (powder and substrate) have high weldability [26]. The high presence of aluminum as an alloying element prevents the formation of intergranular austenite during the solidification of the melt pool and subsequent formation of martensitic structures that are responsible for the residual stresses.

On the other hand, it is possible to note in Fig. 11 that as the distance from the MZI increases (beginning of the SLM process), the pore size also increases slightly. After manufacturing the first layers, the substrate together with the previously melted layers has a significant gain in temperature and, consequently, a reduction in the temperature gradient occurs. This increases the temperature of the manufactured part, which can result in material vaporization and entrapment in the melt pool [27, 28], with the formation of pores in the middle/top portion of the specimens (Fig. 11).

Figure 12 shows the stereoscope photo of the MZI between the machined and SLMed materials.

(a)

(b)
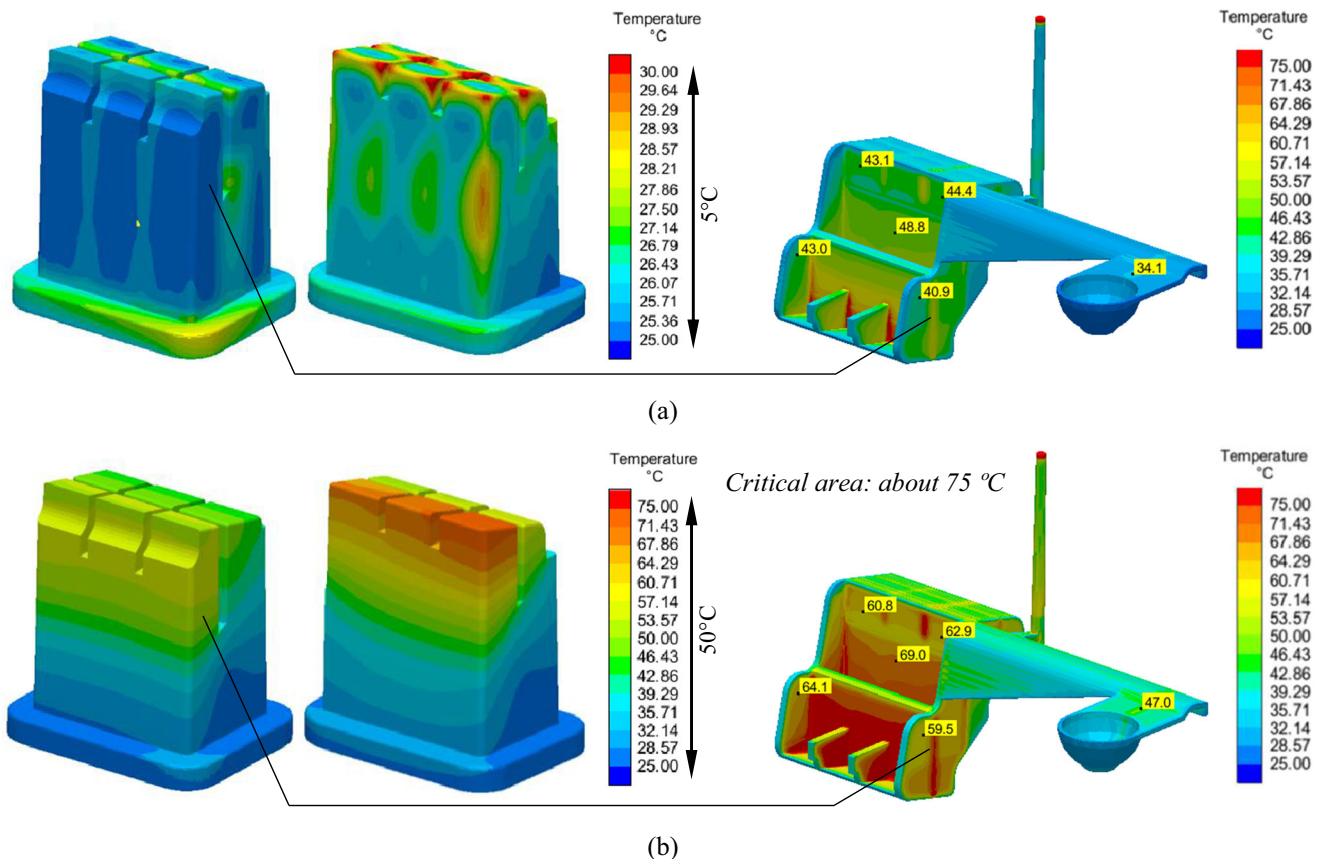
Fig. 15 Analysis of the temperature of plastic parts and inserts (fixed and movable). **a** Proposed conformal cooling inserts. **b** Conventional baffle inserts

Fig. 16 The temperature of the fixed mold inserts measured at the end of the cycle
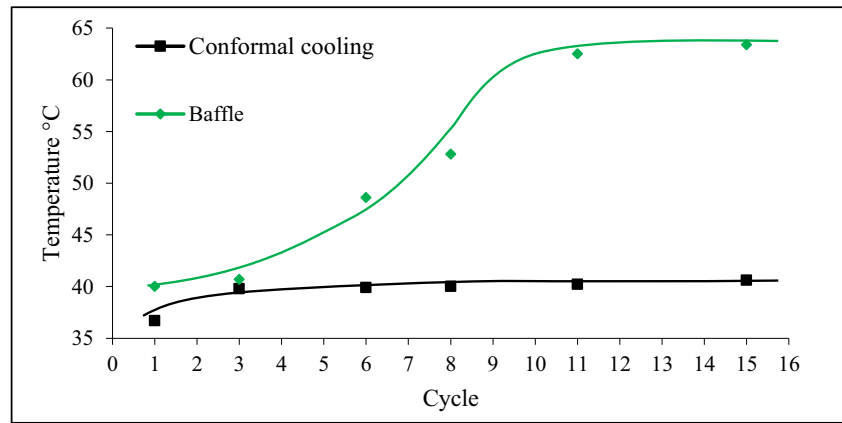

Figure 12 shows that the MZI had a thickness of 0.3 mm and no defects could be detected visually. The analysis was carried out to better understand some of the mechanical properties of this zone. Figure 13 shows the hardness (HV 0.5 ISO 6507-1:2008) values for the MZI (at 0.0 mm), for the SLMed portion (from −0.5 to −5 mm), and the machined portion (from 0.5 to 5 mm). The average hardness was 346 HV ± 6 (~35 HRC), for values obtained at 21 positions along with the specimens.

The hardness of the cold-rolled PH13-8Mo portion had higher uniformity than the portion manufactured by SLM. After the manufacture of the first layer by SLM, the hardness increases slightly. This phenomenon is because of the rapid solidification of the molten pool that results in the formation of a coarse martensitic structure [28].

The hardness tends to reduce at around 4.5 mm from the MZI on the SLM portion. This is probably due to an increase in the temperature in this region, resulting in a heat-affected zone that possibly underwent high-temperature tempering, which can reduce the strength and the hardness. In addition, this reduction in the hardness may be related to the presence of a greater number of pores, as observed in Fig. 11.

To verify the resistance of the MZI between the SLM portion and the machined substrate, tensile tests were conducted on two ASTM 370 specimens (S1 and a replica S2). A ductile fracture with the formation of necking occurred on the SLM portion (Fig. 14).

The fracture did not occur at the melted zone interface as expected, but around 5 mm from the MZI on the SLM portion, probably due to the higher concentration of pores in this region. This demonstrates that the MZI produced by hybrid manufacturing is not a limitation. Also, it should be noted that the ultimate tensile strength was around 1030 MPa and this value is 7% lower than that of the ordinary rolled solution-treated Corrax® (1100 MPa) [26].

Combining all of the results of this experimental phase, it is possible to draw a close correlation:

– In the portion of the specimens built by SLM, at beyond 5 mm from the MZI, there were more pores present compared with the first layers.
– The hardness of the SLMed portion decreased in this region (around 5 mm after the melted zone).
– The fracture of ASTM 370 specimens occurred at around 5 mm from the melted zone.

Therefore, the results show that in the SLM process, the properties of the specimens altered during their construction. However, there was a relatively small reduction in the ultimate tensile strength together with good mechanical properties in the melted zone. This demonstrates that the proposed hybrid-manufacturing process can be used successfully for many applications. These results

Fig. 17 Dimensional deviation of injected plastic parts. **a** Baffle inserts. **b** Conformal cooling inserts
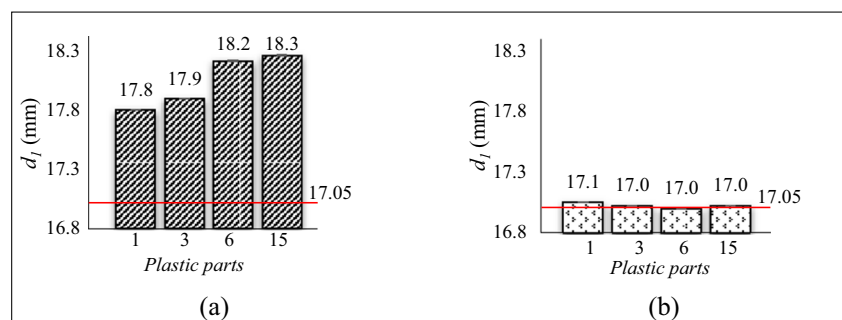
Fig. 18 Visual inspection to identify defects in injected parts produced with **a** baffle inserts and **b** conformal cooling inserts

(a)   (b)
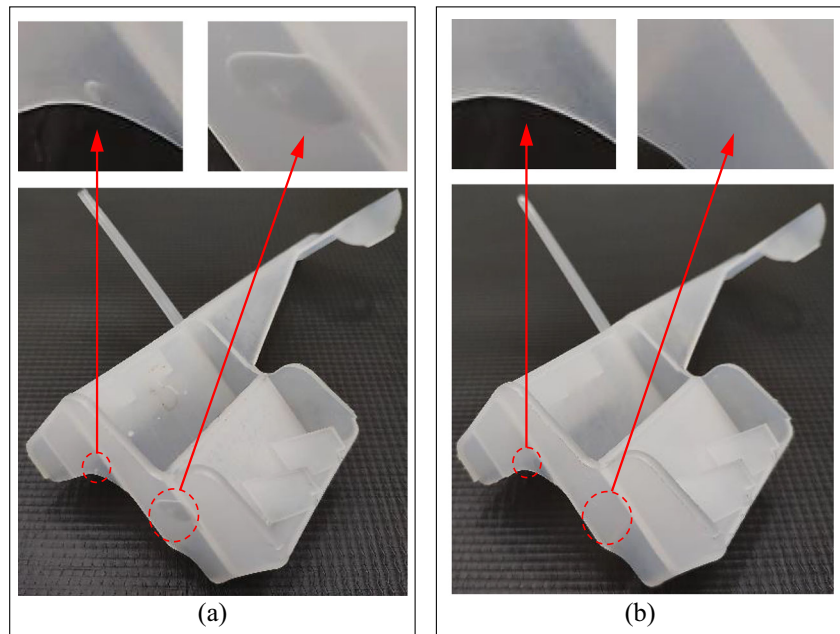
motivated the continuation of this study and the manufacturing of the injection mold was then carried out.

4.2 Proposed conformal cooling performance evaluation

4.2.1 Simulation analysis

The simulations highlighted the variation in temperature along with the inserts at the end of the cycles. With the same coolant feed flow, the proposed conformal cooling inserts showed better heat exchange efficiency than the conventional baffle cooling, as seen in Fig. 15.

Besides the low values, the conformal cooling inserts led to a high homogeneity in terms of temperature, with a difference between colder and hotter areas of around 5°C. In the case of the baffle inserts, this difference was 10 times higher. This low homogeneity of the conventional baffle inserts could increase the warpage and the deformation of the molded plastic part.

4.2.2 Evaluation of injection molding process and plastic parts

Figure 16 shows the temperature of the mold at the measurement point (Fig. 5), taken with the digital infrared thermometer after the injection cycles, for both cases investigated (baffle and conformal cooling systems). For the mold with baffles, the temperature increased more than 50% (42 to 63°C) from the first cycles up to stabilization (steady-state regime), which was reached after the 11th part produced. These first plastic parts produced are wasted. However, for the mold with conformal cooling, the number of cycles required to reach the steady-state regime is negligible, and the temperature remained constant at around 40°C. This means that the parts tend to have the same quality starting from the first cycles, thus avoiding wastage. Equations (4) to (9) help to understand why the transient regime is different and the homogeneity of the mold differs from conformal cooling to baffle cooling channels, even the cross section on the inlet fluid is the same. Besides these, it correlated to the design parameters of the channels with the efficiency of the bifurcated cooling systems.

Fig. 19 Simulation to enhance the process using the mold with baffle inserts

Critical area - about 50°C
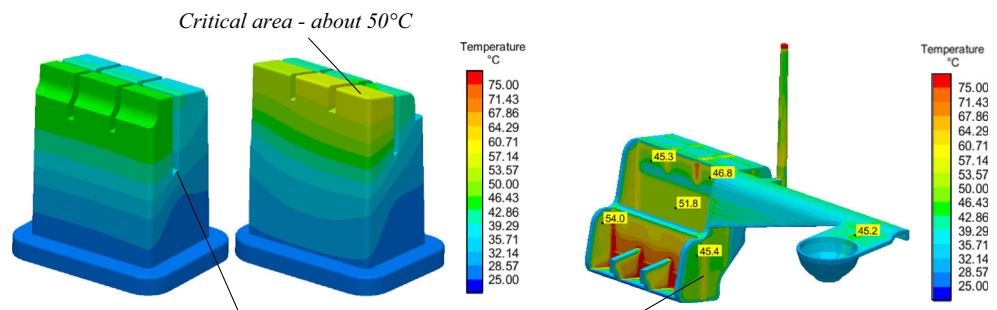
Table 4 Reduction in the SLM volume using hybrid manufacturing

Insert	Total volume (mm^3)	SLM volume (mm^3)	Machined volume (mm^3)	SLM reduction (%)
Movable	141.1	45.8	95.3	67.5
Fixed	156.7	51.5	105.2	67.0

Considering the molding process in the steady-state regime, the temperature of the conformal cooling mold was around 40% lower than that of the baffle cooling mold. It is important to mention that the divergence between real and simulated temperatures at the measurement point was low (around 8%).

Besides the difference between the maximum temperatures on the molds, which influences the molding cycle time, the difference in the temperatures along the insert is also important in relation to maintaining the accuracy of the plastic part.

Figure 17 shows the results for the form error of the plastic parts produced using both molds, in the molding cycles 1, 3, 6, and 15. The inspections were carried out considering dimension d_1 (Fig. 5), which is relevant for the plastic component investigated, with a nominal dimension of 17.05 mm. The parts molded using conformal cooling inserts had a d_1 dimension error lower than 1%, whereas the error for the parts molded using the conventional baffle system was around 7% and, depending on the plastic component, this deviation may not be acceptable.

Considering the parts produced in the first cycles (1 to 3) using the baffle inserts, it can be noted that even with a low temperature in these cycles (Fig. 16), close to the conformal cooling temperature, the d_1 dimension errors were significantly higher (Fig. 17a). This is probably because of a greater variation in temperature for the baffle inserts, whereas the variation was negligible for the conformal cooling inserts. The variation in temperature and the d_1 dimension increased non-linearly until the steady-state regime is reached (Fig. 17a and Fig. 16), for the baffle inserts. In this molding regime, the results of the simulation show that the temperature variation in the inserts with baffle reached 50°C, whereas in the conformal cooling system, it was only 5°C. This shows that the conformal cooling promotes an exceptionally small temperature variation along with the inserts, thus reducing the deviations in the part geometry.

Additionally, a visual inspection revealed shrinkage defects and voids in the parts manufactured using the baffle inserts, as seen in Fig. 18a. These defects were not observed in the parts molded with the conformal cooling inserts (Fig. 18b).

The presence of voids was observed in all parts obtained using the baffle inserts, even when the mold was cooler in the initial cycles. This defect did not occur in the parts manufactured using the mold with conformal cooling. The combination of a higher cooling rate in the conformal cooling channel along with the high crystallization rate of the injected material (PP) could hinder the formation of this type of defect.

Additional simulations showed that to obtain plastic parts with a level of quality similar to that obtained with the conformal cooling system, the injection process using the baffle mold would need to be 36% longer, reducing productivity. Figure 19 shows the results of these simulations.

Figure 19 shows that on increasing the cooling time and the total cycle time to 44 s, the homogeneity of the temperature along with the insert increases, and the temperature difference drops to approximately 10°C, which is considered acceptable by injection mold companies [29], and may avoid problems such as warpage and voids. Thus, obtaining injected parts using the baffle inserts would require a longer cycle time compared to conformal cooling inserts. In addition, it is important to note that, besides the longer time required for the manufacturing of each plastic part, all associated expenses, such as energy consumption, labor costs, maintenance of the mold, and the injection molding machine, would also increase.

4.2.3 Simple evaluation of cost and time associated with the hybrid-manufacturing process

To assess the potential for the industrial application of the proposed hybrid-manufacturing process, a simple evaluation of the cost and time involved in the manufacturing of the inserts was carried out (Table 4).

If only SLM is used to manufacture the mold inserts, a cycle time of 38 h would be required. However, using the proposed hybrid-manufacturing approach, the reduction in the SLM volume was around 67% for each insert and the cycle time is reduced to 15 h.

In relation to practical use, the hybrid-manufacturing procedure could reduce the SLM time by around 60% and the costs by around 53% (from an estimated 7500.00 USD to 3500.00 USD considering the current market).

5 Conclusions

This paper describes a hybrid-manufacturing process, combining machining and SLM, to manufacture injection molds and also a new design of the bifurcated conformal cooling channels combining serial and parallel circuits. A real mold was manufactured applying these concepts and a batch of plastic workpieces was produced. The hybrid-manufacturing process, the injection process, and the plastic parts produced were evaluated and the main conclusions are as follows:

- The melted zone interface (MZI)—between the machined and the SLMed portion—can be considered the first constrain of the hybrid-manufacturing process. In the case investigated, the specimens manufactured by the hybrid process had an MZI of 0.3 mm (depth). No defects were observed.
- Contrary to the expectation, the MZI did not lose its mechanical properties, even though a higher temperature gradient occurs in this region (substrate much cooler than initial SLM layers). The MZI and its vicinity presented a lower number of pores and no cracks were observed.
- The tensile strength test showed that the MZI was not the fragile zone of the hybrid specimens. The rupture occurred in the middle of the SLMed portion, around 5 mm from the MZI, although the ultimate tensile strength was ~7% lower than that of the ordinary rolled material. Thus, the hybrid-manufacturing process did not significantly reduce the resistance of the hybrid specimens.
- Considering the SLM process as the second constraint of the hybrid process, it was observed that as the distance from the MZI increases, the number of pores increases slightly. However, the density of the SLM portion of the specimens was around 99.7%, which is expected in an ordinary SLM process.
- There is a tendency for the hardness to reduce in this region of the SLM portion (5 mm from the melting zone interface), but the hardness reduced by only around 2% (346 ± 6 HV0.5) and it was very similar to that of the substrate.
- The hybrid-manufacturing process was found to be a suitable alternative to reduce manufacturing costs and time. With the use of the mold manufactured in this study, this process saved around 53% in terms of costs and reduced the SLM manufacturing time by around 60%.
- The injection molding process reaches the steady-state regime within the first few cycles with the proposed conformal cooling channels, which is not the case with the baffle mold. This reduces the wastage of material.
- The temperature measured on the proposed conformal cooling mold was ~60% lower than that of the mold with baffle inserts, at the end of one molding cycle. Simulations showed a high homogeneity of the temperature on the conformal cooling inserts. To obtain similar homogeneity using the baffle insert, the injection molding time needs to be extended by 36%.
- The mold with conformal cooling resulted in plastic parts without internal defects. This is because the temperature homogeneity increased by a factor of 10, reducing the dimensional error by a factor of 7.

In general, the hybrid-manufacturing process is reliable, and provides an attractive alternative, saving manufacturing costs and time. The proposed bifurcated conformal cooling design produces better plastic parts and reduces the injection time. Therefore, the results reported herein demonstrate the potential of the concept investigated and suggested topics for future work include investigating the following:

- The influences of the SLM process parameters on the MZI in hybrid manufacturing.
- Mechanical and thermal fatigue in parts manufactured by the hybrid process.
- The precision of the CAE simulation for bifurcated conformal cooling design.

Author contribution Felipe Marin: manufactured the samples (SLM and machining) and the mold for injection molding of plastic parts. Performed injection molding process to produce the workpieces and analyses. Drafted the manuscript.

Adriano Fagali de Souza: planned and coordinated the research project and its funding. Analysis and discussion about the results of SLM and the entire manufacturing costs and times. Coordinated the laboratory activities. Written the final version.

Carlos Henrique Ahrens: analysis and discussion about the results of SLM and the plastic parts. Collaborated to write the literature review and the final version.

Luis Norberto López de Lacalle: general supervision of the work. Analysis and discussion about the results about SLM. Contributed with the structuring of the paper and final revision.

Availability of data and material (data transparency) The datasets obtained during the current work are available from the corresponding author upon request.

Declarations

Competing interests The authors declare no competing interests.

Disclaimer The authors declare that the paper is original and has been written based on the authors' own finding. All the figures and tables are original, and every expression from other published works was acknowledged and referenced. It is confirmed that all the authors are aware and satisfied of the authorship order and correspondence of the paper.

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