Design and fabrication of conformal cooling channels in molds

Feng, Shaochuan; Kamat, Amar M; Pei, Yutao T.

Published in:
International Journal of Heat and Mass Transfer

DOI:
10.1016/j.ijheatmasstransfer.2021.121082

International Journal of Heat and Mass Transfer 171 (2021) 121082

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/hmt

Review

Design and fabrication of conformal cooling channels in molds: Review and progress updates

Shaochuan Feng[a,b,*], Amar M. Kamat[a], Yutao Pei[a]

[a] Department of Advanced Production Engineering, Engineering and Technology Institute Groningen, Faculty of Science and Engineering, University of Groningen, Nijenborgh 4, 9747 AG Groningen, the Netherlands
[b] School of Mechanical Engineering, University of Science and Technology Beijing, Beijing 100083, China

ARTICLE INFO

Article history:
Received 24 December 2020
Revised 28 January 2021
Accepted 8 February 2021

Keywords:
Conformal cooling channels
Injection molding
Structural design
Additive manufacturing
Hybrid additive/subtractive manufacturing

ABSTRACT

Conformal cooling (CC) channels are a series of cooling channels that are equidistant from the mold cavity surfaces. CC systems show great promise to substitute conventional straight-drilled cooling systems as the former can provide more uniform and efficient cooling effects and thus improve the production quality and efficiency significantly. Although the design and manufacturing of CC systems are getting increasing attention, a comprehensive and systematic classification, comparison, and evaluation are still missing. The design, manufacturing, and applications of CC channels are reviewed and evaluated systematically and comprehensively in this review paper. To achieve a uniform and rapid cooling, some key design parameters of CC channels related to shape, size, and location of the channel have to be calculated and chosen carefully taking into account the cooling performance, mechanical strength, and coolant pressure drop. CC layouts are classified into eight types. The basic type, more complex types, and hybrid straight-drilled-CC molds are suitable for simply-shaped parts, complex-shaped parts, and locally complex parts, respectively. By using CC channels, the cycle time can be reduced up to 70%, and the shape deviations can be improved significantly. Epoxy casting and laser powder bed fusion (L-PBF) show the best applicability to aluminum (Al)-epoxy molds and metal molds, respectively, because of the high forming flexibility and fidelity. Meanwhile, laser powder deposition (LPD) has an exclusive advantage to fabricate multi-materials molds although it cannot print overhang regions directly. Hybrid L-PBF/computer-numerical-control (CNC) milling pointed out the future direction for the fabrication of high dimensional-accuracy CC molds, although there is still a long way to reduce the cost and raise efficiency. CC molds are expected to substitute straight-drilled cooling molds in the future, as it can significantly improve part quality, raise production rate and reduce production cost. In addition to this, the use of CC channels can be expanded to some advanced products that require high-performance self-cooling, such as gas turbine engines, photoinjectors and gears, improving working conditions and extending lifetime.

1. Introduction

The thermoforming process plays a key role in manufacturing, where a molten or thermally softened material is injected/compressed into molds and then cooled to resolidify in the form of the designed shape. Almost all the plastic products and some metal products are fabricated by thermoforming processes. According to the type of forming process, thermoforming is further classified into several specific methods such as injection molding, die casting, and hot extrusion, all of which involve a common requirement on molds, namely, their cooling ability. For instance, the injection molding process can be divided into four stages: filling, packing, cooling, and ejection [1]. In injection molding, part quality and cycle time depend strongly on the cooling stage, because the cooling stage accounts for up to 80% of the total cycle time and directly affects shape deviations (e.g. due to shrinkage, bend, and warpage) of the resulted plastic part [2,3].

Cooling channels are mandatory in molds to force the injected materials to cool down, and usually consist of a series of straight-drilled channels. Although they are machined easily and economically, straight-drilled channels cannot provide optimal cooling since their layouts are limited by the cavity shape (to prevent interference between the cavity and channels) and drilling process (only straight holes can be drilled). Therefore, in a sense, straight-

* Corresponding author.
E-mail addresses: shaochuan.feng@rug.nl, fengshaochuan@ustb.edu.cn (S. Feng).

https://doi.org/10.1016/j.ijheatmasstransfer.2021.121082

Nomenclature

A	surface area (m^2)
C_f	surface friction factor
C_p	specific heat ($J \cdot Kg^{-1} \cdot K^{-1}$)
d	cooling channel diameter (m)
h_C	contact heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
k_{st}	thermal conductivity of mold ($W \cdot m^{-1} \cdot K^{-1}$)
L	cooling channel length (m)
R_a	surface roughness of the channel wall (m)
Re	Reynolds number
s	part thickness (m)
T_C	coolant temperature (K)
T_E	ejection temperature (K)
T_i	initial temperature of the cavity (K)
T_M	melt temperature (K)
T_S	average temperature of tool surface (K)
T_W	mold temperature (K)
t_C	cooling time (s)
V	volume of the cavity (m^3)
x	pitch of two neighboring cooling channels (m)
y	distance from cavity surface to center of cooling channel (m)
ΔP	pressure drop (Pa)
δ	distance from cavity surface to conformal cooling line (m, equals to y in value)
ν	viscosity (m^2/s)
ρ	density (kg/m^3)

Acronyms

3D	three dimensional
AM	additive manufacturing
BEM	boundary element method
CC	conformal cooling
CFD	computational fluid dynamics
CNC	computer numerical control
DOE	design of experiments
EBM	electron beam melting
FEM	finite element method
GMAW	gas metal arc welding
L-PBF	laser powder bed fusion
LPD	laser powder deposition

Chemical symbols

Al	aluminum
Cu	copper

drilled circular channels are dictated by manufacturing constraints but may not be optimally suited for the most efficient cooling of the mold.

Consider a straight-drilled channel that is meant to cool down a curved cavity as shown in Fig. 1a [4]. The distance between the straight channel and the curved surface of the cavity varies along the channel, inducing differential cooling rates at the cavity surface and thus a temperature nonuniformity that consequently results in differential shrinkage and warpage in the manufactured part [5]. Moreover, because the part can be ejected from the mold only when the cavity temperature entirely cools down to below the ejection temperature, the cooling time depends on the highest-temperature point in the cavity as well as its local cooling rate. Thus, in the situation shown in Fig. 1a, the cooling time is determined by the temperature and cooling rate of the most left and most right of the cavity surface (where have the longest distance to the cooling channel) but not the middle of the cavity surface (where has the shortest distance to the cooling channel).

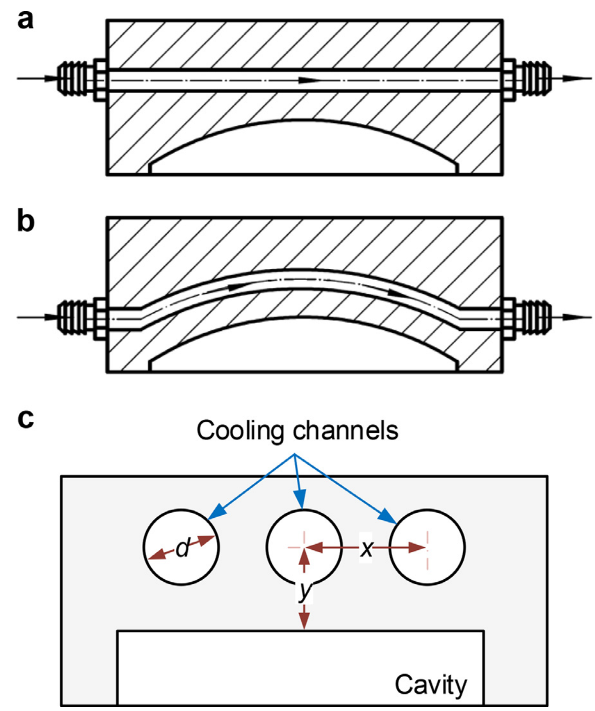

Fig. 1. Schematic of (a) a straight-drilled cooling channel, (b) a conformal cooling channel and (c) cross-sectional view of cooling channels (d – channel diameter, x – pitch of two neighboring channels, y – offset distance from cavity surface to channel center) (Subfigures a and b are reprinted by permission from [4], Copyright 2010 KSPE and Springer).

Therefore, cooling efficiency is not as high as desired when using straight-drilled cooling molds. On the other hand, sharp turns at the connection of two adjacent straight-drilled channels (as shown in Figs. 2a and b [6]) impede the coolant mobility, leading to a sudden pressure drop that weakens the cooling capacity downstream and further enhances the uneven cooling [2].

In most cases, the parts produced by thermoforming possess a thin shell, complex curved surface, and/or deep hollow features [7]. In such cases, differential shrinkage and warpage are more severe and the cooling rates are much lower, since the deep hollow feature tends to induce local heat accumulation [8]. This may require expensive rectification of the mold to ensure the dimensional accuracy of the part [9]. To mitigate the warpage and shorten cooling times, conformal cooling (CC) channels were proposed in the 1990s. The CC channel is designed as a curved channel with a constant distance to the cavity surface, as shown in Fig. 1b [4]. This ensures a uniform cooling rate along the channel and shortens the distance between the channel and the cavity surface. The use of CC channels can thus enhance the cooling performance of the mold significantly by reducing temperature differentials and the induced warpage [10] and increasing the cooling efficiency (reducing both the start-up time and cooling time) [11,12] considerably. In some cases, with proper cooling channel designs, CC channels can reduce the cooling time by as much as 80% [3] and the cycle time by 60–70% [11,13].

It is thus evident that an optimal design of CC channel networks is important to produce parts quickly, reliably, and more efficiently. Some basic design rules need to be obeyed to meet requirements on cooling performance, mechanical strength, coolant fluidity, and so on. Several pivotal design parameters such as cross-sectional shape, size (that specifically refers to the diameter for circular channels), offset distance to the cavity surface, and pitch between two adjacent channels (Fig. 1c), must be chosen carefully in light of the rules. Many methodologies and algorithms for de-

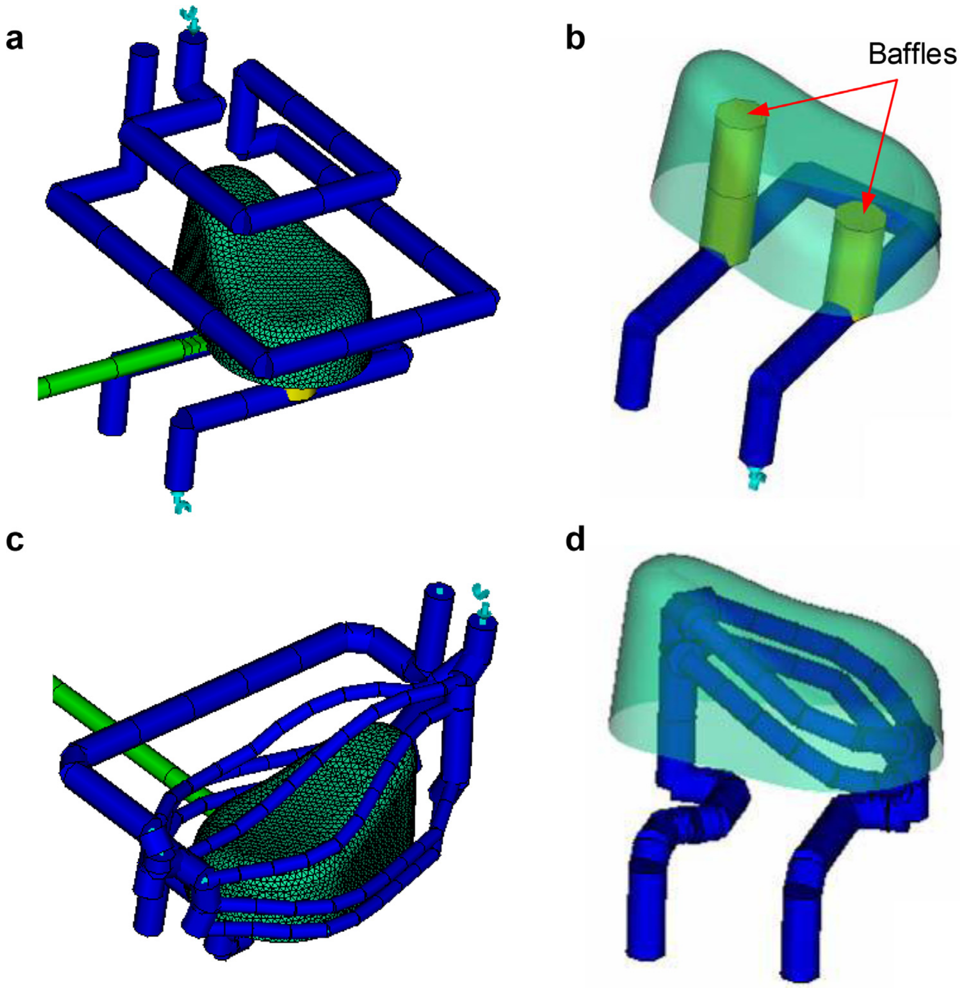

Fig. 2. Comparison of straight-drilled cooling channels and CC channels: straight-drilled cooling channels in cavity insert (a) and in core insert (b), and CC channels in cavity insert (c) and in core insert (d) (Adapted from [6] with permission from the authors).

signing CC channels have been proposed by researchers to enable the intelligent and optimal design of CC systems [14–16], and cooling channel layouts such as spiral [17], zigzag [18], profiled [19], and vascularized [20] have been proposed. However, in spite of the progress made in CC design, several obstacles still exist in front of mold designers and engineers, mainly because there exists no standard and uniform taxonomy and framework for CC system designs (of which there exist many).

While the design of CC channels is an important problem in itself, manufacturing the internal channels poses its own unique challenges. Most CC network designs, optimized for cooling efficiency, possess complex three-dimensional shapes (as shown in Figs. 2c and d [6]) that are difficult (or impossible) to be realized using conventional machining techniques such as drilling. Designers thus need to turn to modern technologies such as additive manufacturing (AM) to build molds containing CC channels. In the past two decades, the emergence of a variety of new metal AM technologies (e.g. powder bed fusion, binder jetting, and direct energy deposition) has enabled the fabrication of molds with complex-shaped CC channels. Although the technology readiness level of AM is lower than that of conventional methods (with respect to factors such as cost, efficiency, and dimensional accuracy), additively manufactured CC molds show considerable promise to compete with and finally substitute straight-drilled molds due to the potential of long-term savings due to more efficient and uniform cooling of the mold.

Although some review papers on the design and manufacturing of CC channels exist [21–23], a comprehensive and systematic classification, comparison, and evaluation of the design methodology and manufacturing techniques are still missing. In this review paper, straight-drilled cooling channels will be introduced briefly in Section 2. Then, the design methods and layouts of CC channels will be classified and reviewed systematically in Section 3. Features and advantages of eight types of CC channel layouts will be discussed in detail and evaluated according to simulation and experimental results of the resulting cooling performance in the mold. In Section 4, manufacturing techniques used historically and currently to fabricate CC molds will be discussed and compared in detail. Finally, the applications of CC channels in plastic and metal thermoforming and fabricating other advanced products will be briefly summarized in Section 5.

2. Straight-drilled cooling channels

2.1. Conventional straight-drilled cooling channels

2.1.1. Straight serial cooling channels

Conventional straight-drilled cooling channels are the most widely used channel systems in molds and dies up to now. They are broadly classified into two types, i.e. serial and parallel, as shown in Fig. 3 [24]. Practically, a straight serial cooling channel network (Fig. 3a) is the simplest and most commonly used cooling

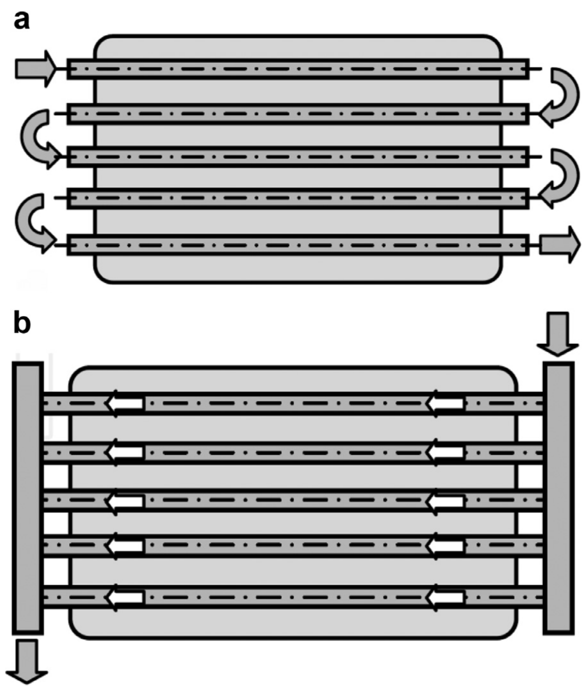

Fig. 3. Two types of conventional straight-drilled cooling channel networks: (a) straight serial cooling channel network and (b) straight parallel cooling channel network (Adapted from [24]).

channel system wherein all the cooling channels in the system are connected end to end to form a single loop with an inlet and an outlet.

2.1.2. Straight parallel cooling channels

A straight parallel cooling channel network (Fig. 3b) consists of a set of cooling channels that are connected to a supply manifold and a collection manifold but not connected directly with each other. For the straight parallel cooling channels, the coolant does not flow through every channel by order and the coolant, as well as its flow characteristics such as flow rate and flow resistance in each channel are independent of each other. Thus, compared to the straight serial cooling channels, the straight parallel cooling channels are more flexible in configuring the cooling rate and coolant temperature. For large molds and dies, more than one set of conventional straight-drilled cooling channels may be employed to implement a more efficient and more uniform coolant effect.

2.2. Straight-drilled cooling channels with baffles

Conventional straight-drilled cooling channels do not represent an ideal design, leaving much room for improvement towards an optimal cooling system. Before the development of laser AM, baffles in straight-drilled cooling channels were used as a compromise between the manufacturing ability and the efficacy of cooling channels [25]. Baffles are a series of tubes installed on the straight-drilled channels, and their endpoints are inside the space where the straight cooling channels are not convenient to be drilled, such as the semi-enclosed convex space in a core insert shown in Fig. 2b (the green tubes inside the core insert are the baffles). As shown in Section 2.1, both two ends of a straight-drilled cooling channel are connected to other channels. For a baffle, only one end is connected to another channel while the other end (far-end) is not connected with any channels, with a wall inside the baffle forcing the coolant flow through the baffle, as shown in Fig. 4 [4]. The far-ends of a series of baffles are equidistant from the cavity surface and much closer to the cavity surface compared to the straight-drilled

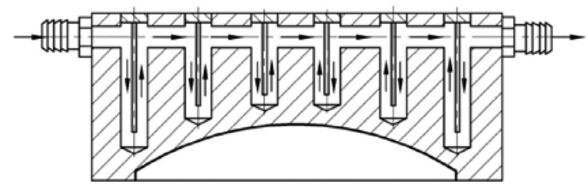

Fig. 4. The array of baffles (Reprinted by permission from [4], Copyright 2010 KSPE and Springer).

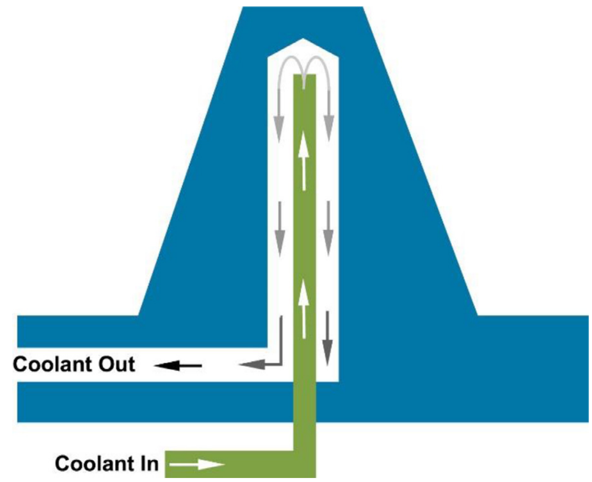

Fig. 5. Schematic of bubbler cooling (Reprinted by permission from [10], Copyright 2015 Elsevier).

channel, so that the baffles can enhance the cooling efficiency and uniformity.

2.3. Straight-drilled cooling channels with bubblers

Another approach to enhance the cooling effect in straight-drilled cooling channels is bubblers, which are similar to baffles. A bubbler is a tubular cavity with a larger diameter than a straight-drilled cooling channel. A concentric tube is nested inside the bubbler, as the inlet, supplying coolant to the innermost end of the bubbler. Meanwhile, a straight-drilled cooling channel is connected to the outermost end of the bubbler as the outlet, as shown in Fig. 5 [10], making it an effective way to ensure that the cooling channels reach the concave areas [26].

3. Structural design of conformal cooling channels

3.1. Physical and mathematical principles in structural design of conformal cooling channels

The goals in the design and optimization of CC channels are to ensure uniformity in the temperature distribution, reduce the cooling time needed to reach the ejection temperature, and minimize shrinkage and part warpage [27,28]. CC is, at its core, a heat and mass transfer process where the coolant flows through the CC channels taking away the heat from the mold cavity and cooling down the injected polymer. The physics of this process is described by the coupling of the Navier-Stokes equations and the convection-diffusion equation [29,30].

In injection molding, most of the heat is taken away by the coolant in CC channels while less than 5% of the heat losses occur through the exterior surfaces of the mold [31]. After several cycles, the molding process reaches a steady state in which the average temperature of the mold is constant. The energy balance principle is applicable to this heat transfer process according to which the

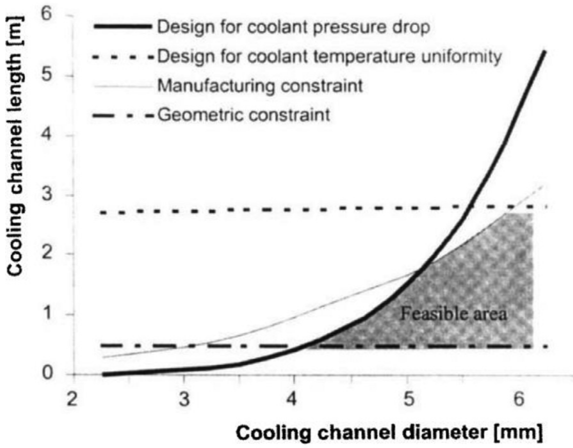

Fig. 6. A CC design window defined by the cooling channel diameter and the cooling line length (Adapted by permission from [35], Copyright 2001 Society of Plastics Engineers).

heat transfer rate from the cavity to the tools is assumed to be equal to that from the tools to the coolant [32]. The cooling time is calculated by [31]:

$$t_C = \frac{[C_p(T_M - T_E)]\rho \frac{s}{2} x}{T_w - T_C} \left\{ \frac{1}{2\pi k_{st}} \ln\left[\frac{2x \sinh\left(2\pi \frac{y}{x}\right)}{\pi d} \right] + \frac{1}{0.03139\pi \, \mathrm{Re}^{0.8}} \right\} \quad (1)$$

where, t_C, T_M, T_E, T_W, T_C, C_p, ρ, s, x, y, k_{st}, d, and Re are the cooling time, melt temperature, ejection temperature, mold temperature, coolant temperature, specific heat, density, part thickness, pitch of two neighboring cooling channels, distance from cavity surface to center of the cooling channel, thermal conductivity of mold, cooling channel diameter and the Reynolds number, respectively. Similarly, a simpler relationship between the average temperature of a tool surface and the cooling time is given by [33]:

$$T_S = \frac{T_i \cdot \exp\left[-\left(\frac{Ah_C}{\rho C_p V}\right) t_C\right] - T_E}{\exp\left[-\left(\frac{Ah_C}{\rho C_p V}\right) t_C\right] - 1} \quad (2)$$

where, T_S, T_i, A, h_C, and V are the average temperature of tool surface, the initial temperature of the cavity, surface area, contact heat transfer coefficient, and volume of the cavity, respectively. More practically, an empirical formula to rapidly estimate the cooling time according to the distance from the cavity surface to the center of a cooling channel was proposed as [34]:

$$t_C = 141.49 \ln[y(\mathrm{mm})] + 733.03 \quad (3)$$

Some constraints and limitations should be taken into account when designing a CC system, e.g. geometric constraints, manufacturing constraints, coolant temperature uniformity, and coolant pressure drop, as shown in Fig. 6 [35]. Theoretically, decreasing the distance from the cavity surface to the center of a cooling channel is necessary for reducing the cooling time. However, there is a lower limit to this cavity-channel distance to maintain the strength of the wall, with the recommended values being $1 \times d$ for steel, $1.5 \times d$ for beryllium, and $2 \times d$ for aluminum (Al) [36] where d is the cooling channel diameter. Moreover, the increasing temperature and the pressure drop of the coolant along the channel passage weaken its heat-carrying ability and cause the temperature nonuniformity in the cavity surface. Better cooling performance can be achieved by using variable offset distances and/or variable channel diameters (Fig. 7) to compensate for this nonuniformity

Fig. 7. A design of a variable diameter CC channel.

Table 1
General recommendations for the cooling channel diameter depending upon cavity thickness [40].

Cavity thickness, s (mm)	Cooling channel diameter, d (mm)
$s \leq 2$	$8 \leq d \leq 10$
$2 < s \leq 4$	$10 < d \leq 12$
$4 < s \leq 6$	$12 < d \leq 14$

[37,38]. The pitch of two neighboring cooling channels is recommended to be 3–5 times d [39]. The cooling channel diameter (d) is usually 8–14 mm depending on the cavity thickness, as listed in Table 1 [40].

In Eq. (1), it can be observed that the Reynolds number is inversely related to the cooling time. The greater the Reynolds number (indicating a higher degree of turbulence in the coolant flow), the lower the average temperature in the molds [41]. Nevertheless, when the Reynolds number of the turbulent coolant flow is greater than 10,000, the rate of pressure drop increases rapidly, but the rate of thermal convection increases slowly, resulting in a decrease of the total heat transfer rate. The Reynolds number is thus recommended to be in the range of 4,000–10,000 with 10,000 being the optimal value [32,42,43].

The pressure drop depends upon the flow conditions as follows [44,45]:

$$\Delta P = \frac{L}{2d} \rho v^2 C_f \quad (4)$$

where, ΔP, L, v and C_f are the pressure drop, cooling channel length, viscosity, and surface friction factor, respectively. For laminar flow, C_f is calculated by

$$C_f = \frac{16}{\mathrm{Re}} \quad (5)$$

The increase of surface roughness leads to the increase of contact area and the enhancement of convection between the coolant and channel surface [46]. When the coolant experiences turbulent flow, however, the surface roughness of the channel wall affects the pressure drop by determining C_f:

$$C_f = \frac{0.25}{1.8^2} \left\{ \log_{10}\left[\left(\frac{R_a}{3.7d} \right)^{1.11} + \frac{6.9}{\mathrm{Re}} \right] \right\}^{-2} \quad (6)$$

where R_a is the surface roughness of the channel wall. It can be concluded that the rougher the wall, the larger the pressure drop, and the smaller the flow rate, especially when the coolant flow is completely turbulent [34,47].

Although a higher coolant flow rate is beneficial to reduce the maximum and average temperatures, it also induces a higher pressure drop and thus requires a stronger coolant pumping system (meaning a higher financial investment) [48]. Reducing the required flow rate will not only save costs related to the coolant supply system but will also ensure adequate cooling of the molds, especially for multi-cavity molds. Finite element method (FEM) simulation results have shown that although the coolant flow rate in CC channels is less than half of that for straight cooling channels, the cycle time achieved by the former method can be less than two-thirds of the latter because of much higher cooling efficiencies [8].

3.2. Methodology for structural design and optimization of conformal cooling channels

3.2.1. Experimental based design

Design of experiments (DOE) is a convenient and well-established methodology to correlate design parameters and process parameters with the cooling performance of a CC system. A number of DOE techniques, such as full factorial design [48], orthogonal design [49], Taguchi method [50–52], response surface methodology [53–55], and optimal Latin hypercube method [53], have been adopted to design and optimize CC systems. Here, the experiments can be conducted either physically or numerically. In addition to injection molding trials, FEM or computational fluid dynamics (CFD) simulations are more economical and efficient approaches to evaluate the cooling performance than injection molding trials due to the high costs of money and time in mold manufacturing although the fidelity of simulation needs to be verified. Based on the simulation result, a formula was proposed to calculate the size (diameter and length) and position of spiral CC channels for injection molds of plastic cups in all dimensions with upper limit of 5 mm on thickness [56]. An optimization indicator, viz. the ratio of product cooling rates and coolant pumping energy, was employed to yield the most advantageous outcome from the viewpoints of both cooling performance and economy.

Combining orthogonal experiment with range analysis, Li et al. proposed an optimized parameter combination with a cooling channel diameter of 4 mm, an offset-diameter ratio (the ratio of the distance of cavity wall from the center of cooling channel and the cooling channel diameter) of 2.2, a cooling water temperature of 25 °C, and a surface roughness of cooling channel wall of 0.05 μm [49]. However, this optimized parameter combination was obtained from the numerical simulation results. It can be noted that the required wall roughness of 0.05 μm is very difficult to achieve practically. Jahan et al. proposed an optimum design configuration in thermal-mechanical performance and provided a guideline chart that is visual and practical for mold designers to choose design parameters by using DOE combined with a trade-off technique [57,58]. DOE is a simple approach since it does not need any specialized optimization algorithms. However, a limitation is that the design parameters can only be chosen from the experimental ranges and cannot be expanded to a wider range. If a design does not fall into the range of the experimental data, the guideline chart will be rendered impractical.

3.2.2. Design and optimization based on the conformal cooling line

CC lines (or CC surfaces in 3D) are the most widely used approach to design and optimize the CC channels [6,59,60]. CC lines/surfaces are a series of curves/curved surfaces (Γ_3 in Fig. 8) offset from the cavity profile (Γ_2 in Fig. 8) [61]. By using CC lines, the procedures to design CC channels are generally divided into two steps: (a) extracting the conformal loops based on the geometric contour of the part, and (b) blending these loops to generate spiral CC channels, as shown in Fig. 9 [17].

Some methods have been proposed to determine the arrangement of the CC channels, e.g. the offset of the channel with respect to the cavity and the spacing between the adjacent channels. A triangular method was proposed based on the energy balance principles, as shown in Fig. 10 [32]. Boundary-distance maps were introduced to generate evenly distributed channels [62]. In the work of Agazzi et al., the fluid temperature was optimized by minimizing an objective function related to the level and surface distribution of the part temperature [59].

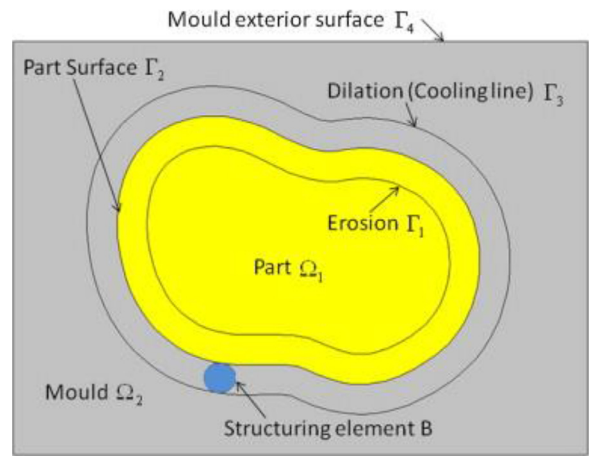

Fig. 8. Schematic of CC line/surface (Reprinted by permission from [61], Copyright 2012 Elsevier).

For a complex shaped part, a practical method is to decompose the complex surface into simpler sub-surfaces and design individual sub-cooling channel systems for these sub-surfaces [17,63,64], as shown in Fig. 11. These sub-cooling channel systems may have individual inlet and outlet or share an inlet and outlet by connecting with each other.

3.2.3. Optimization using expert algorithms

The design approaches based on experiments and experience are not adequate when designing molds and dies for parts with more complex geometric shapes. Some automatic methods have been developed to design and optimize the layout of the (straight-drilled) cooling channels, such as configuration space (C-space) method combined with heuristics genetic algorithms [65], two-stage automatic design method with a heuristic-search-based graph traversal algorithm [66], boundary element method (BEM) [9], and two-phase evolutionary algorithm [67].

In light of the design principles and procedures for CC channels, an increasing number of research groups reported their approaches and strategies of structural optimization for CC channels. In recent years, the automated and intelligent implementation in the design and optimization of CC channels by employing sophisticated algorithms has been gaining traction. A bottom-up approach was proposed to generate automatically cooling channel systems following the design procedure of preliminary design, layout design and detailed design [14]. Multi-objective optimization for CC channels is usually employed to shorten the cooling time and reduce the warpage [68]. Objective functions were correspondingly proposed to increase the cooling rate and homogenize the temperature distribution on cavity surfaces [69]. A number of methods/algorithms were developed to solve these objective functions and find their Pareto optimal frontiers [53,69,70], e.g. a conjugate gradient algorithm coupled with a Lagrangian approach [69], Voronoi diagram algorithms [71,72], and a genetic algorithm [73].

Recently, gradient-based algorithms (GBA) and robust genetic algorithms (RGA) were respectively combined with COMSOL Multiphysics software to optimize the geometric layout of spiral CC channels [15]. The simulation result shows that both GBA and RGA provided better designs as compared to conventional design with significant improvements in the cooling time, temperature uniformity, and warpage, with the RGA-optimized design proving superior to the GBA-optimized design.

Cycle-averaged approach and BEM were adopted to design and optimize the meshy-topological CC channel systems [74]. By using these methods, the nodes of the channel network were optimized and the topology was simplified and smoothed. For cool-

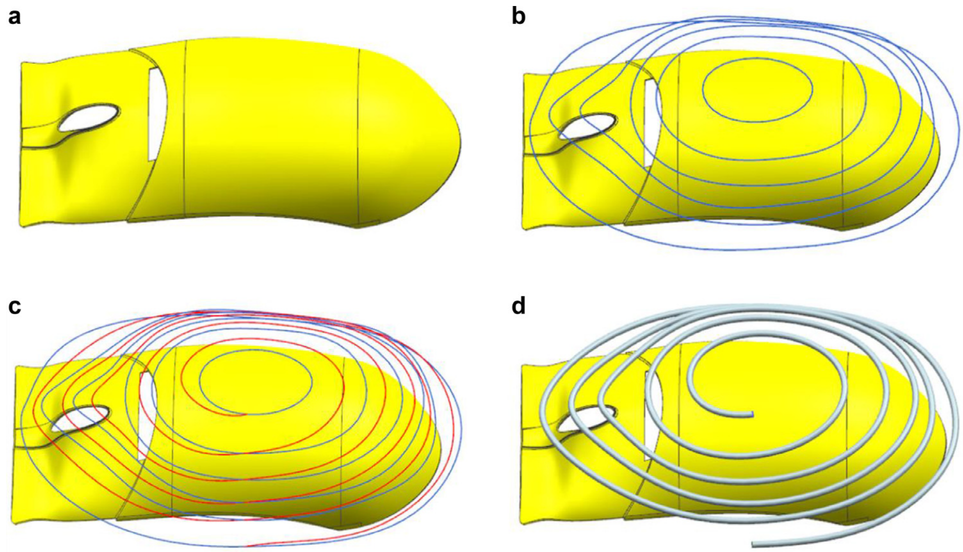

Fig. 9. A two-step method to generate CC channels: (a) geometric shape of a part to be injected, (b) generation of conformal loops, (c) generation of spiral curve, and (d) generation of the CC channel (Adapted from [17]).

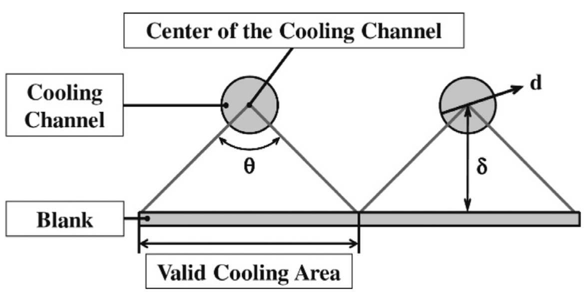

Fig. 10. Triangular method for arranging cross-sections of cooling channels on a CC line (δ is the offset of the CC line) (Reprinted by permission from [32], Copyright 2013 Springer-Verlag London).

Fig. 11. A design consisting of two sub-CC channel systems (Reprinted by permission from [64], Copyright 2009 KSAE and Springer).

ing systems with a more complex topology, a Lagrange multipliers method was employed by defining a geometric parameter, svelteness (equals to external length scale divided by internal length scale), to minimize the local pressure drop and along-channel pressure drop [16]. Besides, a visibility technique was proposed to generate automatically CC channels for a complex-shaped cavity surface without requiring the engineer to have experience in the design of conventional straight-drilled cooling channels [75].

3.2.4. Modular/parametrical design of conformal cooling channels

Modular and parametric design resembles a block building process. The CC channel system is rapidly built by locating and connecting several standard cells. The basic steps are (i) determining the space for cooling channels, e.g. to determine the CC surface by offsetting the cavity surface; (ii) dividing the space into small units such that each unit corresponds to a cooling cell; and (iii) connecting (sub-) channels in each cell and setting coolant inlet and outlet. The procedure of designing a 2D modular CC system is schematically illustrated in Fig. 12 [76]. The offsetting method [77] and duality principle [76] were employed respectively as the main design method and principle for modular CC channels. Details on modularly/parametrically designed CC channels will be reviewed in Section 3.3.5.

3.2.5. Solid modeling based on topology optimization

In addition to the above methods, another approach to design CC channels is based on topology optimization. This is typically used for heterogeneous (dual-materials) modeling and lightweight designs. Using this approach, the channel position problem is replaced with a topology optimization problem taking into account flow resistance, heat conduction, and forced/natural convection [78]. Shin proposed a heterogeneous solid modeling approach for CC channels made of functionally graded materials [79]. In this model, a weighting function was defined to specify the distribution (volume fraction) of each material composition, with an exponent being used to control the form of the weighting function (linear, parabolic, etc.). In the work of Huang and Fadel [80], a two-step method was devised for bi-objective optimization of heterogeneous cooling channels. This is a generic method for designing both straight-drilled and CC channels. In the first step, a single fundamental mold material was assumed, and optimal cooling channel sizes, locations, and coolant flow rates were obtained through a gradient-based optimization method. Based on the optimal results from the first step, the second step was to find sensitive areas and distribute both fundamental and secondary materials in these areas through a genetic algorithm. Further, the authors [80] also proposed three design rules regarding materials selection for heterogeneous cooling channels: a) the difference between the thermal diffusivities of the two mold materials must be large enough, b) the fundamental mold material must be a metal or alloy with sufficient strength and hardness, and c) ceramics, metal, or alloy with reasonable strength and hardness can be selected as the secondary mold material.

The problem of weight minimization is solved by gradient-based optimization after analytically deriving the sensitivity of the

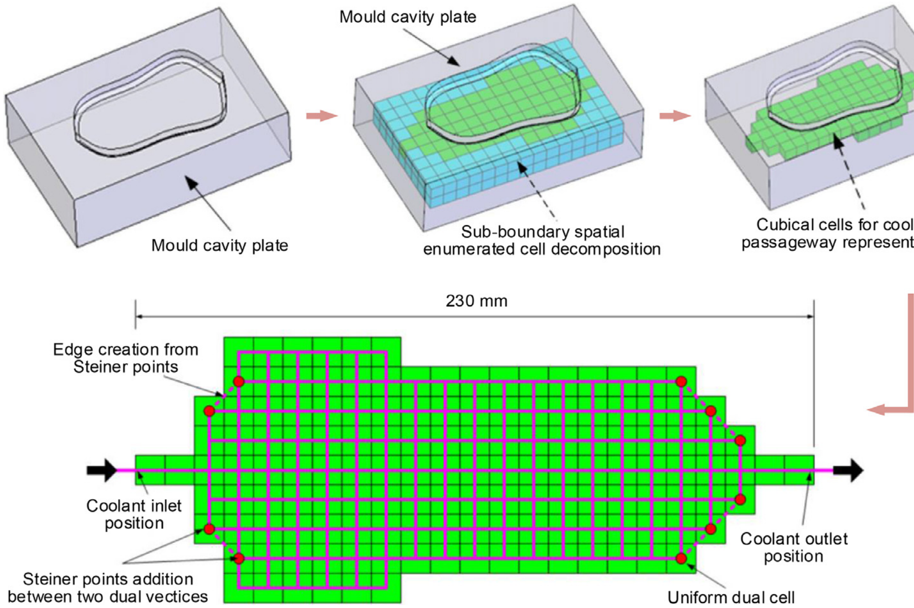

Fig. 12. Procedures of designing a 2D modular CC system (Adapted by permission from [76], Copyright 2011 Elsevier).

coupled thermo-fluid model using the adjoint method [30]. The gradient-based solver can also be used to solve the polynomial interpolation of the homogenization properties seeking the most lightweight solution satisfying the constraint conditions [81]. A 2D conceptual model for the generation of thermal-mechanical porous structures was proposed to design the lightweight CC channels for the purpose of reducing weight, saving material and manufacturing cost, and enhancing thermal performance [82]. In this two-objective optimization model, the optimized topology optimization for both steady heat conduction and structural stability was calculated by assigning them linear weight factors. This work showed the potential of efficiently reducing the materials between cavity and coolants without significantly decreasing the performance of the components. The maximum volume reduction of the materials was expected to be as high as 60%.

3.3. Types and layouts of conformal cooling channels

3.3.1. Conformal cooling channels with basic topology

The spiral shape is one of the simplest and most common basic topologies for CC channels, as shown in Fig. 9d [17] and Fig. 11 [64]. Besides spiral, the linear shape (zigzag type) is another popular option for the topology of CC channels, as shown in Fig. 13 [18]. It must be noted that as compared to the spiral type, the zigzag shape has many sudden turns that increase the pressure drop, thereby slowing down the flow rate and consequently weakening the cooling efficiency [41]. According to the kind of connection between each channel, CC channels can also be classified into either series or parallel types [28,48], similar to conventional straight-drilled cooling channels (Fig. 3). For instance, the spiral CC channel system can be classified as: (i) a single spiral in series connection, (ii) double (multiple) spirals in series connection, or (iii) spirals in parallel connection [17].

3.3.2. Meshy-topological conformal cooling channels

The applicability of spiral CC channels reduces as the complexity of the geometric shape of the part increases. Compared to spiral CC channels, meshy-topological CC channels are more suitable for this situation, as shown in Fig. 14 [71]. The vascularized CC system, inspired by the design of blood vessels, is another meshy-topological layout [83]. This biomimetic design [16] was proposed

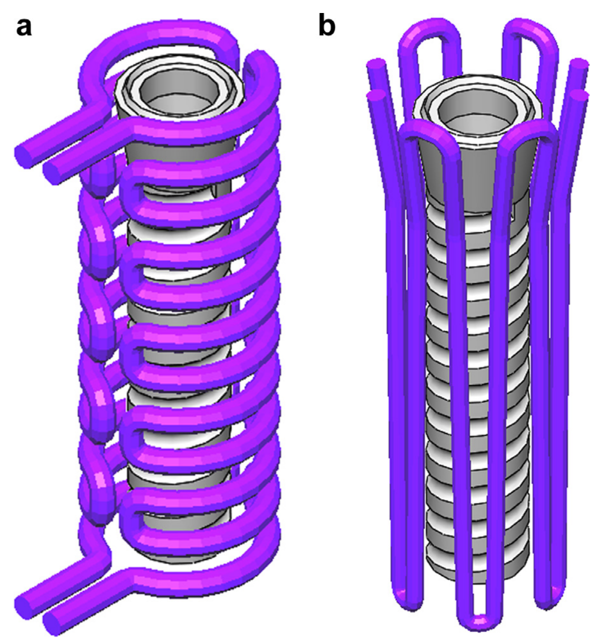

Fig. 13. Two zigzag CC system designs (Reprinted from [18] with permission from the authors).

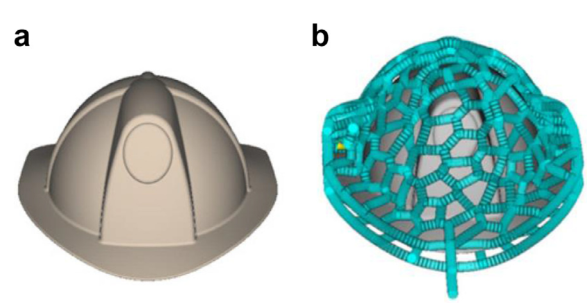

Fig. 14. Design of a meshy-topological CC channel system: (a) injected part and (b) layout of CC channels (Adapted by permission from [71], Copyright 2011 Elsevier).

Fig. 15. Vascularized CC system (Adapted from [20] with permission from the authors).

to address the hot spots in complex-shaped parts with narrow and deep hollow areas, such as an automotive oil filter housing, as shown in Fig. 15 [20]. In this design, the major artery branches into sub-arteries, which could further divide into capillary tubes, thus eliminating local heat accumulation and achieving uniform temperature distribution.

The two main characteristics of meshy-topological CC channel systems are the complex topology and the non-uniform diameter, as shown in Fig. 16 [74]. Consequently, the flow distribution and pressure drop should be paid more attention to when designing a meshy-topological CC system, since the usual design rules are derived for simpler topologies with uniform channel diameters and shapes. Further, corresponding to the allowable pressure drop, there exists a minimum channel diameter below which the channel cannot be further divided into sub-branches [72].

3.3.3. Conformal cooling channels with non-circular cross-sections

Although circular cross-sections are the most common in the design of CC channels (since traditionally drilled holes are necessarily circular in shape), some attempts have also been made to develop CC channels with non-circular cross-sections such as square, rectangular, diamond, trapezoidal, elliptical, and other polygons [51,84–86]. This is increasingly viable due to the recent progress in metal AM which does not impose any constraints on the channel shape. Although the stiffness of a rectangular channel is less than that of its circular counterpart, the former is more efficient and homogeneous in cooling because its effective cooling surface area is larger than the latter for the same cross-sectional area [87,88]. The width of the main grooves (l_w) is recommended to be in the range of 10–20 mm, and the recommended values for the groove depth, the pitch between two neighboring groove walls, and the groove offset from the cavity surface are $(0.3–0.4)l_w$, $(1–1.5)l_w$ and $(0.7–1.5)l_w$, respectively [8]. To enhance its cooling effect by enlarging the contact area, Kamarudin et al. proposed a modified design by adding sub-grooves to the square-shaped CC channels [89], as shown in Fig. 17.

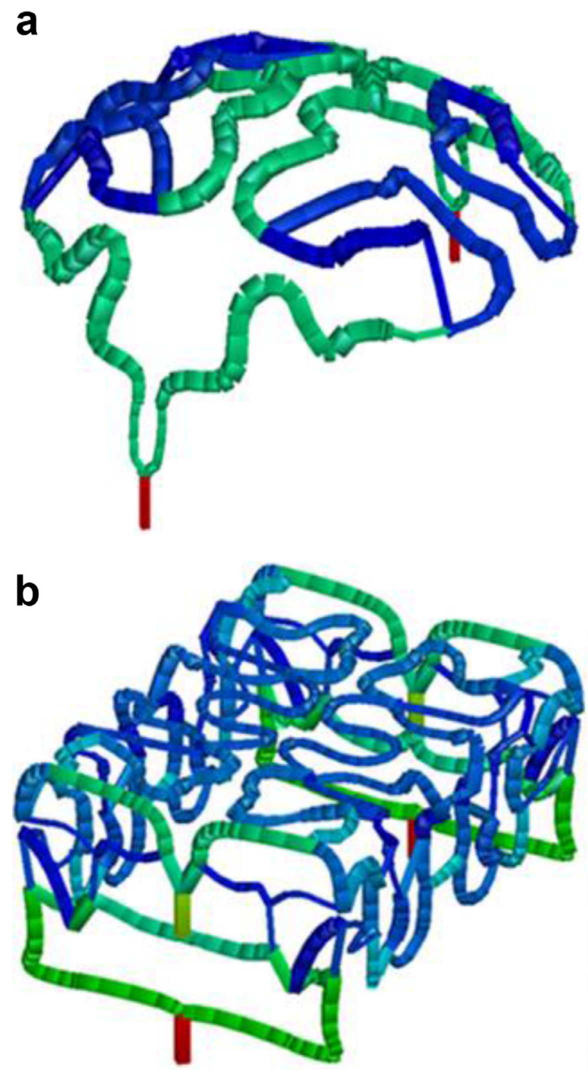

Fig. 16. Two instances of meshy-topological CC channel systems (Adapted by permission from [74], Copyright 2017 Springer-Verlag London).

In addition to sub-grooves, ribbed channel designs, wherein ribs (inclined [90], wavy [91,92], V-shaped [92], rod array [93], etc.) were designed on the inner surface of the channel (shown in Fig. 18), can also enlarge the contact area between coolant and channel surface. Similarly, a design with fins in the circular or square channels was proposed to further enlarge the surface area of CC channels (thus leveraging the potential of AM) as shown in Figs. 19a-d [94]. The CFD simulation result (Figs. 19e and f) showed that the heat transfer to the coolant was significantly enhanced by adding fins [94]. However, manufacturing this complex fin shape will be a considerable challenge to AM (especially considering its printing accuracy) because of the small thickness of the fins (0.2–0.6 mm). Moreover, before this proposal could be realistically implemented using AM, several practical issues need to be addressed, e.g. how to remove the metal powder (in the case of powder bed fusion) from the narrow and curved slit-like channels.

To avoid shape deviation (or even collapse) at the top of the horizontal circular channel [95], a self-supporting teardrop profile was proposed in which the upper half of the circular profile was modified to a “triangular roof” with two 40°–45° inclines, as shown

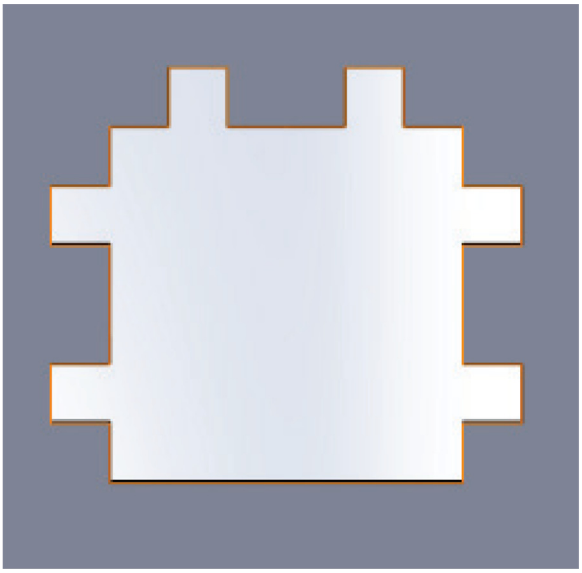

Fig. 17. The cross-sectional shape of a square-shaped CC channel with sub-grooves (Adapted by permission from [89], Copyright 2017 AIP Publishing).

in Fig. 20 [96]. Although the design modification reduced the shape deviation of the additively manufactured channel, this was an undesired compromise since the modification was not necessarily optimal from the cooling efficiency point of view but rather a concession for manufacturability. Furthermore, the teardrop shape features a stress concentrator at the sharp corner, reducing its fatigue resistance.

Circular cooling channels can induce uneven heat dissipation just by virtue of their shape; e.g., consider the situation in Fig. 21a where, even though the channel is conformal with the cavity surface in the axial direction, the distance from the edges of the circular cross-sectional profile to the cavity (namely in the radial direction) is not constant. The issue can be resolved by employing a profiled (semicircular) CC channel to further enhance the uniformity of heat dissipation [50,97]. The modified cross-sectional contour consists of two parts, i.e. a half-circular part and a straight part, with the straight part being parallel to the cavity contour, as shown in Fig. 21b. The profiled CC channel is more in line with the concept of CC. The simulation results showed that the cooling time using the profiled CC channel is shorter than using the circular CC channel due to better thermal dissipation (in the study of Altaf et al., the heat flow increase and cooling time reduction were 14.6% [97] and 22% [19], respectively). However, the sharp corner at the junction of the half-circular part and the straight part may induce stress concentration and crack propagation. This stress concentration was found in the work of Hopkinson and Dickens, who fabricated CC channels with star-shaped cross-sections using laser AM [98]. From the point of view of fracture mechanics, 3D effects near sharply-V-notches play an important role in crack initiation and rapid propagation, finally leading to brittle failure [99–101].

Therefore, the profiled CC channel raises the difficulty of design and manufacturing. It is necessary to find a balance between the cooling effect and the cost by further investigation. Further, CC channels with varying cross-sections have been proposed to achieve more efficient and homogenous cooling. An example is shown in Fig. 22 where the channels are locally widened at the hot spots to increase heat transfer where needed [61].

3.3.4. Conformal cooling bubbler

A CC bubbler is a chamber in the thin wall mold that does not look like a tubular channel but is essentially a CC channel with varying diameter and/or profiled cross-sectional shape [102]. In a conformal bubbler cooling mold, the wall thickness is kept constant and web or ribs are added to the mold construction in order to withstand pressure on the mold surface and to prevent its deflection during the plastic injection cycle, as shown in Fig. 23 [10]. This strengthening of the structures may, however, lead to additional pressure drop in the coolant flow, and a tradeoff must be maintained between pressure drop and mechanical strength through careful calculations when designing CC bubblers.

3.3.5. Modularly/parametrically designed conformal cooling channels

Mercado-Colmenero et al. designed a cooling cell consisting of six hexagonal-distributed inlet channels and a single outlet channel to realize the CC system, as shown in Fig. 24a [73]. Using parametric design methodology reduces the requirements for expertise and experience of designers. This simplifies the design process of complex CC channel systems and reduces the development costs

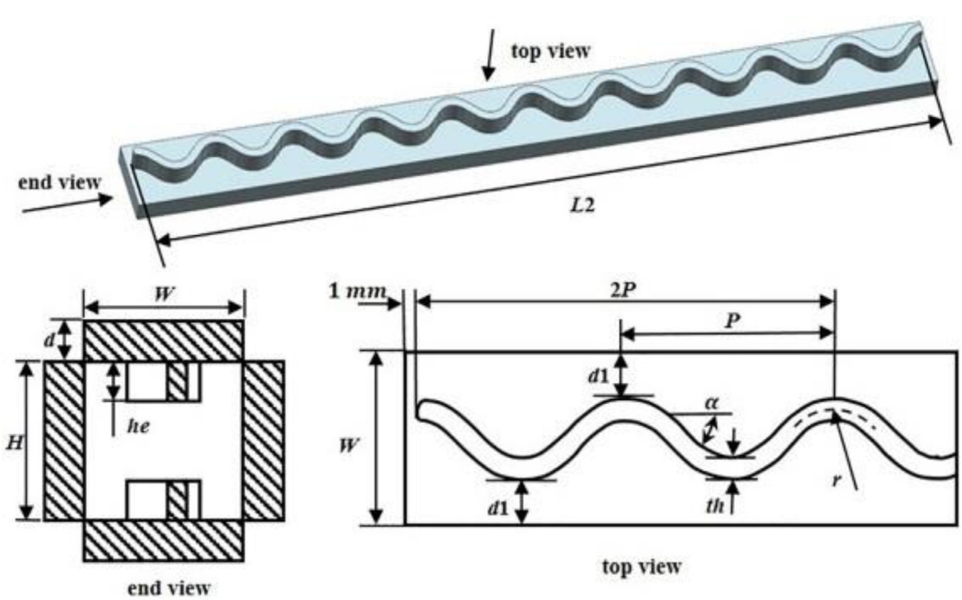

Fig. 18. Design of a rectangular channel with wavy ribs (Reprinted by permission from [92], Copyright 2018 Elsevier).

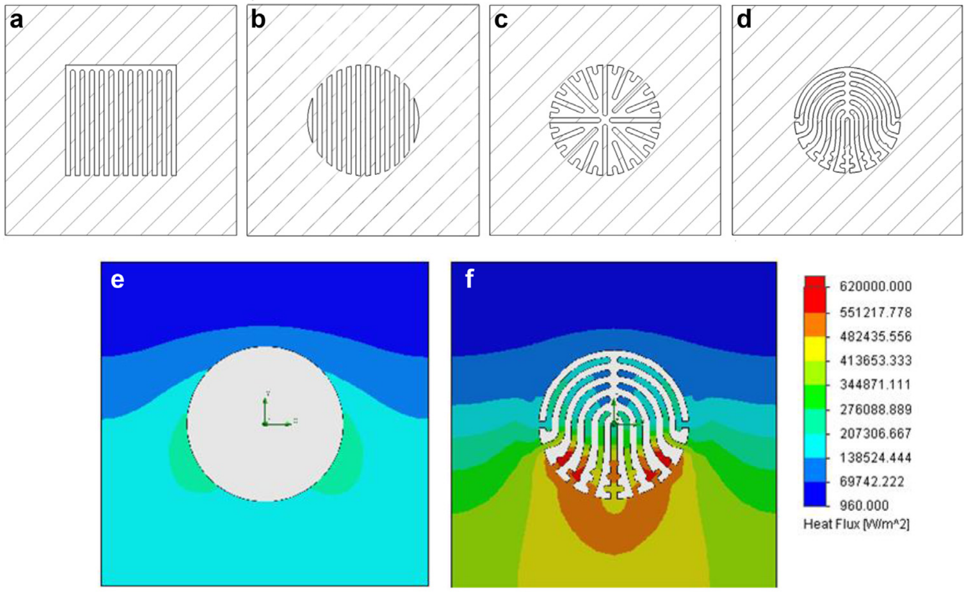

Fig. 19. Designs of fins in CC channels (a-d), and heat flux of (e) a normal circular channel and (f) a channel with fins (Adapted from [94]).

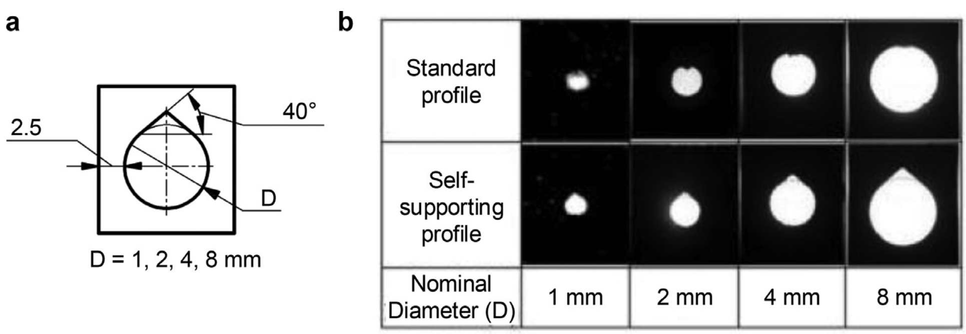

Fig. 20. (a) Design of self-supporting profile and (b) comparison of printed circular and self-supporting profiles (Adapted by permission from [96], Copyright 2016 Emerald Publishing Limited).

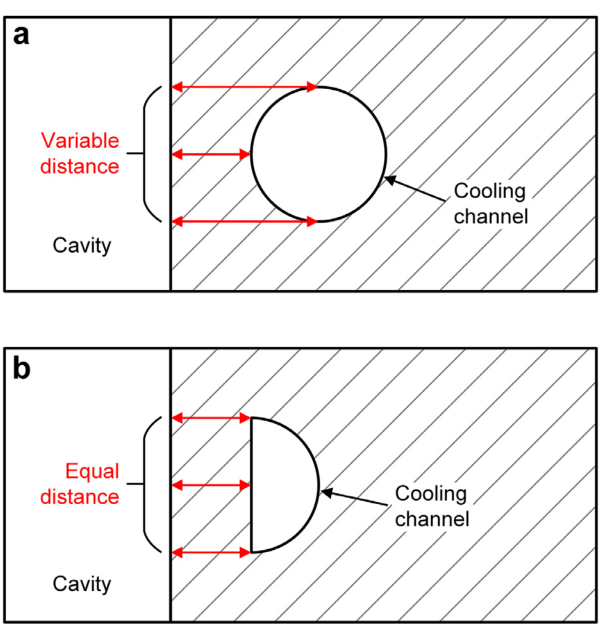

Fig. 21. (a) Circular (conformal) cooling channel and (b) profiled (conformal) cooling channel.

and cycles. However, due to the densely distributed channels and their complex topology inside the molds, some important factors, such as pressure drop, mechanical strength, and manufacturability, should also be taken into consideration when conducting modular and parametric design. Particularly, for the design of Mercado-Colmenero et al. shown in Fig. 24b [73], there may be spatial interference between inlet and outlet channels in the case of complex part geometries.

3.3.6. Lattice/porous structure in conformal cooling channels

Lattice structural CC channels are a special type of modularly and parametrically designed CC channels. A scaffolding architecture with cubic basic cells, developed by Au and Yu, represents a typical case of modular design for CC channels, as shown in Fig. 25 [76,77]. By using the orthogonal support structures in the scaffolding architecture, the volume of cooling channels is greatly expanded. The support structures strengthen the mechanical strength and heighten the manufacturability of AM by reducing the span of the overhang regions. Further, support structures provide the possibility of integrating numerous parallel CC channels into an interconnected layer. Therefore, these lattice cooling structures are more often referred to as CC layers (as opposed to simply 'channels').

Cubic lattices with orthogonal struts limit the outline of the CC layer to step-like, as shown in Fig. 25c. To make the CC layer more conformal, a modified scaffolding layout was proposed, as shown

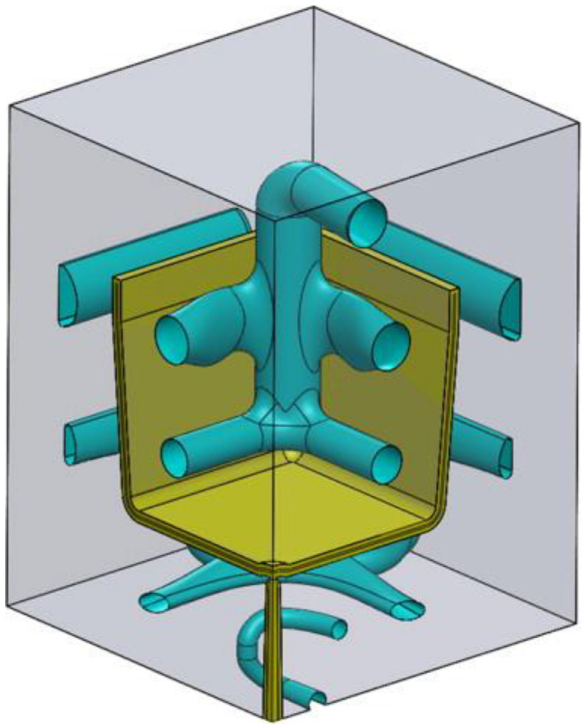

Fig. 22. A design of CC system with varying cross-sections (quarter of the part) (Reprinted by permission from [61], Copyright 2012 Elsevier).

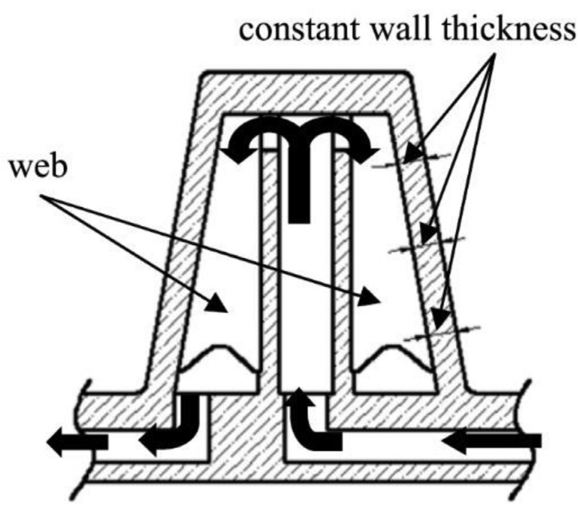

Fig. 23. Conformal bubbler cooling in a mold core (Reprinted by permission from [10], Copyright 2015 Elsevier).

in Fig. 26. The size and shape of each unit cell were varied according to the shape of an injection molded part, providing a more flexible layout (occurring, however, at the cost of a complicated design procedure) [103]. Attempts were also made to build the support structures in other forms, such as cross-type and N-type unit cells, as shown in Fig. 27 [104]. Some design principles were proposed, such as: (a) the struts are ideally over 45° from the horizontal and with low enough aspect ratios, (b) the overhang span should be as small as possible while not impeding flow, and (c) the unit cells need a base level of symmetry.

The lattices enhance the heat transfer due to increased interfacial surface areas and fluid vorticity [104,105]. The simulation results, however, indicated that only the average mold temperature decreased to some extent by using the CC layers as com-

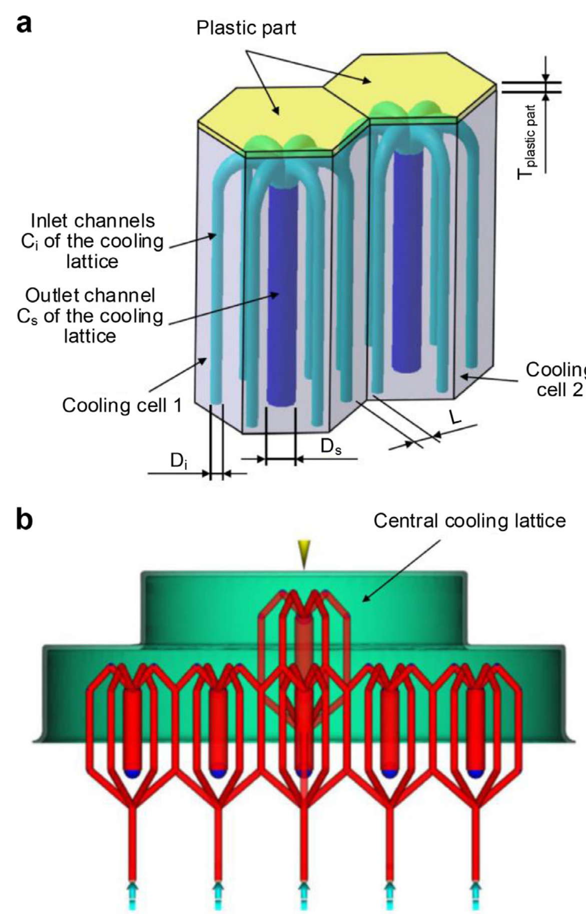

Fig. 24. Parametric CC channels designed by Mercado-Colmenero et al.: (a) design of a cooling cell and (b) cooling channel system combined by cooling cells (Reprinted by permission from [73], Copyright 2019 Springer-Verlag London).

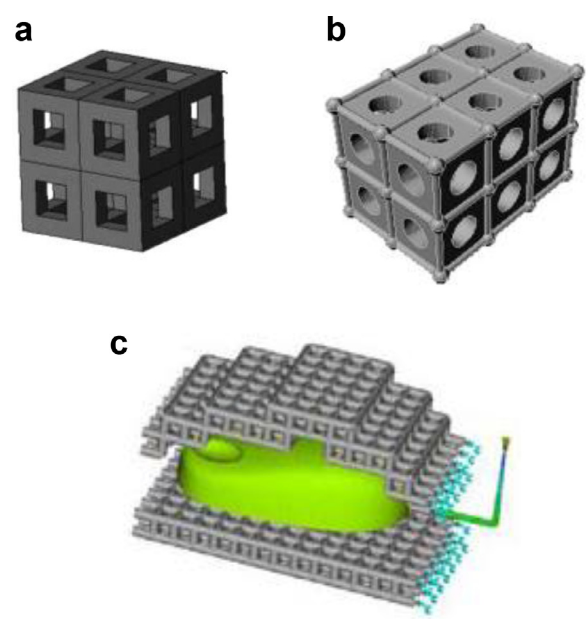

Fig. 25. CC channels with scaffolding architecture: (a) basic cells of design I, (b) basic cells of design II, and (c) channel distribution in a mold (Subfigures a and c are adapted by permission from [77], Copyright 2006 Springer-Verlag London; subfigure b is adapted by permission from [76], Copyright 2011 Elsevier).

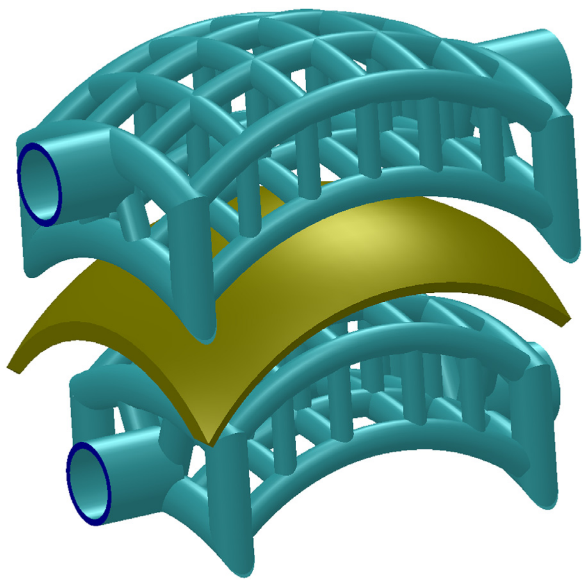

Fig. 26. A modified CC layer with variable unit cells.

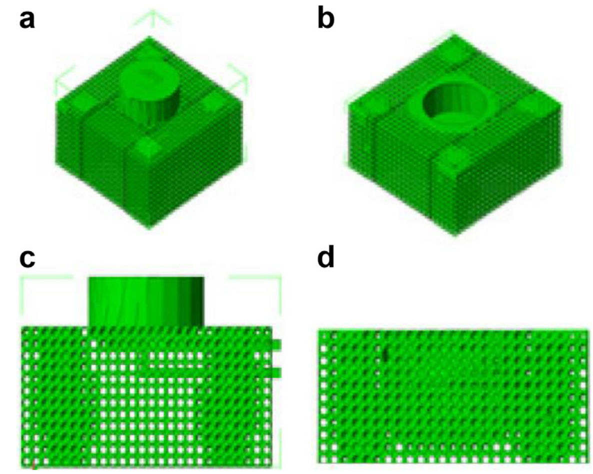

Fig. 28. Porus lightweight design of a mold core (a and c) and a mold cavity (b and d) (Adapted by permission from [107], Copyright 2016 The Authors, Published by Elsevier).

pared to circular cooling channels. There was no statistical difference between the two CC layouts on the reduction of cooling time, warpage, and sink marks. At present, it seems that the costs incurred in fabricating and using a CC layer are much more than their benefits. Besides the pressure drop, mechanical strength can also be a considerable concern. Therefore, more efforts need to be made on investigating the competitiveness of CC layers.

Another lattice structural CC channel layout, similar to the scaffolding architecture, was proposed to minimize the weight of molds while satisfying the CC performance requirements [81]. This design differed from its predecessors in that the cubic cells in the lattice structural layout had variable volume fraction (porosity) while the cubic cells in the scaffolding architecture were uniformly sized. In this design, weight reduction of 17.25% and 37% were achieved for the cavity insert and core insert, respectively. Moreover, the thermal performance was improved 30% by using this porosity-varied lattice structural layout as compared to the uniform-porosity scaffolding layout [106].

Besides employing the lattice structure as a CC layer, a lightweight lattice (porous) structure was also employed to construct the main body of mold inserts (core and cavity) [82,107], as shown in Fig. 28. This was an interesting attempt because the building of CC system had developed from channel to lattice structures. A preliminary design was proposed based on simulation results to reduce the weights of the cavity insert and core insert by 40% and 50%, respectively. Though the heat conductivity and the stiffness reduced in such a design, it still showcased the potential to apply this design in injection molding. However, more investigations will have to be conducted on detailed structural design and experimental validation in the future.

3.3.7. Dual-material conformal cooling channels

Tool steel is the most commonly used material for molds and dies due to its high strength and wear resistance. However, due to its low thermal conductivity, it is not an ideal option from the point of view of heat transfer efficiency. Although increasing the coolant flow rate could raise the cooling efficiency, this may be limited by the mold layout, and may lead to higher coolant pumping costs [8]. A more feasible solution is to fabricate CC inserts using materials with higher thermal conductivity such as copper (Cu). A simulation study showed that molds made of Cu or its alloys (e.g. beryllium copper) reduced the cooling time by 25–30% as compared to molds made of tool steel [108]. However, Cu molds may not fulfill strength requirements. The adoption of multi-material CC channels combines the advantages of tool steel with that of other well thermally conductive materials and presents a more desirable cooling effect. In contrast to single-material molds, multi-materials molds are made of more than one material (usually two, such as tool steel/Cu [109], although triple-material molds have also been proposed [110,111]). One solution to the dual-material mold is to sinter a steel/Cu alloy [112]; on the other hand, a more popular solution is to make the main part of

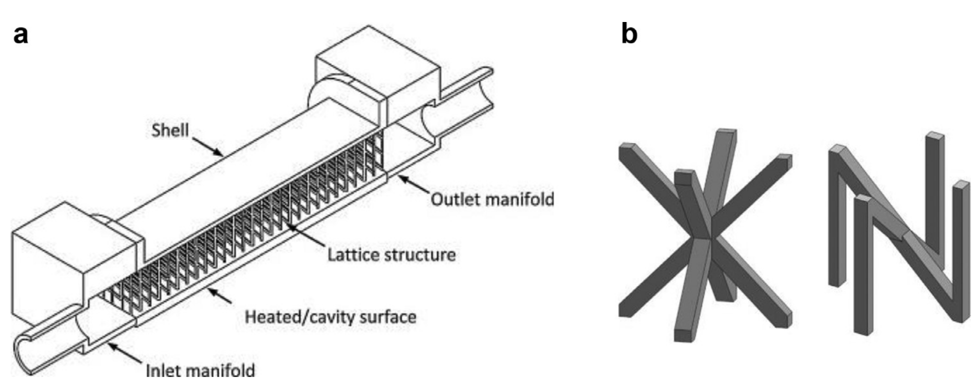

Fig. 27. CC layer and its unit cells proposed by Brooks and Brigden: (a) overview of the CC layer and (b) unit cells: cross (left) and N (right) (Reprinted by permission from [104], Copyright 2016 Elsevier).

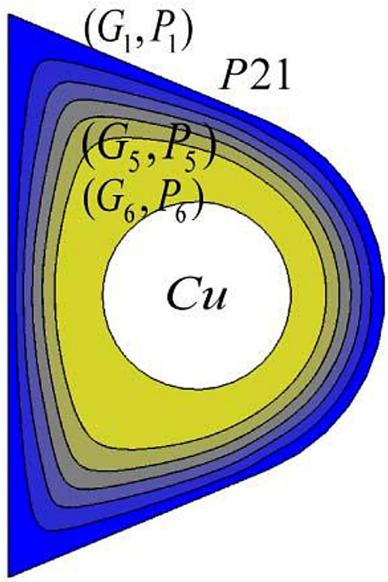

Fig. 29. A design of dual-materials CC channel made of P21/Cu graded materials (Reprinted by permission from [79], Copyright 2019 KSME & Springer).

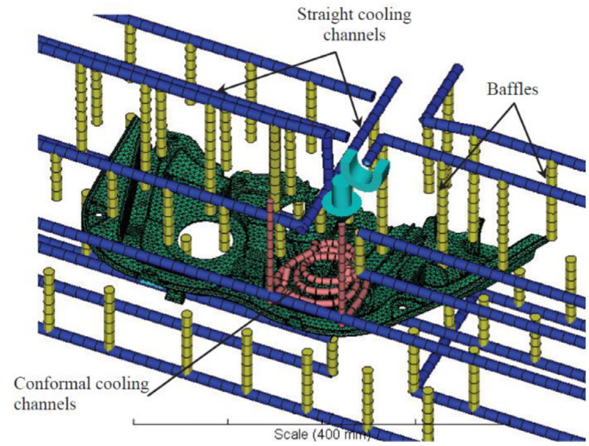

Fig. 30. Local CC channels combining with straight-drilled cooling channels and baffles (Reprinted by permission from [41], Copyright 2017 The Authors, Published by Elsevier).

the mold out of tool steel and the CC channels out of Cu. By inserting Cu tubes, not only the cooling efficiency but also the longevity of the cooling channels was increased [113,114].

To minimize the thermal stresses caused by the mismatch of thermal expansion coefficients, there is usually an intermediate layer (referred to as 'functionally graded material') that smoothly transitions the material properties from one to another one. Shin designed CC channels made of linear-graded or parabolic-graded P21 tool steel/Cu layers [79,115], as shown in Fig. 29. A P21/Cu graded layer was designed to join two materials, achieving a smooth transition in material structure (related to strength) and function (thermal conductivity). FEM analysis results showed that the graded P21/Cu layered cooling channel exhibited faster cooling rates and similar thermal stress levels compared to the single-material (P21) cooling channel.

Huang and Fadel designed steel/ceramic and steel/bronze heterogeneous cooling channels [80]. Their FEM analysis showed interesting results: for thermal-stress-resistant polymers, a secondary mold material with high thermal diffusivity (e.g. bronze) was preferred for obtaining fast cooling, while a second mold material with very low thermal diffusivity (e.g. ceramics) was preferred for obtaining uniform cooling. This represented an innovative attempt to apply ceramics in mold fabrication. However, it must be noted that laser AM for ceramics is still a challenging task at present. Similarly, Al insert was employed between the cavity and CC channels in epoxy molds to enhance the thermal diffusivity, achieving a cooling time reduction of approximately 66% [116].

3.3.8. Combination of conformal cooling channels with other cooling/heating techniques

Combining CC channels with other techniques is another interesting way to achieve a better cooling effect. This idea derives from the combination of straight-drilled cooling channels with other cooling/heating techniques (such as baffles or bubblers). A combination of CC channels with heat sinks (heat thermocouples) was proposed to improve the cooling rate and shorten the solidification time for space-limited situations [117,118]. This is an effective but costly solution since it highly increases the complexity of manufacturing. A two-step manufacturing processing involving laser AM and conventional machining was employed to realize this combined mold. Therefore, it is not a preferred option for general situations.

Although CC channels were proposed as a substitution of conventional straight-drilled cooling channels, some cases warrant the use of the two designs together. CC channels and straight-drilled cooling channels can be combined in two ways. The first way is to locally (partially) use CC channels for producing parts with locally complex structures, while conventional straight-drilled cooling channels and/or baffles were employed for regions with relatively simple structures [41,53], as shown in Fig. 30. The locally CC channels may have individual coolant inlet/outlet, or be (serially) connected with straight-drilled cooling channels. This design was proposed to control the production cost of the molds. However, the cooling performance was also reduced compared to a full CC system. The second way is to design a mixed full-conformal/straight-drilled cooling system [119]. In this design, some straight cooling channels were additionally drilled on a full CC mold to further increase the cooling performance.

In addition to being used in the cooling stage, CC channels can also be used in rapid heat cycle molding (also known as dynamic temperature control) where the cavity is rapidly heated to a high temperature before plastic melt injection [120,121]. The rapid heat cycle molding technique, in which heating is implemented by the CC/heating channels or extra electric resistance built in the molds, is used to improve the fluidity of molten polymer during the filling stage, especially in the case of complex geometric cavities. The combination of the rapid heat cycle molding technique with CC channels is expected to further enhance the part quality and shorten the cycle times.

3.4. Performance evaluation of conformal cooling channels

3.4.1. Numerical simulation

Although the heat and mass transfer taking place in CC channels can be clearly described by physical and mathematical equations, it is a difficult challenge to solve these equations due to their high complexity and nonlinearity. Numerical simulation methods such as FEM [122] and CFD [123] are commonly used tools to obtain solutions for these problems. Various commercial software packages, such as Moldflow® [124,125], Ansys [126] and COMSOL Multiphysics® [127], have been employed to conduct simulations on thermal [128], mechanical [73] and fluid flow [30] analysis. In some simple cases, it is reasonable to approximate the 3D heat transfer problem as a 2D one because the CC channels are equidistant from the cavity surfaces [120]. For complex and critical parts,

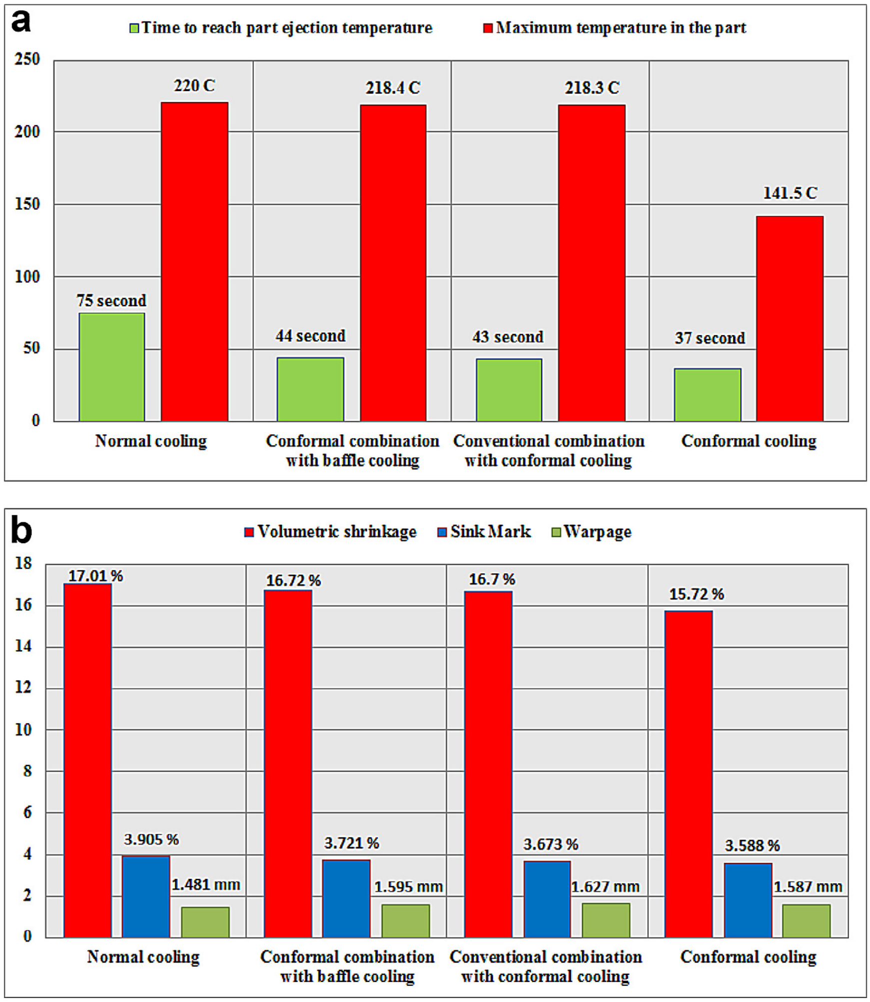

Fig. 31. Simulated results comparing the performance of normal straight-drilled cooling channels, CC channels with baffles, combined straight-drilled and CC channels and fully CC channels: (a) time to reach ejection time and maximum temperature and (b) volumetric shrinkage, sink mark and warpage (Reprinted from [27]).

a full 3D thermal stress analysis and warpage prediction are necessary for more accurate results [8].

To obtain higher-fidelity simulation results, hot plate method and differential scanning calorimetry were employed to respectively determine the thermal conductivity and specific heat, which are the two most important thermal parameters using in the simulation [129]. Maximum temperature, average temperature, temperature uniformity, cooling time (time to reach ejection temperature), pressure drop, warpage, residual stresses, and length of weld lines are some of the main indicators used to evaluate the cooling performance of a cooling channel system [48,70,130]. Although many simulations have been performed in the literature under different process parameters and conditions, all of their results pointed to similar conclusions, viz. the CC systems showed better cooling performance than conventional straight-drilled cooling systems. A representative simulation result, is shown in Fig. 31 [27], where the fully CC channel system was seen to be the most suitable one as compared to other cooling channel systems since it provided the lowest volumetric shrinkage, sink mark percentage, and time to reach the ejection temperature, resulting in near-uniform cooling and less cooling time. Weld lines were also reduced when using a CC channel system [70]. The more complex the core mold, the more difficult it is to cool by conventional cooling channels, and the greater the potential for cooling time reduction with CC channels [131]. The efficiency of the thermal exchange in the cooling phase is particularly improved for plastic parts with large concavities, slender details, internal turrets, and housings [73]. 3D simulation results showing the average temperature of molds and time to reach ejection temperature in molding a complex automotive part are illustrated in Fig. 32 [41]. Both the average temperature and the temperature difference can be seen to be significantly reduced by using CC channel systems [41,64]. Moreover, it is more effective to apply CC channels to the convex core where more heat is accumulated than the concave side [72]. Also, it is expected that a better cooling performance is achieved by combining CC channels with pulse cooling [130].

The cooling performance is affected by the flow behavior of coolant. As expected, a lower coolant temperature (indicating a greater temperature gradient between coolant and cavity) results in more heat transfer and lower warpage defects, while a lower coolant flow rate enhances the temperature rise at the coolant outlet (indicating a greater temperature gradient of coolant along the passage, and thus inducing uneven cooling) [132]. Further, the flow front of the molten plastic is mainly determined by its viscosity, and the more the molten plastic is cooled down the more it tends to be viscous and solidifies. As compared to only one injection point, multiple injection points reduce the filling time as well as the injection pressure, although not drastically [133]. However, multiple injection points lead to weld lines between each flow front in addition to air bubbles, thus weakening the continuity and the strength of the molded part/material. From this aspect, a single injection gate arranged in the center of the mold is a pre-

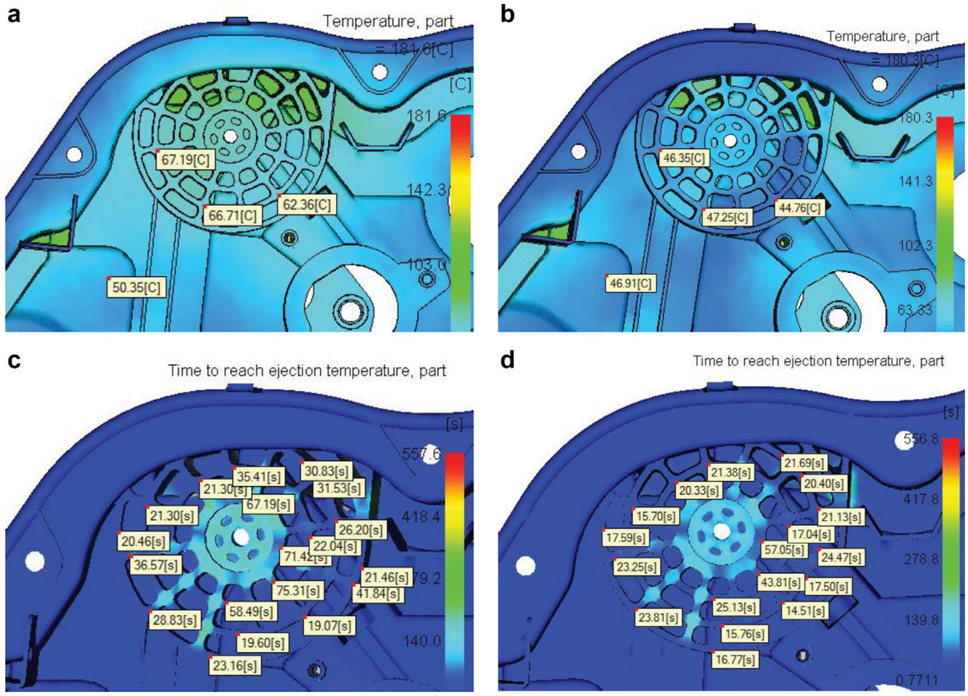

Fig. 32. Simulated results comparing the average temperature and time to reach ejection temperature of straight-drilled cooling channels and CC channels: (a) average temperature, straight-drilled cooling channels, (b) average temperature, CC channels, (c) time to reach ejection temperature, straight-drilled cooling channels, and (d) time to reach ejection temperature, CC channels (Reprinted by permission from [41], Copyright 2017 The Authors, Published by Elsevier).

ferred option to obtain a proper geometry with no defects caused by air bubbles, weld lines, or differential shrinkage [133,134].

By comparing the CC channels with different cross-sectional shapes, circular, semicircular, elliptical, and rectangular, it is found by Shinde and Ashtankar [135] that surface area of CC channels is the important parameter for reduction of cooling time and improvement of part quality irrespective of cross-sectional shape. In the case of a constant volume of CC channels, moreover, rectangular CC channels give better results on account of the larger surface area as compared to CC channels with other cross-sectional shapes [135]. Further, the cooling performance is affected by the channel connection pattern. Numerical simulations have shown that the series CC channels perform better than the parallel ones in reducing average temperatures (indicating higher cooling rates) and improving temperature uniformity, especially for parts with complex shapes [42,48]. This is because the flow rate is insufficient to maintain the turbulence in the parallel CC channels, especially in complex channel layouts. Moreover, a combination of series and parallel patterns is superior to the series pattern in cooling ability, although this may increase the complexity in design and manufacturing [136]. However, in the case of an improper design of a CC system, e.g. the presence of dead flow zones in the channels which lead to increase in pressure drop and decrease in flow rate [72], the cooling time may not be lessened even if the surface area and/or volume of the CC system is/are larger than a conventional cooling system [12,42,117].

3.4.2. Molding/casting experiments

Although there exist several articles in the literature numerically evaluating the performance of CC channels, experimental studies are comparatively lower due to the capital intensity required for manufacturing injection molds in the lab. Although numerical simulations are important for qualitative validation of concepts and/or predictive modeling, molding/casting experiments and prototyping are crucial for proof of concepts and validation. In some cases, as verified by Norwood et al. in their die casting ex-

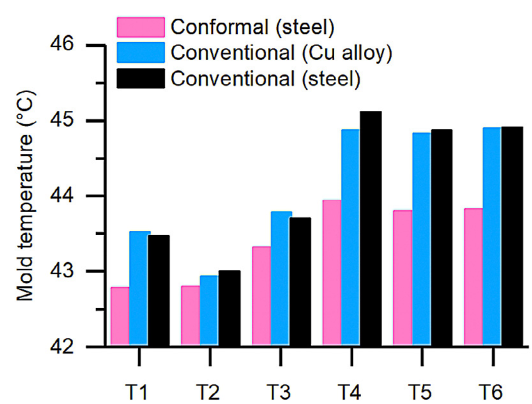

Fig. 33. Comparison of mold temperature in CC mold and conventional cooling mold (data from [137]).

periments, there could be a considerable difference between simulated and experimental results [12]. Běhálek and Dobránsky conducted injection molding by additively manufacturing CC molds [137]. The mold was made of maraging steel 1.2709 and fabricated by laser powder bed fusion (L-PBF), one of the laser AM approaches that will be discussed in Section 4.5.2. The injected material was polypropylene (Mosten MT 230) with good flow properties (e.g. low viscosity) that are suitable for injecting thin-walled parts. From the temperature field distribution in the injection mold, it was concluded that in comparison with conventional cooling systems, the CC channels revealed a higher rate of heat removal intensity and higher temperature uniformity, as shown in Fig. 33.

The reduction of the cycle time strongly depends on the conformability of the cooling channels and the complexity of the part. For a locally CC channel system, 30% of the cycle time can be reduced [41]. Meanwhile, when using a full CC channel system, the reduction of the cycle time can be more than 50% for parts with complex shapes and structures [131], or even be as high as 70%

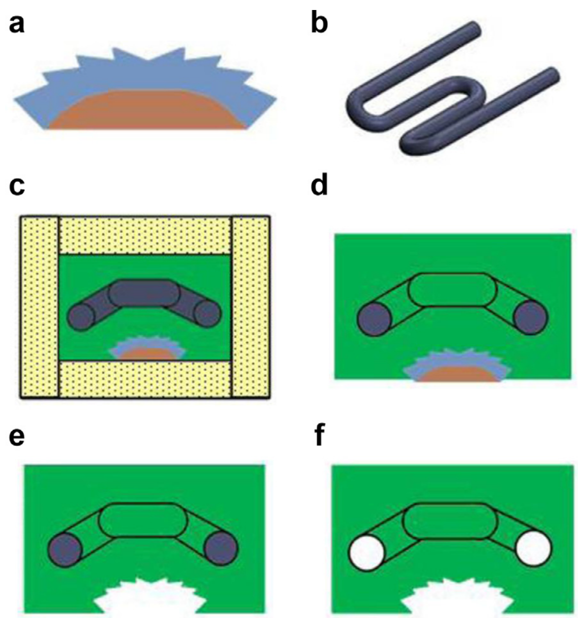

Fig. 34. Fabricating procedures of an epoxy CC mold by epoxy casting: (a) preparing the master model (pattern of the molded part), (b) preparing the pattern of CC channels, (c) pouring Al-filled epoxy resins, (d) curing the mold and removing the frame, (e) removing master model, and (f) removing cooling channels (Adapted by permission from [142], Copyright 2016 Springer-Verlag London).

for some specific cases [11,138]. Also, it is found that the proper topological design could result in a higher cooling efficiency even if molds with a lower heat conductivity are used [20].

4. Manufacture of conformal cooling channels

In addition to a proper design to meet the requirement of cooling performance, there is an equally important concern pertaining to the CC channel system, namely its manufacturability [66]. Due to the complex 3D internal structures that are characteristic of optimal CC designs, it's impossible to machine CC channels using conventional mechanical cutting methods (subtractive manufacturing). Several methods have been proposed to fabricate CC molds since the late 1990s [139–141]. These methods can be summarized as follows: casting [142], welding [10], U-groove milling [143], laminated tooling [12], and powder-based AM (binder jetting [139], laser powder bed fusion [144,145], laser powder deposition [146], and electron beam melting). Moreover, surface quality and dimensional accuracy of cooling channels affect the cooling performance. Thus, surface finishing [138] using mechanical methods and the combination of additive/subtractive manufacturing [141] were also proposed to improve the surface quality and dimensional accuracy of the additively manufactured mold inserts. More details about these methods are provided in the subsections below.

4.1. Casting

4.1.1. Epoxy casting

Injection molds can be classified into two types according to the materials of the mold, i.e. metal mold and epoxy mold. Metal molds, made of tool steel and/or Cu as explained in Section 3.3.7, represent the mainstream and are usually fabricated by mechanical machining and/or metal AM. On the other hand, epoxy molds are fabricated using epoxy casting, wherein a series of procedures are undertaken to produce epoxy molds, as schematically shown in Fig. 34 [142]. The first step is to prepare the master model (i.e. the pattern of the molded part, which can be made of either wax [147] or other materials, such as acrylonitrile butadiene styrene, ABS [148]) and the wax pattern of CC channels [149]. Then, the Al-filled epoxy resin powders are poured into an Al frame in which the wax pattern was pre-located by designed supports [150,151]. The support to locate and fix the patterns can be made of the same material as the mold, i.e. Al-filled epoxy, so that there is no need to remove the support in the following process [151]. During the final curing phase, the wax pattern is melted away from the epoxy mold, leaving behind the cavity and CC channels [116,147].

The wax pattern of CC channels is usually made using rapid-prototyping techniques such as 3D wax printing [147,152], fused deposition modeling [153], or wax injection molding [154]. The wax filament should be prepared before 3D printing [155]. The as-printed wax pattern is usually subjected to post-printing processes such as polishing (10 s immersion in 85 °C water) to obtain high surface quality, which determines the surface roughness of the final epoxy channels [156]. In the curing stage, both the epoxy and wax are heated wherein the former is cured and the latter is melted. However, the wax pattern cannot be melted earlier than the epoxy being cured to enough strength otherwise the mold would deviate or collapse. Therefore, the type of wax has to be chosen specifically to ensure the melt temperature of the wax not lower than the curing temperature of the epoxy [157]. As an alternative to wax patterns, Kuo et al. proposed acrylonitrile butadiene styrene (ABS) patterns which can be either solid or hollow and removed by acetone liquid [148,158].

Metal molds are compatible with batch production due to their robustness, long lifetime, and mechanical strength. On the other hand, epoxy molds (known as "soft" molds [159]) are more suitable for sample trial production or small-batch (short-run) production due to their weaker mechanical strength and lifetime [147,155]. The advantages of epoxy molds include high-quality channel surfaces and ease of post-processing using mechanical approaches (due to the lower mechanical strength and hardness compared to a tool steel mold), although the procedures of fabricating an epoxy mold are complex and consist of many steps [154]. Moreover, precision molds with micro features can be fabricated [160]. However, the cooling time is much longer compared to metallic tools due to the poorer thermal conductivity of epoxy, despite the presence of Al particles [116,142].

4.1.2. Metal casting

Metal casting [161] and spray forming [162] are two other processes to fabricate metallic molds with CC channels. The removal of the master model and/or patterns of CC channels can be accomplished in two ways: (a) using acetone liquid and pressurized water to remove sand-filled epoxy master and patterns (metal casting) [161], or (b) heating up to melt away the patterns made of low-melting-temperature metal such as Cu (spray forming) [162]. By using these improved fabrication methods, both the mechanical strength and lifetime of the mold can be improved as compared to that of the Al-filled epoxy mold.

4.2. Milled groove method

The milled groove method is a practical approach to fabricate CC channels as an alternative to laser AM [163,164]. In this method, the designed mold insert (cavity, core or both, depending on where the milled-groove is designed) is divided into two halves so that one half is used to mill grooves and the other half is used to cover (seal) the grooves. The grooves are usually milled on the side closed to the cavity surface (i.e. the half with cavity surfaces) to improve the cooling effect, as shown in Fig. 35 [87]. The two halves can be joined by bolts [165] or vacuum diffusion bonding [166]. For bolted conjunction, sealing is an important concern to prevent coolant leakage, requiring the use of sealants, gaskets,

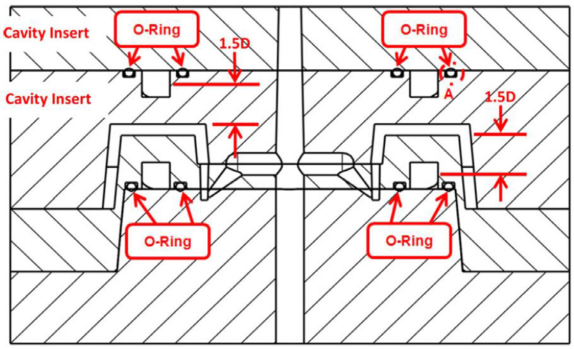

Fig. 35. Design of a CC mold with milling-grooved channels (Reprinted by permission from [87], Copyright 2015 Wiley Periodicals, Inc.).

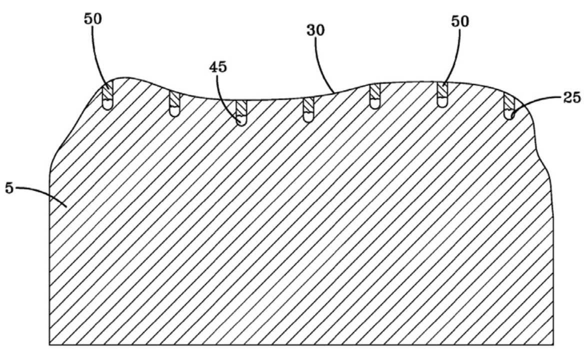

Fig. 36. Another design of milling-grooved CC mold proposed by Hughes (Reprinted from [167]).

and O-rings between the halves, in ejector pinholes, and screw holes, and surrounding the milled grooves [8,87,165]. For vacuum diffusion bonding, additional sealing is not needed. However, this method is costly in spite of being effective. An innovative approach to fabricate milling-grooved CC molds was proposed by Hughes wherein the grooves are milled directly on the cavity surface and then sealed by welding, as shown in Fig. 36 [167].

In the milled groove method, the cross-sectional shape depends on the shape of the milling tool used, e.g. square, rectangular, or U-shaped [165]. Some non-conventional machining methods, such as electrical discharge machining, serve as auxiliary processes for machining corners or other intricate geometries that are difficult for milling [8].

4.3. Laminated tooling

Laminated tooling is a layer-by-layer manufacturing process and essentially a non-powder AM approach employed to fabricate injection molds and dies [12]. In laminated tooling of injection molds and dies, the geometry design of a mold/die is firstly sliced into layers. The thickness of the layers (usually several millimeters) is determined by the tradeoff between dimensional accuracy and processing costs [168,169]. Thus, the layer thickness of laminated tooling is much larger than that of powder-based AM (usually tens to hundreds of microns), so that it is more applicable to fabricate larger CC molds [170]. After the slicing, the laminates are cut by laser cutting [12,171] or abrasive waterjet [170] according to the sliced profile. Finally, the laminates are bonded and sealed to complete the CC mold. There are several ways to bond the laminates, the most popular being to braze the laminates. For tool steel, nickel alloy is the preferred choice as the filler metal due to its appropriate melting temperature and machinability. To ensure a good bond between the laminates, the laminates are required to be processed to remove burrs, oxide layers and grease before

Fig. 37. Stair-stepping channel surface after laminated tooling (Reprinted by permission from [173], Copyright 2007 Emerald Publishing Limited).

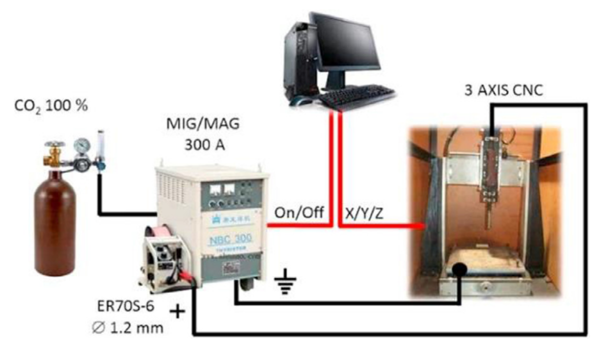

Fig. 38. Schematic of manufacturing equipment for GMAW deposition (Reprinted by permission from [10], Copyright 2015 Elsevier).

brazing [12]. Bolting is another way that can bond the laminates rapidly and inexpensively. However, the joining interface between two adjacent laminates, especially around the hole of cooling channels, has to be well sealed using adhesive to prevent leakage of the coolant [170,172].

Laminated tooling is a practical approach to fabricate CC channels. However, its cross-sectional profile is step-like whose accuracy is limited by the thickness of the lamina sheet, as shown in Fig. 37 [173]. Therefore, some post-processing may be required to remove the stair-stepping effect in the channel profile [169]. Besides, some measures need to be taken to ensure the bonding and sealing quality satisfies requirements on mechanical strength and thermal conductivity.

4.4. Welding

Eiamsa-ard and Wannissorn proposed a metal deposition process by gas metal arc welding (GMAW) to fabricate CC bubblers [10]. In principle, this was essentially an AM approach wherein the weld bead was deposited track by track and layer by layer. A machine setup was built by attaching a GMAW torch onto a computer-numerical-control (CNC) machine, as schematically illustrated in Fig. 38. ER70S-6 wire (Ø 1.2 mm) was used in this machine setup. By minimizing weld splash, an optimal set of process parameters were proposed including a 19 V voltage, a 100 A current, a 10 mm standoff distance, a 15 L/min shielding gas flow rate, and a 300 mm/min travel speed. Under this optimal parameter set, samples with an average hardness of 19.16 in the HRC scale and an average grain size of 11.1 ± 3.1 μm were obtained. Out of the two deposition paths tested by the authors i.e. offset and

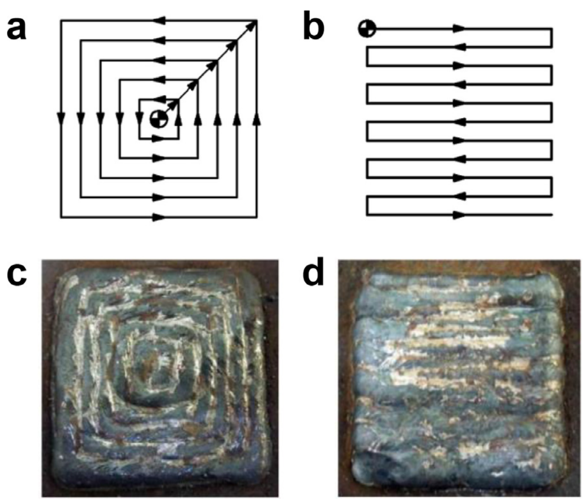

Fig. 39. Deposition paths of GMAW deposition: offset (a and c) and zigzag (b and d) (Reprinted by permission from [10], Copyright 2015 Elsevier).

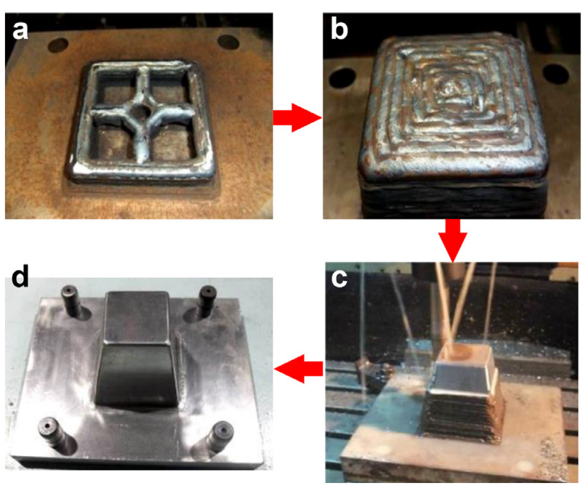

Fig. 40. The process workflow of manufacturing a CC bubbler by GMAW deposition: (a) deposition of the bubble, (b) deposition of the top, (c) milling the surfaces, and (d) finished surfaces (Adapted by permission from [10], Copyright 2015 Elsevier).

zigzag (Fig. 39), the perimeter of the offset patch was found to be smoother compared to that of the zigzag patch [10].

Due to the welding tracks, the surface after GMAW deposition is corrugated, as shown in Figs. 39c and d. Milling is employed to finish the surface, which will be further discussed in Section 4.7.2. The process workflow of manufacturing a CC bubbler by GMAW deposition is illustrated in Fig. 40 [10].

4.5. Powder-based additive manufacturing

Powder-based AM technology is a general term for a class of techniques where metal powder is deposited and welded layer by layer to build 3D metal parts. It is particularly suited to fabricate parts with complex 3D shapes (such as CC molds) without considering the tool-part interference, thus overcoming the structural limitations of part design.

4.5.1. Binder jetting

Binder jetting is a unique and interesting implementation of powder-based AM wherein the powder particles are glued selectively and then sintered in a furnace. It is not similar to powder bed fusion (PBF) which uses a high-energy beam (laser or electron) to melt and bond powder particles. Binder jetting consists of a series of complex procedures to fabricate 3D parts including printing the green part, powder removal, de-binding and sintering, infiltration, and finishing. In the stage of green part printing, the powder particles are selectively glued by (a) binder ink-jet such as aqueous acrylic co-polymer emulsion [174], or (b) a laser beam to solidify polymer mixed in the metal powder [175]. The utility of binder jetting to fabricate CC channels was reported by Wylonis and Sachs et al. before 2000 [139,174]. Around 2013, thin-shelled molds made of plaster-ceramic composite powder were printed to cast low-temperature metal [176]. Compared to PBF, binder jetting is much cheaper but the as-printed quality is inferior such as high porosity (indicating low strength) and shrinkage (inducing low dimensional accuracy). Thus, small features (< 2 mm) should be mechanically machined after printing [177,178].

Table 2
L-PBF processed channel and the straight-drilled channel on their cooling performance [47].

Cooling channel	Heat transfer coefficient (at different pressure of coolant) ($W \cdot m^{-2} \cdot K^{-1}$)	Friction factor
L-PBF printed	22,000 (0.4 MPa) 28,000 (0.6 MPa)	0.042–0.05
Straight-drilled	25,000–28,000 (0.4 MPa) 31,000–35,000 (0.6 MPa)	0.023–0.03

4.5.2. Laser powder bed fusion

L-PBF, wherein a laser beam is used to fuse and bind metal powder, is the most commercially mature metal AM method to fabricate CC molds/dies made of metal (such as P21 steel [41], H13 tools steel [96], hot working steel CL50WS [179], and bronze [98,180]). Using this technique, CC channels with different cross-sectional shapes and architectures, such as circular, self-supporting, and lattice [96] (which were explained in Sections 3.3.3 and 3.3.6) can be easily built. The L-PBF printed stainless steel sample can achieve a density of 99.99% (H13) at the optimized process parameters [96] but some as-printed mechanical properties, e.g. tensile strength (H13) [5] and/or fatigue strength (H13 and 316 L) [5,181], are usually not as good as conventional wrought material. In addition, the printability of the bronze-based powder was poorer than the steel-based powder [98].

Although the L-PBF printed CC molds/dies show the ability to reduce cycle time and improve part quality, the surface quality and dimensional accuracy of L-PBF printed cooling channels are not as good as straight-drilled cooling channels. The dimensional accuracy of an L-PBF printed channel strongly depends on the channel orientation with respect to the build direction [182]. Horizontal channels show the worst dimensional accuracy due to the lack of support to overhang regions (Fig. 41 [47]). Delamination and crack propagation were the main issues to the unsupported downfaces and sharp corners, respectively [98]. In addition, surface roughness increases with the increased overhang angle (with respect to the build direction) [181]. The top surface roughness is much larger than the bottom surface roughness due to powder adhesion (dross formation) at the top of the channel [96,183]. As a result, the heat transfer coefficient of an L-PBF printed channel is smaller than a straight-drilled channel with the same designed inner diameter. Further, the friction factor of the L-PBF printed channel is larger than the straight-drilled channel due to the higher surface roughness. A comparison between the L-PBF printed channel and the straight-drilled channel on their cooling performance is listed in Table 2 [47]. Moreover, the unmelted powder was hard to be blown away by compressed air and thus may block the channel with diameter smaller than 6 mm [98].

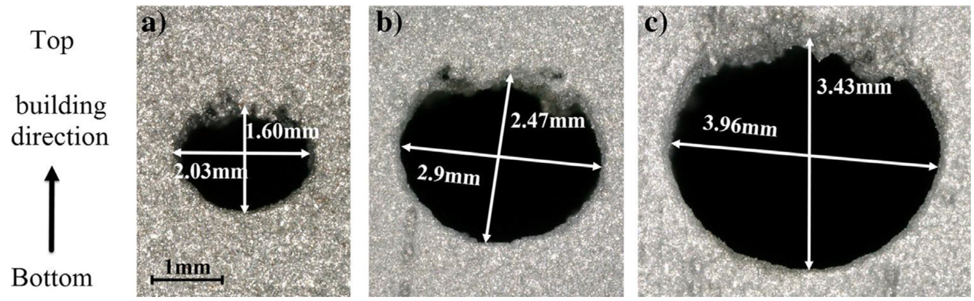

Fig. 41. Dimensions of the L-PBF printed horizontal cooling channels (from left to right: designed inner diameter = 2 mm, 3 mm, and 4 mm, respectively) (Reprinted by permission from [47], Copyright 2018 Springer-Verlag London).

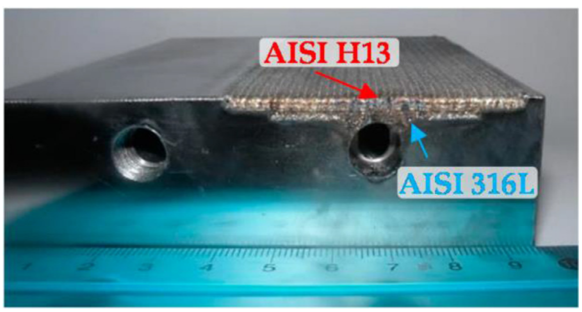

Fig. 42. An LPD printed dual-material mold that the interior region was made of 316 L stainless steel and the surface was made of H13 hot work steel (Reprinted from [146]).

4.5.3. Laser powder deposition

Laser powder deposition (LPD, also known as direct metal deposition [109]) is technically the same as L-PBF excluding the powder-supply pattern. The powder bed is recoated layer by layer in L-PBF while in LPD the powder is locally fed into the melt pool via a nozzle co-axial with the laser [184]. Compared to L-PBF, LPD enables greater build speeds at the cost of lower resolution and higher surface roughness. The greater the size of the metal part, the greater the benefits of using LPD over L-PBF. Similar to L-PBF, LPD has also been used to fabricate CC channels [138]. As compared to L-PBF, moreover, another advantage of LPD is the flexibility of feeding mixtures of powders (e.g. of multi-metals/alloys) with locally-varying proportions. This makes it theoretically feasible to fabricate CC channels with functionally graded materials. An example of LPD printed dual-material mold is shown in Fig. 42, where the interior region was made of 316 L stainless steel and the surfaces were made of H13 hot work steel [146]. The fabricated coupon showed good bonding between the two kinds of steels. However, the printing quality of steel/Cu graded material was not as good as steel/steel, as shown in Fig. 43 [79]. The microscopic images (Figs. 43c and d) show that large porosities were observed on the 100%-Cu sublayer, indicating poor printability of Cu as compared to P21 tool steel. As a result, although the nominal thermal conductivity increased with the increasing Cu percent, the effective thermal conductivity was much less than the theoretical value. Therefore, more work needs to be done to improve the printability and quality of Cu-based graded materials.

Moreover, the method of powder supply means that LPD cannot print an overhang region directly, unlike the L-PBF process. In L-PBF, the powder is recoated layer by layer, so that there is an unconsolidated powder bed below the overhang region; while in LPD, nothing is below the overhang region since the powder is not supplied to the no-printing region. Due to the lack of powder bed below the overhang region, the powder particles supplied to the overhang region would fall off onto the substrate (unless support structures are printed) when printing an overhang region in LPD. As a result, the printing of the overhang region can not be conducted successfully. Therefore, some special printing strategies have to be adopted when printing an overhang region using LPD, such as rotating the part to eliminate the overhang region during the printing, as shown in Fig. 44 [146].

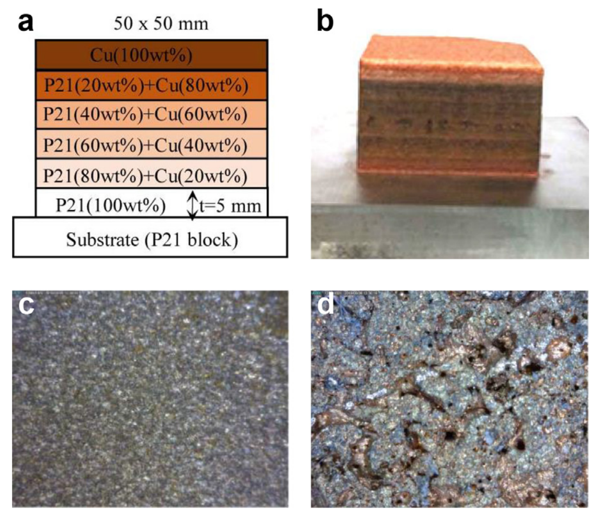

Fig. 43. Linear graded P21/Cu layer (a and b) and microscopic images (c: P21 100 wt%-Cu 0 wt% and d: P21 0 wt%-Cu 100 wt%) (Adapted by permission from [79], Copyright 2019 KSME & Springer).

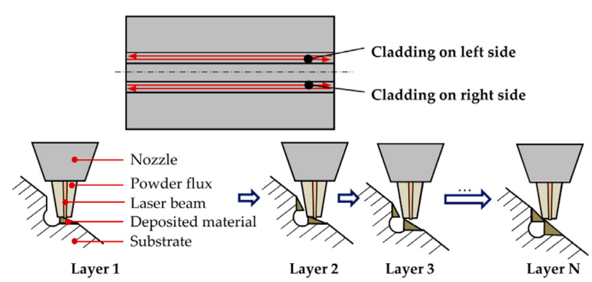

Fig. 44. Deposition strategy of the upper-half of a channel in LPD process (Reprinted from [146]).

4.5.4. Electron beam melting

Electron beam melting (EBM) is a powder-based AM process that is highly similar to L-PBF. The only difference between them is that in EBM an electron beam is used as the heat energy source instead of a laser beam. Although EBM has also been used to fabricate CC molds [185–187], they are typically bulkier and more expensive than L-PBF systems due to vacuum requirements for the build chamber.

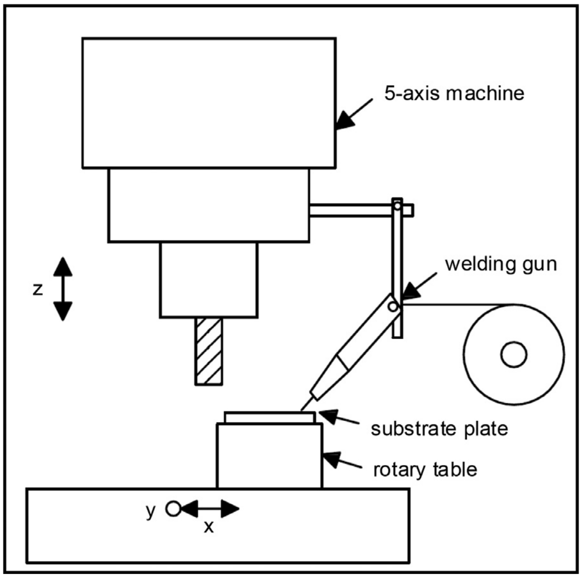

Fig. 45. Schematic of hybrid welding/milling equipment (Reprinted from [141] with permission from the authors).

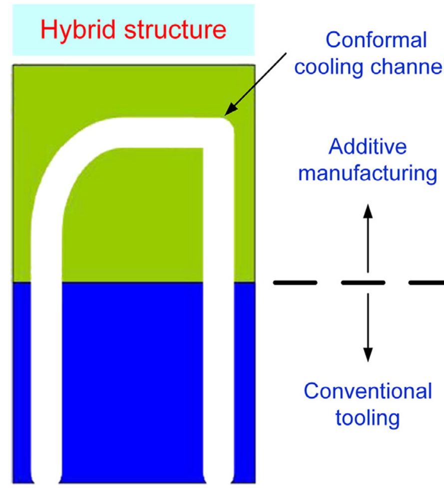

Fig. 46. Schematic of hybrid additively/subtractively manufactured CC mold (Adapted by permission from [154], Copyright 2019 Springer-Verlag London).

4.6. Hybrid additive/subtractive manufacturing

AM and conventional machining have merits that can complement each other. AM has the ability to build complex-shaped structures (such as CC channels) flexibly and efficiently, while conventional machining can machine parts with high dimensional accuracy. For the fabrication of CC channels, combining AM and conventional machining stands to achieve a better result. This combined technique is known as hybrid additive/subtractive manufacturing, wherein the part is processed alternately by AM and conventional machining layer by layer. Although AM breaks through the structural limitation on the fabrication of CC channels, the as-built channel surface possesses an undesired degree of surface roughness. Further, it is difficult to finish the channel surface after the mold is printed completely. A possible way around this is to mechanically finish the interior wall of the currently printed layer before the next layer begins to be printed [10]. In this approach, each layer is additively manufactured first and then subtractively machined.

Theoretically, hybrid additive/subtractive manufacturing can be a combination of any additive/subtractive methods. However, the actual choice is subjected to the machine tool. To conduct two different manufacturing methods (one is additive and the other one is subtractive) jointly, two manufacturing systems should be integrated by sharing the same operation space and coordinate origin; meanwhile, it should prevent the interference between the additive system and cutting tool. This implies that hybrid additive/subtractive manufacturing approaches require specialized machine tools. Its development can be traced back to the 1990s and started from the hybrid welding/milling method whose equipment is schematically shown in Fig. 45 [140,141]. In this method, the welding process can be either GMAW [188] or metal inert gas cladding [189]. As compared to the welding, the merits of the hybrid welding/milling are not only the surface roughness but also the dimensional accuracy, especially in the Z direction.

From the angle of AM, powder-based AM (such as L-PBF and LPD) is more desirable than wire-based AM (such as welding), because the size of powder particles (several tens of microns) is much smaller than the size of wire (~ 1 mm), making powder-based AM more applicable for fine structures. Recently, a large step in the development of the equipment of hybrid additive/subtractive manufacturing was made by the company DMG Mori wherein it combined LPD and conventional cutting onto a CNC platform. The laser head and cutting tools can be exchanged discretionarily and automatically in the spindle, leading to the development of the first commercially-used hybrid LPD/cutting machine tool (DMG Mori LASERTEC series) worldwide [190]. It further increases the manufacturing flexibility and improves the dimensional accuracy and surface quality of both outer and inner surfaces significantly. These considerable merits make the development of this method promising, although the high cost of the machine tool limits the popularization of this method at the current stage.

4.7. Combination of additive manufacturing and subtractive manufacturing

The advantages of hybrid additive/subtractive manufacturing have been discussed in Section 4.6. However, considering the high cost of the specialized machine tool, a more economical approach is to use two separate machine tools to achieve the additive and subtractive manufacturing respectively. There are two purposes to jointly use additive and subtractive manufacturing in this way, i.e. (a) to fabricate hybrid molds and (b) to post-process the as-printed surfaces.

4.7.1. Fabrication of hybrid mold

Sometimes, a mold insert is divided into two parts, such that the one is fabricated using AM and the other is fabricated using subtractive manufacturing [191]. Usually, the subtractively manufactured part (Part I) is the housing or the straight-drilled channel insert of a mold, while the additively manufactured part (Part II) is the CC insert (schematically shown in Fig. 46) [154,192]. There are two approaches to bond these two parts, i.e. bolting [193] or laser AM of Part II on Part I (i.e. using Part I as the build plate on which Part II is additively built up). In the latter approach, Part I is manufactured by conventional machining methods, such as milling and drilling, while the CC insert (Part II) is fabricated by laser AM on Part I [138,194]. An important concern in the combined use of additive/subtractive manufacturing is the joining characteristics (bond strength) between the additively-manufactured region and the subtractively-manufactured region, especially when these two regions are made of different materials, as shown in Fig. 47 [138]. Besides, it must be ensured that the part is aligned correctly when dismounting the part from one machine tool and mounting on another machine tool, failing which the cavity surface and the channels of Part I and Part II may be mismatched [195].

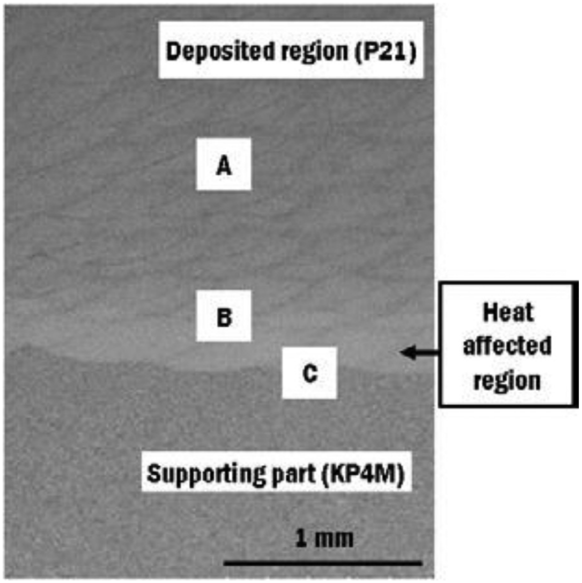

Fig. 47. Microstructures in the vicinity of the joined regions (upper half: manufactured by LPD, made of P21 tool steel; lower half: manufactured by high-speed machining, made of KP4M tool steel) (Reprinted by permission from [138], Copyright 2010 KSPE and Springer).

4.7.2. Surface finishing

In general, laser-additive-manufactured surfaces cannot compete with mechanically machined surfaces in surface quality [196]. Hence, they should be finished (using mechanical machining, electro discharge machining, lapping, and/or heat treatment, etc. [78,138]) appropriately to improve the dimensional accuracy and surface roughness. If mechanical machining is used to improve the dimensional accuracy, the printed part should be larger (adding 0.5–1 mm in length to all surfaces) than the designed one to ensure there is redundant material to be mechanically removed [177]. The internal surface of CC channels can be polished by abrasive flow machining due to the complexity of channel shapes and flexibility of abrasive flow [173,197]. In addition, it is found that the abrasive flow polishing can also improve the sealing of laminated-tooled molds [173].

5. Applications of conformal cooling channels in industries

Although the concept of CC channels was initially proposed for injection molding, theoretically, CC channels can be applicable to all the tools/parts that have complex cooling/heating profiles and require efficient and uniform cooling/heating. Nowadays, CC channels have started to show their potential and be utilized in various industrial applications as discussed below.

5.1. Plastic molding

Plastic molding processes such as injection molding, transfer molding, blow molding and hot embossing, are important industrial manufacturing methods that produce most or all plastic products in use today. Molds are required in these processes, where CC channels play crucial roles to improve cooling performance. The concept of CC was primarily developed for injection molding [198–200] to reduce the warpage and residual stresses of injection-molded parts with variable thickness, large size, and/or complex shapes, flat parts with partly thick volumes [201], complex large automotive parts [20,41,202], and (local) thin-walled parts [203,204]. Moreover, CC has shown promise for high precision parts with very low dimensional tolerances, such as screw caps [130], contact lens [205], and large-diameter aspheric plastic lenses (Fig. 48) [15]. It is seen in Fig. 48 that the lenses injection-molded using spiral CC channels showed good birefringence properties and fringe patterns.

Although channels in transfer molds are used to heat but not to cool the cavity, which is different from that in injection molds, conformal channels are also recommended in transfer molding to obtain more uniform and efficient heating in this application. Conformal channels in transfer molding are known as conformal heating channels instead of CC channels but the design and layout of conformal heating channels (and indeed, the physics of the process) are identical to that of CC channels in injection molds [206].

Besides injection molding and transfer molding, blow molding is another important polymer processing technology that is used to produce hollow-shaped plastic parts such as plastic bottles [207]. Similar to injection molding, the cooling stage takes up approximately two-thirds of the cycle in blow molding, which affects not only production efficiency but also production quality. CC channels can also be applied to blow molding owing to the similarity of mold designs for injection molding and blow molding [208]. Hot embossing is used to fabricate plastic parts with micro features. By using CC hot embossing molds, the reductions of cooling time and cost can be more than 90% and 70%, respectively [142]. Finally, vacuum forming [209] (a simplified thermoforming process where single-surface molds are employed) and profile extrusion [210] which produce plastic parts have also benefited from CC molds.

5.2. Metal die forming

Besides plastic molding, metal die forming is another important manufacturing field in which CC channels play a crucial role in formation quality and cycle time. The implementation approaches of metal die forming mainly include die casting [12], extrusion [211], hot stamping [212,213], hot forging [118], and hot sheet metal forming [214]. By using CC dies in metal die casting, the cooling capacity is enhanced effectively so that the requirement for extra spray cooling is lessened [215]. Using air as a coolant instead of water can also provide sufficient cooling effect so that the casting process of Al could be safer due to the elimination of probable explosion hazards [216]. Moreover, using CC dies can improve the shrinkage porosity and surface finish of the fabricated part [215].

CC channels can also be used in hot extrusion dies to prevent overheating of the workpiece materials (Al, Al alloy, etc.) and speed up the production [127,179]. CC channels are positioned close to the forming zone to dissipate heat locally, raising the production rate by as much as 300% without affecting the extrusion force significantly. Moreover, since the as-printed surface roughness does not affect the material flow, the surface does not need to be finished after L-PBF printing [171].

In hot stamping, the uneven cooling affects the uniformity and thus the strength of the stamped parts. To address this problem, CC channels were employed in hot stamping dies for larger structural parts, such as roof sides and pillars of an automobile [32,53], as shown in Fig. 49. The experimental results showed that the uniformity and strength of the part improved after using CC dies [32].

5.3. Other advanced products

In addition to plastic and metal thermoforming molds/dies, innovative applications of CC channels can be found in the fabrication of advanced products with self-cooling features to enhance the cooling effect of these products. A typical case of this kind of application is the gas turbine engine. Fuel is burned in the combustion chamber, and high-temperature gas is ejected from the

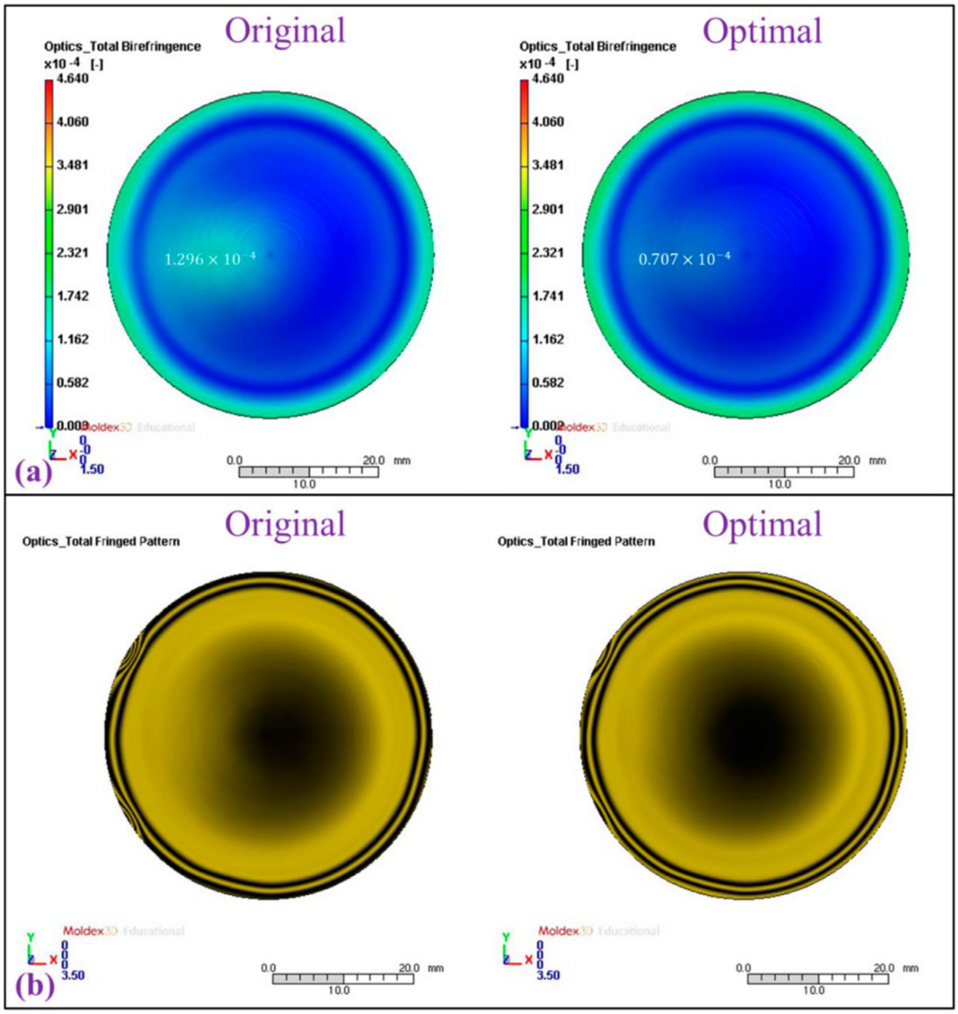

Fig. 48. (a) Birefringence properties and (b) fringe patterns of injection-molded large-diameter aspheric plastic lenses (left: conventional; right: conformal) (Reprinted from [15]).

nozzle. Cooling channels are thus required to prevent overheating which can severely jeopardize the mechanical properties of the alloys used in the engine. To fit the complex shapes of the gas turbine engine components better, it is desirable to design the cooling channels conformal to the shape of the turbine [217]. Further, it is promising to combine the CC channel design with the existing ribbed channel design to obtain a more desired cooling ability. In addition to gas turbine engines, some other instances, such as photoinjector [218,219] and self-cooling gears [220], have also been proposed where CC channels provided enhanced cooling effect to reduce the working temperature and extend the component lifetime.

6. Conclusions and future outlook

The design, manufacturing and application of CC channels were reviewed and evaluated systematically and comprehensively in this review paper. The core goal of using CC channels is to achieve a uniform and rapid cooling. A proper design is crucial to achieving this goal as cooling performance may not be enhanced by an improper design even if the channels are conformal. Some key design parameters of CC channels, such as cross-sectional shape and size, surface area, distance to cavity surface, and pitch between two adjacent channels, have to be calculated and chosen carefully after taking into account the cooling rate and time, temperature gradient, mechanical strength of mold, and coolant pressure drop. In light of this, five classes of design methods for CC channels were employed, namely (i) empirical method (experimental or simulation-based design), (ii) design according to CC curves, (iii) modular design, (iv) automatic or intelligent design using expert algorithms, and (v) design based on the topology optimization (mainly for design dual-materials molds).

Although many CC layouts had been proposed in the literature, they can be roughly classified into eight types, namely (i) basic type (spiral and linear), (ii) meshy type, (iii) non-circular cross-sectional type, (iv) CC bubbler, (v) modularly constructed type, (vi) lattice type, (vii) dual-materials type, and (viii) a combination with other cooling techniques (such as hybrid straight-drilled-CC molds). One cannot simply say which design is the best, since the choice depends on the complexity of the part. The basic type of design can provide sufficient cooling capacity for simple part shapes, while more complex types (such as meshy type and non-circular cross-sectional type) are recommended for complex-shaped parts. On the other hand, hybrid straight-drilled CC molds are suitable choices for locally complex parts. The use of CC channels can reduce the cycle time by up to 70% in addition to reducing the shape deviations (such as differential shrinkage and warpage) significantly. The more complex the core mold, the more difficult it is

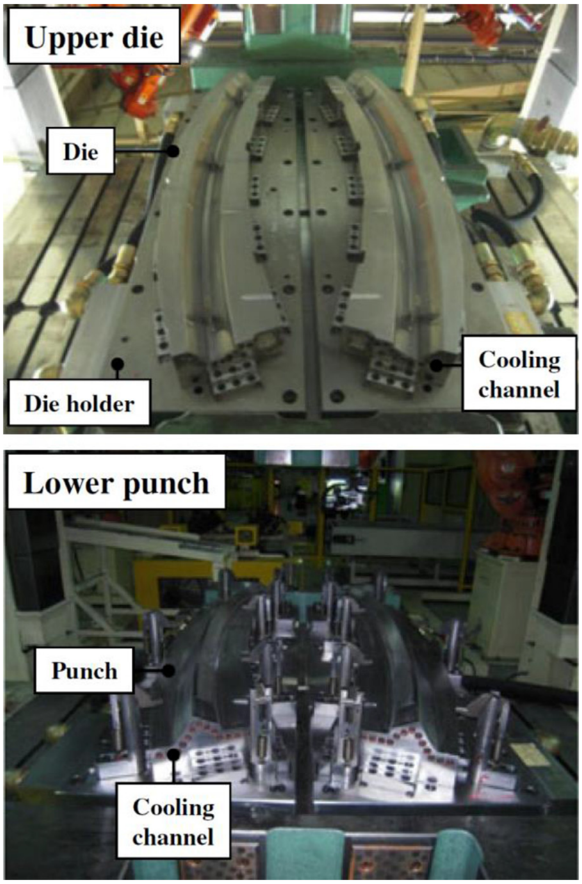

Fig. 49. Hot stamping tools with CC channels (Reprinted by permission from [32], Copyright 2013 Springer-Verlag London).

to cool by conventional cooling channels, and the greater the potential for cooling time reduction with CC channels.

In recent years, the rapid development of AM (which allows a greater design freedom) has given a great boost to the development of CC systems. A number of techniques were employed to fabricate CC mold, e.g. epoxy casting, laminated tooling, welding, powder-based AM (including binder jetting, L-PBF, LPD and EBM). All of these techniques demonstrated the feasibility of fabricating CC molds. In particular, epoxy casting and L-PBF showed the best applicability to Al-epoxy molds and metal (steel) molds, respectively, because of the high forming flexibility and fidelity. Meanwhile, LPD has an exclusive advantage to fabricate multi-materials molds although it cannot print overhang regions directly. Dimensional accuracy is the biggest concern needing attention and improvement in AM. Hybrid additive/subtractive manufacturing (hybrid L-PBF/CNC milling) shows great promise in the future for the fabrication of high dimensional-accuracy CC molds, provided these methods reach the maturity of conventional techniques in terms of costs and efficiency.

CC channels show the potential and competitiveness in a variety of industrial applications such as plastic molding (including injection molding, blow molding and transfer molding) and metal thermoforming (including die casting and hot extrusion). It is expected to substitute straight-drilled cooling molds in the future, as it can significantly improve part quality, raise production rates and lower production costs. In addition to this, the use of CC channels can be expanded to some advanced products that require high-performance self-cooling, such as gas turbine engines, photoinjectors, and gears. This will benefit a great number of advanced products to improve their functionality and extend their lifetime.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was financially supported by Beijing Natural Science Foundation (3214049); Fundamental Research Funds for the Central Universities, China (FRF-TP-18-055A1); the Partnership Program (project number 15808/S16044) of the Materials innovation institute M2i (www.m2i.nl) and the Technology Foundation TTW (www.stw.nl), which is part of the Netherlands Organization for Scientific Research (www.nwo.nl); and the ICD Advanced Additive program (Innovation Cluster Drachten, the Netherlands). Amar M. Kamat acknowledges financial support from the ITEA Daytime project (ITEA-2018-17030-Daytime). Mr. Bin Feng is thanked for drawing Figs. 7 and 26.

References

[1] I. Adam, W.B. Du Preez, J. Combrinck, Design considerations for additive manufacturing of conformal cooling channels in injection moulding tools, Interim Interdiscip. J. 15 (2016) 35–44.
[2] A.B.M. Saifullah, S.H. Masood, Finite element thermal analysis of conformal cooling channels in injection moulding, in: Proc. 5th Australas. Congr. Appl. Mech., Engineers Australia, Brisbane, Australia, 2007.
[3] S.H. Masood, N.N. Trang, Thermal analysis of conformal cooling channels in injection moulding, in: Proc. 3rd BSME-ASME Int. Conf. Therm. Eng, Dhaka, Bangladesh, 2006.
[4] H.S. Park, X.P. Dang, Optimization of conformal cooling channels with array of baffles for plastic injection mold, Int. J. Precis. Eng. Manuf. 11 (2010) 879–890, doi:10.1007/s12541-010-0107-z.
[5] M. Mazur, P. Brincat, M. Leary, M. Brandt, Numerical and experimental evaluation of a conformally cooled H13 steel injection mould manufactured with selective laser melting, Int. J. Adv. Manuf. Technol. 93 (2017) 881–900, doi:10.1007/s00170-017-0426-7.
[6] J. Meckley, R. Edwards, A study on the design and effectiveness of conformal cooling channels in rapid tooling inserts, Technol. Interface J. 10 (2009) 1–28.
[7] D.E. Dimla, M. Camilotto, F. Miani, Design and optimisation of conformal cooling channels in injection moulding tools, J. Mater. Process. Technol. 164–165 (2005) 1294–1300, doi:10.1016/j.jmatprotec.2005.02.162.
[8] Y.F. Sun, K.S. Lee, A.Y.C. Nee, Design and FEM analysis of the milled groove insert method for cooling of plastic injection moulds, Int. J. Adv. Manuf. Technol. 24 (2004) 715–726, doi:10.1007/s00170-003-1755-2.
[9] E. Mathey, L. Penazzi, F.M. Schmidt, F. Rondé-Oustau, Automatic optimization of the cooling of injection mold based on the boundary element method, AIP Conf. Proc. 712 (2004) 222–227, doi:10.1063/1.1766527.
[10] K. Eiamsa-Ard, K. Wannissorn, Conformal bubbler cooling for molds by metal deposition process, Comput.-Aided Des. 69 (2015) 126–133, doi:10.1016/j.cad.2015.04.004.
[11] T. Evens, W. Six, J. De Keyzer, F. Desplentere, A. Van Bael, Experimental analysis of conformal cooling in SLM produced injection moulds: effects on process and product quality, AIP Conf. Proc. 2055 (2019) 070017, , doi:10.1063/1.5084861.
[12] A.J. Norwood, P.M. Dickens, R.C. Soar, R. Harris, G. Gibbons, R. Hansell, Analysis of cooling channels performance, Int. J. Comput. Integr. Manuf. 17 (2004) 669–678, doi:10.1080/0951192042000237528.
[13] M. Blaško, V. Tittel, M. Ridzoň, CAE analysis of conformal cooling application–case study, Ann. Fac. Eng. Hunedoara - Int. J. Eng. 10 (2012) 115–118, http://annals.fih.upt.ro/pdf-full/2012/ANNALS-2012-3-17.pdf.
[14] J.M. Jauregui-Becker, H. Tragter, F.J.A.M. van Houten, Toward a bottom-up approach to automate the design of cooling systems for injection molding, Comput.-Aided Des. Appl. 6 (2009) 447–459, doi:10.3722/cadaps.2009.447-459.
[15] C.-.Y. Chung, Integrated optimum layout of conformal cooling channels and optimal injection molding process parameters for optical lenses, Appl. Sci. 9 (2019) 4341, doi:10.3390/app9204341.
[16] M.R. Clemente, M.R. Oliveira Panão, Introducing flow architecture in the design and optimization of mold inserts cooling systems, Int. J. Therm. Sci. 127 (2018) 288–293, doi:10.1016/j.ijthermalsci.2018.01.035.
[17] Y. Zhang, B. Hou, Q. Wang, Y. Li, Z. Huang, Automatic design of conformal cooling channels in injection molding tooling, IOP Conf. Ser. Mater. Sci. Eng. 307 (2018) 012025, , doi:10.1088/1757-899X/307/1/012025.
[18] O. Tuteski, A. Kočov, Conformal cooling channels in injection molding tools – design considerations, Mach. Technol. Mater. 12 (2018) 445–448.
[19] K. Altaf, A.M.B.A. Rani, Numerical study of profiled conformal cooling channels for cooling time reduction in injection mould tools, Int. J. Eng. Syst. Model. Simul. 7 (2015) 230–237, doi:10.1504/IJESMS.2015.072508.

[20] G.R. Berger, D. Zorn, W. Friesenbichler, F. Bevc, C.J. Bodor, Efficient cooling of hot spots in injection molding. A biomimetic cooling channel versus a heat-conductive mold material and a heat conductive plastics, Polym. Eng. Sci. 59 (2019) E180–E188, doi:10.1002/pen.25024.
[21] M.S. Shinde, K.M. Ashtankar, Additive manufacturing-assisted conformal cooling channels in mold manufacturing processes, Adv. Mech. Eng. 9 (2017) 1–14, doi:10.1177/1687814017699764.
[22] M.S. Shinde, K.M. Ashtankar, A.M. Kuthe, S.W. Dahake, M.B. Mawale, Direct rapid manufacturing of molds with conformal cooling channels, Rapid Prototyp. J. 24 (2018) 1347–1364, doi:10.1108/RPJ-12-2016-0199.
[23] G.S. Phull, S. Kumar, R.S. Walia, Conformal cooling for molds produced by additive manufacturing: a review, Int. J. Mech. Eng. Technol. 9 (2018) 1162–1172.
[24] H.-.S. Park, X.-.P. Dang, Design and simulation-based optimization of cooling channels for plastic injection mold, in: C. Volosencu (Ed.), New Technol. - Trends, Innov. Res., InTech, 2012, pp. 19–44.
[25] B.O. Rhee, C.S. Park, H.K. Chang, H.W. Jung, Y.J. Lee, Automatic generation of optimum cooling circuit for large injection molded parts, Int. J. Precis. Eng. Manuf. 11 (2010) 439–444, doi:10.1007/s12541-010-0050-z.
[26] F. Kria, M. Hammami, M. Baccar, Conformal heating/cooling channels design in rapid heat cycle molding process, Mech. Ind. 18 (2017) 109, doi:10.1051/meca/2016033.
[27] O.A. Mohamed, S.H. Masood, A. Saifullah, A simulation study of conformal cooling channels in Plastic injection molding, Int. J. Eng. Res. 2 (2013) 344–348, doi:10.1017/S1355617704105109.
[28] M. Khan, S.K. Afaq, N.U. Khan, S. Ahmad, Cycle time reduction in injection molding process by selection of robust cooling channel design, ISRN Mech. Eng. 2014 (2014) 968484, , doi:10.1155/2014/968484.
[29] M. Frings, M. Behr, S. Elgeti, A simplified simulation model for a HPDC die with conformal cooling channels, AIP Conf. Proc. 1896 (2017) 170002, , doi:10.1063/1.5008200.
[30] T. Wu, A. Tovar, Design for additive manufacturing of conformal cooling channels using thermal-fluid topology optimization and application in injection molds, in: Proc. ASME Des. Eng. Tech. Conf., Quebec City, Canada, 2018 DETC2018-85511, doi:10.1115/DETC201885511.
[31] M.S. Shinde, K.M. Ashtankar, Cycle time reduction in injection molding by using milled groove conformal cooling, Comput. Mater. Contin. 53 (2017) 207–217.
[32] W.S. Lim, H.S. Choi, S.Y. Ahn, B.M. Kim, Cooling channel design of hot stamping tools for uniform high-strength components in hot stamping process, Int. J. Adv. Manuf. Technol. 70 (2014) 1189–1203, doi:10.1007/s00170-013-5331-0.
[33] O. Hamada, Tool Temperature Control, Sigma Publishing Co. Ltd, Tokyo, 1995.
[34] C.-.C. Kuo, Z.-.F. Jiang, J.-.H. Lee, Effects of cooling time of molded parts on rapid injection molds with different layouts and surface roughness of conformal cooling channels, Int. J. Adv. Manuf. Technol. 103 (2019) 2169–2182, doi:10.1007/s00170-019-03694-2.
[35] X. Xu, E. Sachs, S. Allen, The design of conformal cooling channels in injection molding tooling, Polym. Eng. Sci. 41 (2001) 1265–1279, doi:10.1002/pen.10827.
[36] D.V. Rosato, M.G. Rosato, Injection Molding Handbook, 3rd ed., Springer US, , 2000, , doi:10.1007/978-1-4615-4597-2.
[37] K.M. Au, K.M. Yu, Variable distance adjustment for conformal cooling channel design in rapid in rapid tool, J. Manuf. Sci. Eng. Trans. ASME. 136 (2014) 044501, , doi:10.1115/1.4026494.
[38] K.M. Au, K.M. Yu, Variable radius conformal cooling channel for rapid tool, Mater. Sci. Forum. 532–533 (2006) 520–523, doi:10.4028/www.scientific.net/msf.532-533.520.
[39] J. Shoemaker, Moldflow Design Guide: A Resource For Plastics Engineers, Hanser Verlag, 2006.
[40] Z.C. Lin, M.H. Chou, Design of the cooling channels in nonrectangular plastic flat injection mold, J. Manuf. Syst. 21 (2002) 167–186, doi:10.1016/S0278-6125(02)80160-1.
[41] H. Park, X. Dang, Development of a smart plastic injection mold with conformal cooling channels, Procedia Manuf. 10 (2017) 48–59, doi:10.1016/j.promfg.2017.07.020.
[42] S. Marques, A.F. De Souza, J. Miranda, I. Yadroitsau, Design of conformal cooling for plastic injection moulding by heat transfer simulation, Polimeros 25 (2015) 564–574, doi:10.1590/0104-1428.2047.
[43] D.S. Singraur, B.T. Patil, Y.T. Rampariya, Finite element analysis of conformal cooling for reduction of cycle time to enhance performance in plastic injection molding process, in: A.K. Parwani, P. Ramkumar (Eds.), Recent Adv. Mech. Infrastruct., Springer Nature Singapore Pte Ltd., Singapore, 2020, pp. 255–264, doi:10.1007/978-981-32-9971-9_26.
[44] J. Fay, Introduction to Fluid Mechanics, MIT Press, 1995.
[45] X. Xu, E. Sachs, S. Allen, M. Cima, Designing conformal cooling channels for tooling, in: 1998 Int. Solid Free. Fabr. Symp., 1998, pp. 131–146.
[46] M. Kang, L.K. Hwang, B. Kwon, Computationally efficient optimization of wavy surface roughness in cooling channels using simulated annealing, Int. J. Heat Mass Transf. 150 (2020) 119300, , doi:10.1016/j.ijheatmasstransfer.2019.119300.
[47] C. Liu, Z. Cai, Y. Dai, N. Huang, F. Xu, C. Lao, Experimental comparison of the flow rate and cooling performance of internal cooling channels fabricated via selective laser melting and conventional drilling process, Int. J. Adv. Manuf. Technol. 96 (2018) 2757–2767, doi:10.1007/s00170-018-1799-y.
[48] P. Hu, B. He, L. Ying, Numerical investigation on cooling performance of hot stamping tool with various channel designs, Appl. Therm. Eng. 96 (2016) 338–351, doi:10.1016/j.applthermaleng.2015.10.154.
[49] H. Li, Y. Mei, B. Lin, H. Xiao, Design and optimization of conformal cooling system of an injection molding chimney, Mater. Sci. Forum. 850 (2016) 679–686, doi:10.4028/www.scientific.net/MSF.850.679.
[50] S.G. Sharma, D.S. Singraur, D.S.S. Sudhakar, Transient analysis of an injection mould with conformal cooling channels, in: A.K. Parwani, P. Ramkumar (Eds.), Recent Adv. Mech. Infrastruct., Springer Nature Singapore Pte Ltd., Singapore, 2020, pp. 235–244, doi:10.1007/978-981-32-9971-9_24.
[51] G. Venkatesh, Y.Ravi Kumar, Thermal analysis for conformal cooling channel, Mater, Today Proc. 4 (2017) 2592–2598, doi:10.1016/j.matpr.2017.02.113.
[52] Z. Shayfull, S. Sharif, A. Mohd Zain, R. Mohd Saad, M.A. Fairuz, Warpage analysis with straight drilled and conformal cooling channels on front panel housing by using taguchi method, Key Eng. Mater. 594–595 (2014) 593–603, doi:10.4028/www.scientific.net/KEM.594-595.593.
[53] B. He, L. Ying, X. Li, P. Hu, Optimal design of longitudinal conformal cooling channels in hot stamping tools, Appl. Therm. Eng. 106 (2016) 1176–1189, doi:10.1016/j.applthermaleng.2016.06.113.
[54] Y.P. Qian, Y. Wang, J.H. Huang, X.Z. Zhou, Study on the optimization of conformal cooling channels for plastic injection mold, Adv. Mater. Res. 591–593 (2012) 502–506, doi:10.4028/www.scientific.net/AMR.591-593.502.
[55] M.H.M. Hazwan, Z. Shayfull, S. Sharif, S.M. Nasir, M.M. Rashidi, Warpage optimisation on the moulded part with conformal cooling channels using response surface methodology (RSM) and glowworm swarm optimisation (GSO), in: MATEC Web Conf, 97, 2017, p. 01104, doi:10.1051/matecconf/20179701104.
[56] I. Fauzun, M. Hamdi, A.E. Tontowi, T. Ariga, Formulation of the size and position of spiral cooling channel in plastic injection mold based on Fluent simulation results, in: 2008 IEEE Int. Conf. Ind. Eng. Eng. Manag., IEEE, 2008, pp. 1728–1733, doi:10.1109/IEEM.2008.4738168.
[57] S. Jahan, H. El-Mounayri, A thermomechanical analysis of conformal cooling channels in 3D printed plastic injection molds, Appl. Sci. 8 (2018) 2567, doi:10.3390/app8122567.
[58] S.A. Jahan, T. Wu, Y. Zhang, J. Zhang, A. Tovar, H. Elmounayri, Thermo-mechanical design optimization of conformal cooling channels using design of experiments approach, Procedia Manuf. 10 (2017) 898–911, doi:10.1016/j.promfg.2017.07.078.
[59] A. Agazzi, V. Sobotka, R.Le Goff, D. Garcia, Y. Jarny, A methodology for the design of effective cooling system in injection moulding, Int. J. Mater. Form. 3 (2010) 13–16, doi:10.1007/s12289-010-0695-2.
[60] W.R. Schmidt, R.D. White, C.E. Bird, J.V. Bak, Conformal cooling versus conventional cooling: an injection molding case study with P-20 and 3DP™-processed tooling, Mater. Res. Soc. Symp. - Proc. 625 (2000) 51–56, doi:10.1557/PROC-625-51.
[61] A. Agazzi, V. Sobotka, R. Legoff, Y. Jarny, Optimal cooling design in injection moulding process-A new approach based on morphological surfaces, Appl. Therm. Eng. 52 (2013) 170–178, doi:10.1016/j.applthermaleng.2012.11.019.
[62] Y. Wang, K.M. Yu, C.C.L. Wang, Spiral and conformal cooling in plastic injection molding, Comput.-Aided Des. 63 (2015) 1–11, doi:10.1016/j.cad.2014.11.012.
[63] H.S. Park, N.H. Pham, Automatically generating conformal cooling channel design for plastic injection molding, in: Ann. DAAAM Proc., DAAAM International Vienna, 2007, pp. 539–541.
[64] H.S. Park, N.H. Pham, Design of conformal cooling channels for an automotive part, Int. J. Automot. Technol. 10 (2009) 87–93, doi:10.1007/s12239-009-0011-7.
[65] C.G. Li, C.L. Li, Y. Liu, Y. Huang, A new C-space method to automate the layout design of injection mould cooling system, Comput.-Aided Des. 44 (2012) 811–823, doi:10.1016/j.cad.2012.01.005.
[66] C.L. Li, C.G. Li, A.C.K. Mok, Automatic layout design of plastic injection mould cooling system, Comput.-Aided Des. 37 (2005) 645–662, doi:10.1016/j.cad.2004.08.003.
[67] L. Tudose, S. Haragas, O. Buiga, C. Tudose, Increasing injection molding speed through cooling system geometry optimization, Mater. Plast. 51 (2014) 252–257.
[68] S. Kitayama, H. Miyakawa, M. Takano, S. Aiba, Multi-objective optimization of injection molding process parameters for short cycle time and warpage reduction using conformal cooling channel, Int. J. Adv. Manuf. Technol. 88 (2017) 1735–1744, doi:10.1007/s00170-016-8904-x.
[69] A. Agazzi, V. Sobotka, R. LeGoff, Y. Jarny, Inverse method for the cooling system design in injection moulding - application to a “T-shaped” piece, Inverse Probl. Sci. Eng. 22 (2014) 707–726, doi:10.1080/17415977.2013.823412.
[70] S. Kitayama, K. Tamada, M. Takano, S. Aiba, Numerical optimization of process parameters in plastic injection molding for minimizing weldlines and clamping force using conformal cooling channel, J. Manuf. Process. 32 (2018) 782–790, doi:10.1016/j.jmapro.2018.04.007.
[71] Y. Wang, K.-.M. Yu, C.C.L. Wang, Y. Zhang, Automatic design of conformal cooling circuits for rapid tooling, Comput.-Aided Des. 43 (2011) 1001–1010, doi:10.1016/j.cad.2011.04.011.
[72] J.H. Choi, J.S. Kim, E.S. Han, H.P. Park, B.O. Rhee, Study on an optimized configuration of conformal cooling channel by branching law, in: Proc. ASME 2014 12th Bienn. Conf. Eng. Syst. Des. Anal, Copenhagen, Denmark, American Society of Mechanical Engineers, 2014, p. 20431, doi:10.1115/ESDA2014-20431.
[73] J.M. Mercado-Colmenero, C. Martin-Doñate, M. Rodriguez-Santiago, F. Moral-Pulido, M.A. Rubio-Paramio, A new conformal cooling lattice design procedure for injection molding applications based on expert algorithms, Int. J. Adv. Manuf. Technol. 102 (2019) 1719–1746, doi:10.1007/s00170-018-03235-3.

[74] Z. Li, X. Wang, J. Gu, S. Ruan, C. Shen, Y. Lyu, Y. Zhao, Topology optimization for the design of conformal cooling system in thin-wall injection molding based on BEM, Int. J. Adv. Manuf. Technol. 94 (2018) 1041–1059, doi:10.1007/s00170-017-0901-1.
[75] K.M. Au, K.M. Yu, W.K. Chiu, Visibility-based conformal cooling channel generation for rapid tooling, Comput.-Aided Des. 43 (2011) 356–373, doi:10.1016/j.cad.2011.01.001.
[76] K.M. Au, K.M. Yu, Modeling of multi-connected porous passageway for mould cooling, Comput.-Aided Des. 43 (2011) 989–1000, doi:10.1016/j.cad.2011.02.007.
[77] K.M. Au, K.M. Yu, A scaffolding architecture for conformal cooling design in rapid plastic injection moulding, Int. J. Adv. Manuf. Technol. 34 (2007) 496–515, doi:10.1007/s00170-006-0628-x.
[78] S. Jahan, T. Wu, Y. Shin, A. Tovar, H. El-Mounayri, Thermo-fluid topology optimization and experimental study of conformal cooling channels for 3D printed plastic injection molds, Procedia Manuf. 34 (2019) 631–639, doi:10.1016/j.promfg.2019.06.120.
[79] K.-.H. Shin, A method for representation and analysis of conformal cooling channels in molds made of functionally graded tool steel/Cu materials, J. Mech. Sci. Technol. 33 (2019) 1743–1750, doi:10.1007/s12206-019-0326-x.
[80] J. Huang, G.M. Fadel, Bi–objective optimization design of heterogeneous injection mold cooling systems, J. Mech. Des. Trans. ASME. 123 (2001) 226–239, doi:10.1115/1.1347992.
[81] T. Wu, S.A. Jahan, Y. Zhang, J. Zhang, H. Elmounayri, A. Tovar, Design optimization of plastic injection tooling for additive manufacturing, Procedia Manuf. 10 (2017) 923–934, doi:10.1016/j.promfg.2017.07.082.
[82] T. Wu, S.A. Jahan, P. Kumaar, A. Tovar, H. El-Mounayri, Y. Zhang, J. Zhang, D. Acheson, K. Brand, R. Nalim, A framework for optimizing the design of injection molds with conformal cooling for additive manufacturing, Procedia Manuf. 1 (2015) 404–415, doi:10.1016/j.promfg.2015.09.049.
[83] A. Agazzi, V. Sobotka, R. Legoff, Y. Jarny, Uniform cooling and part warpage reduction in injection molding thanks to the design of an effective cooling system, Key Eng. Mater. 554–557 (2013) 1611–1618, doi:10.4028/www.scientific.net/KEM.554-557.1611.
[84] S.A. Jahan, H. El-Mounayri, Optimal conformal cooling channels in 3D printed dies for plastic injection molding, Procedia Manuf. 5 (2016) 888–900, doi:10.1016/j.promfg.2016.08.076.
[85] A.B.M. Saifullah, S.H. Masood, Optimum cooling channels design and thermal analysis of an Injection moulded plastic part mould, Mater. Sci. Forum. 561–565 (2007) 1999–2002, doi:10.4028/www.scientific.net/msf.561-565.1999.
[86] M.S. Wahab, A.A.A. Raus, I. Amir, A. Ahmed, K. Kamarudin, The thermal effect of variate cross-sectional profile on conformal cooling channels in plastic injection moulding, Int. J. Integr. Eng. 10 (2018) 156–163, doi:10.30880/ijie.2018.10.05.023.
[87] S.Z.A. Rahim, S. Sharif, A.M. Zain, S.M. Nasir, R. Mohd Saad, Improving the quality and productivity of molded parts with a new design of conformal cooling channels for the injection molding process, Adv. Polym. Technol. 35 (2016) 21524, doi:10.1002/adv.21524.
[88] J. Collomb, P. Balland, P. Francescato, Y. Gardet, D. Leh, P. Saffré, Thermomechanical optimization and comparison of a low thermal inertia mold with rectangular heating channels and a conventional mold, Adv. Mater. Sci. Eng. 2019 (2019) 1–13, doi:10.1155/2019/3261972.
[89] K. Kamarudin, M.S. Wahab, M.F.M. Batcha, Z. Shayfull, A.A. Raus, A. Ahmed, Cycle time improvement for plastic injection moulding process by sub groove modification in conformal cooling channel, AIP Conf. Proc. 1885 (2017) 020176, , doi:10.1063/1.5002370.
[90] L. Xi, J. Gao, L. Xu, Z. Zhao, Y. Li, Study on heat transfer performance of steam-cooled ribbed channel using neural networks and genetic algorithms, Int. J. Heat Mass Transf. 127 (2018) 1110–1123, doi:10.1016/j.ijheatmasstransfer.2018.08.115.
[91] L. Wang, S. Wang, F. Wen, X. Zhou, Z. Wang, Heat transfer and flow characteristics of U-shaped cooling channels with novel wavy ribs under stationary and rotating conditions, Int. J. Heat Mass Transf. 126 (2018) 312–333, doi:10.1016/j.ijheatmasstransfer.2018.05.123.
[92] L. Wang, S. Wang, F. Wen, X. Zhou, Z. Wang, Effects of continuous wavy ribs on heat transfer and cooling air flow in a square single-pass channel of turbine blade, Int. J. Heat Mass Transf. 121 (2018) 514–533, doi:10.1016/j.ijheatmasstransfer.2018.01.004.
[93] G. Jiang, J. Gao, X. Shi, F. Li, L. Xu, Flow and heat transfer characteristics of the mist/steam two-phase flow cooling the rectangular channel with column-row-ribs, Int. J. Heat Mass Transf. 156 (2020) 119737, , doi:10.1016/j.ijheatmasstransfer.2020.119737.
[94] P. Freitas, C. Santos, P. Carreira, A. Mateus, High efficiency cooling and heating channels for injection moulding, Appl. Mech. Mater. 890 (2019) 43–53, doi:10.4028/www.scientific.net/amm.890.43.
[95] A.M. Kamat, Y. Pei, An analytical method to predict and compensate for residual stress-induced deformation in overhanging regions of internal channels fabricated using powder bed fusion, Addit. Manuf. 29 (2019) 100796, , doi:10.1016/j.addma.2019.100796.
[96] M. Mazur, M. Leary, M. McMillan, J. Elambasseril, M. Brandt, SLM additive manufacture of H13 tool steel with conformal cooling and structural lattices, Rapid Prototyp. J. 22 (2016) 504–518, doi:10.1108/RPJ-06-2014-0075.
[97] K. Altaf, V.R. Raghavan, A.M.A. Rani, Comparative thermal analysis of circular and profiled cooling channels for injection mold tools, J. Appl. Sci. 11 (2011) 2068–2071, doi:10.3923/jas.2011.2068.2071.
[98] N. Hopkinson, P. Dickens, Conformal cooling and heating channels using laser sintered tools, in: Solid Free. Fabr. Conf., Texas, 2000, pp. 490–497, doi:10.26153/tsw/3075.
[99] M. Maurizi, F. Berto, 3D effects on Fracture Mechanics: corner point singularities, Procedia Struct. Integr. 26 (2020) 336–347, doi:10.1016/j.prostr.2020.06.043.
[100] F. Berto, P. Lazzarin, A. Kotousov, On higher order terms and out-of-plane singular mode, Mech. Mater. 43 (2011) 332–341, doi:10.1016/j.mechmat.2011.03.004.
[101] L.P. Pook, A. Campagnolo, F. Berto, Coupled fracture modes of discs and plates under anti-plane loading and a disc under in-plane shear loading, Fatigue Fract. Eng. Mater. Struct. 39 (2016) 924–938, doi:10.1111/ffe.12389.
[102] N. Ivaşcu, C. Fetecău, Dynamic temperature control in injection molding with new conformal heating/cooling system, Ann. "Dunarea Jos" Univ. Galati, Fascicle V, Technol. Mach. Build. 28 (2010) 5–11, https://www.gup.ugal.ro/ugaljournals/index.php/tmb/article/view/1831.
[103] Y. Tang, Z. Gao, Y.F. Zhao, Design of conformal porous structures for the cooling system of an injection mold fabricated by additive manufacturing process, J. Mech. Des. Trans. ASME. 141 (2019) 1–11, doi:10.1115/1.4043680.
[104] H. Brooks, K. Brigden, Design of conformal cooling layers with self-supporting lattices for additively manufactured tooling, Addit. Manuf. 11 (2016) 16–22, doi:10.1016/j.addma.2016.03.004.
[105] L. Crema, M. Sorgato, G. Lucchetta, Thermal optimization of deterministic porous mold inserts for rapid heat cycle molding, Int. J. Heat Mass Transf. 109 (2017) 462–469, doi:10.1016/j.ijheatmasstransfer.2017.02.023.
[106] T. Wu, N. Upadhyaya, D. Acheson, A. Tovar, Structural optimization of injection molds with lattice cooling, in: Proc. ASME 2017 Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf., ASME, Cleveland, Ohio, USA, 2017, pp. 1–12.
[107] S.A. Jahan, T. Wu, Y. Zhang, H. El-Mounayri, A. Tovar, J. Zhang, D. Acheson, R. Nalim, X. Guo, W.H. Lee, Implementation of conformal cooling & topology optimization in 3D printed stainless steel porous structure injection molds, Procedia Manuf. 5 (2016) 901–915, doi:10.1016/j.promfg.2016.08.077.
[108] K. Prashanth Reddy, B. Panitapu, High thermal conductivity mould insert materials for cooling time reduction in thermoplastic injection moulds, Mater. Today Proc. 4 (2017) 519–526, doi:10.1016/j.matpr.2017.01.052.
[109] H. Natu, J. Mazumder, Modeling of cooling times for molds with conformal cooling channels and heat sinks, in: Int. Congr. Appl. Lasers Electro-Optics, Laser Institute of America, 2000, pp. E1–E10, doi:10.2351/1.5059538.
[110] D.-.G. Ahn, H.-.W. Kim, K.-.Y. Lee, Design of the thermally conductive mould to improve cooling characteristics of injection mould for a mouse, Trans. Korean Soc. Mech. Eng. A. 33 (2009) 201–209, doi:10.3795/KSME-A.2009.33.3.201.
[111] J. Fessler, A. Nickel, G. Link, F. Prinz, P. Fussell, Functional gradient metallic prototypes through shape deposition manufacturing, 1997 Int. Solid Free. Fabr. Symp. (1997) 521–528, http://hdl.handle.net/2152/71430.
[112] P. Martinho, P.J. Bártolo, M.P. Queirós, A.J. Pontes, A.S. Pouzada, Hybrid moulds: the use of combined techniques for the rapid manufacturing of injection moulds, in: Virtual Model. Rapid Manuf. - Adv. Res. Virtual Rapid Prototyp, 2005, , pp. 421–427,. http://hdl.handle.net/1822/34152.
[113] A.B.M. Saifullah, S.H. Masood, I. Sbarski, Thermal-structural finite element analysis of injection moulding dies with optimized cooling channels, Mater. Sci. Forum. 654–656 (2010) 1646–1649, doi:10.4028/www.scientific.net/MSF.654-656.1646.
[114] A.B.M. Saifullah, S.H. Masood, I. Sbarski, Thermal-structural analysis of bi-metallic conformal cooling for injection moulds, Int. J. Adv. Manuf. Technol. 62 (2012) 123–133, doi:10.1007/s00170-011-3805-5.
[115] K. Shin, Modeling of cooling channels of injection mould using functionally graded material, Trans. Korean Soc. Mech. Eng. - A. 35 (2011) 1647–1653, doi:10.3795/KSME-A.2011.35.12.1647.
[116] K. Altaf, A.M. Abdul Rani, F. Ahmad, M. Baharom, V.R. Raghavan, Determining the effects of thermal conductivity on epoxy molds using profiled cooling channels with metal inserts, J. Mech. Sci. Technol. 30 (2016) 4901–4907, doi:10.1007/s12206-016-1055-z.
[117] I. Hatos, B. Kocsis, H. Hargitai, Conformal cooling with heat-conducting inserts by direct metal laser sintering, IOP Conf. Ser. Mater. Sci. Eng. 448 (2018) 012027, , doi:10.1088/1757-899X/448/1/012027.
[118] B.-.A. Behrens, A. Bouguecha, M. Vucetic, M. Bonhage, I.Y. Malik, Numerical investigation for the design of a hot forging die with integrated cooling channels, Procedia Technol 26 (2016) 51–58, doi:10.1016/j.protcy.2016.08.008.
[119] S. Yun, J. Kwon, W. Cho, D. Lee, Y. Kim, Performance improvement of hot stamping die for patchwork blank using mixed cooling channel designs with straight and conformal channels, Appl. Therm. Eng. 165 (2020) 114562, , doi:10.1016/j.applthermaleng.2019.114562.
[120] G. Wang, G. Zhao, H. Li, Y. Guan, Analysis of thermal cycling efficiency and optimal design of heating/cooling systems for rapid heat cycle injection molding process, Mater. Des. 31 (2010) 3426–3441, doi:10.1016/j.matdes.2010.01.042.
[121] D.F. Walczyk, M.A. Lettko, Design and analysis of composites manufacturing tooling for rapid heating and cooling, J. Manuf. Process. 36 (2018) 487–495, doi:10.1016/j.jmapro.2018.10.039.
[122] Z. Zheng, H.O. Zhang, G.L. Wang, Y.P. Qian, Finite element analysis on the injection molding and productivity of conformal cooling channel, J. Shanghai Jiaotong Univ. 16 (2011) 231–235, doi:10.1007/s12204-011-1128-1.
[123] R.Appermont W.Six, F. Desplentere, J. Dekeyzer, A. Van Bael, Design and simulation of conformal cooling channels in SLM produced injection molds:

effects on process and product quality, in: Proc. 32nd Int. Polym. Process. Soc. Conf., 2016.
[124] G. Venkatesh, Y.Ravi Kumar, G. Raghavendra, Comparison of straight line to conformal cooling channel in injection molding, Mater. Today Proc. 4 (2017) 1167–1173, doi:10.1016/j.matpr.2017.01.133.
[125] S. Marques, A.F. De Souza, Evaluating the conformal cooling system in moulds for plastic injection by CAE simulation, in: Proc. 9th Int. Conf. Ind. Tools Mater. Process. Technol., Ljubljana: Slovenian Tool and Die Development Centre, 2014.
[126] A. Bolattürk, O. Ipek, K. Kurtuluş, M. Kan, Design of conformal cooling channels using numerical methods in a metal mold and calculating exergy destruction in channels, Sci. Iran. 26 (2019) 3255–3261, doi:10.24200/sci.2018.50090.1502.
[127] B. Reggiani, I. Todaro, Investigation on the design of a novel selective laser melted insert for extrusion dies with conformal cooling channels, Int. J. Adv. Manuf. Technol. 104 (2019) 815–830, doi:10.1007/s00170-019-03879-9.
[128] Z. Shayfull, S. Sharif, A.M. Zain, S.M. Nasir, R.M. Saad, Improving warpage with milled groove square shape conformal cooling channels, Key Eng. Mater. 700 (2016) 31–41, doi:10.4028/www.scientific.net/KEM.700.31.
[129] J.G. Kovács, F. Szabó, N.K. Kovács, A. Suplicz, B. Zink, T. Tábi, H. Hargitai, Thermal simulations and measurements for rapid tool inserts in injection molding applications, Appl. Therm. Eng. 85 (2015) 44–51, doi:10.1016/j.applthermaleng.2015.03.075.
[130] E. Dimla, J. Rull-Trinidad, A.A. Garcia-Granada, G. Reyes, Thermal comparison of conventional and conformal cooling channel designs for a non-constant thickness screw cap, J. Korean Soc. Precis. Eng. 35 (2018) 95–101, doi:10.7736/KSPE.2018.35.1.95.
[131] H.-.S. Park, X.-.P. Dang, D.-.S. Nguyen, S. Kumar, Design of advanced injection mold to increase cooling efficiency, Int. J. Precis. Eng. Manuf. Technol. 7 (2020) 319–328, doi:10.1007/s40684-019-00041-4.
[132] F.H. Hsu, K. Wang, C.T. Huang, R.Y. Chang, Investigation on conformal cooling system design in injection molding, Adv. Prod. Eng. Manag. 8 (2013) 107–115, doi:10.14743/apem2013.2.158.
[133] E. Dimla, Design considerations of conformal cooling channels in injection moulding tools design: an overview, J. Therm. Eng. 1 (2015) 627–635, doi:10.18186/jte.09602.
[134] S.C. Nian, M.H. Li, M.S. Huang, Warpage control of headlight lampshades fabricated using external gas-assisted injection molding, Int. J. Heat Mass Transf. 86 (2015) 358–368, doi:10.1016/j.ijheatmasstransfer.2015.03.027.
[135] M.S. Shinde, K.M. Ashtankar, Effect of different shapes of conformal cooling channel on the parameters of injection molding, Comput. Mater. Contin. 54 (2018) 287–306, doi:10.3970/cmc.2018.054.287.
[136] F. Marin, J.R. de Miranda, A.F. de Souza, Study of the design of cooling channels for polymers injection molds, Polym. Eng. Sci. 58 (2018) 552–559, doi:10.1002/pen.24769.
[137] L. Běhálek, J. Dobránsky, Conformal cooling of the injection moulds, Appl. Mech. Mater. 308 (2013) 127–132, doi:10.4028/www.scientific.net/AMM.308.127.
[138] D.G. Ahn, S.H. Park, H.S. Kim, Manufacture of an injection mould with rapid and uniform cooling characteristics for the fan parts using a DMT process, Int. J. Precis. Eng. Manuf. 11 (2010) 915–924, doi:10.1007/s12541-010-0111-3.
[139] E.M. Wylonis III, Production of Injection Molding Tooling With Conformal Cooling Channels Using the Three Dimensional Printing Process, Massachusetts Institute of Technology, 1995.
[140] Y. Song, S. Park, H. Jee, 3D welding and milling - a direct approach for fabrication of injection molds, in: Proc. Solid Free. Fabr. Symp, 1999, pp. 793–800.
[141] Y. Song, S. Park, K. Hwang, D. Choi, H. Jee, 3D welding and milling for direct prototyping of metallic parts, in: 1998 Int. Solid Free. Fabr. Symp., 1998, pp. 495–502, doi:10.26153/tsw/638.
[142] C.C. Kuo, B.C. Chen, Development of hot embossing stamps with conformal cooling channels for microreplication, Int. J. Adv. Manuf. Technol. 88 (2017) 2603–2608, doi:10.1007/s00170-016-8970-0.
[143] Y.F. Sun, K.S. Lee, A.Y.C. Nee, The application of U-shape milled grooves for cooling of injection moulds, Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. 216 (2002) 1561–1573, doi:10.1243/095440502321016314.
[144] S. Mayer, Optimised mould temperature control procedure using DMLS, EOS GmbH (2009) http://www.3dimpuls.com/sites/default/files/download/eos_optimizedmouldtemperaturecontrolprocedureusing_dmls.pdf.
[145] E. Vojnová, The benefits of a conforming cooling systems the molds in injection moulding process, Procedia Eng. 149 (2016) 535–543, doi:10.1016/j.proeng.2016.06.702.
[146] M. Cortina, J. Arrizubieta, A. Calleja, E. Ukar, A. Alberdi, Case study to illustrate the potential of conformal cooling channels for hot stamping dies manufactured using hybrid process of laser metal deposition (LMD) and milling, Metals 8 (2018) 102, doi:10.3390/met8020102.
[147] K. Altaf, A. Majdi Abdul Rani, V.R. Raghavan, Prototype production and experimental analysis for circular and profiled conformal cooling channels in aluminium filled epoxy injection mould tools, Rapid Prototyp. J. 19 (2013) 220–229, doi:10.1108/13552541311323236.
[148] C.C. Kuo, W.H. Chen, J.W. Zhang, D.A. Tsai, Y.L. Cao, B.Y. Juang, A new method of manufacturing a rapid tooling with different cross-sectional cooling channels, Int. J. Adv. Manuf. Technol. 92 (2017) 3481–3487, doi:10.1007/s00170-017-0423-x.
[149] C.C. Kuo, W.H. Chen, X.Z. Liu, Y.L. Liao, W.J. Chen, B.Y. Huang, R.L. Tsai, Development of a low-cost wax injection mold with high cooling efficiency, Int. J. Adv. Manuf. Technol. 93 (2017) 2081–2088, doi:10.1007/s00170-017-0596-3.
[150] K. Altaf, A.M.A. Rani, V.R. Raghavan, Fabrication of circular and profiled conformal cooling channels in aluminum filled epoxy injection mould tools, in: 2011 Natl. Postgrad. Conf.„ IEEE, 2011, pp. 1–4, doi:10.1109/NatPC.2011.6136406.
[151] C.C. Kuo, W.H. Chen, W.C. Xu, A cost-effective approach for rapid manufacturing wax injection molds with complex geometrical shapes of cooling channels, Int. J. Adv. Manuf. Technol. 91 (2017) 1689–1695, doi:10.1007/s00170-016-9886-4.
[152] G.Q. Gao, Y.S. Liu, Y.J. Cai, Analysis and manufacturing of conformal cooling channels in injection mold, Appl. Mech. Mater. 651–653 (2014) 630–633, doi:10.4028/www.scientific.net/AMM.651-653.630.
[153] C.C. Kuo, Z.Y. You, A cost-effective approach for rapid fabricating cooling channels with smooth surface, Int. J. Adv. Manuf. Technol. 95 (2018) 1135–1141, doi:10.1007/s00170-017-1328-4.
[154] C.C. Kuo, Y.J. Zhu, Y.Z. Wu, Z.Y. You, Development and application of a large injection mold with conformal cooling channels, Int. J. Adv. Manuf. Technol. 103 (2019) 689–701, doi:10.1007/s00170-019-03614-4.
[155] C.C. Kuo, Z.Y. You, Development of injection molding tooling with conformal cooling channels fabricated by optimal process parameters, Int. J. Adv. Manuf. Technol. 96 (2018) 1003–1013, doi:10.1007/s00170-018-1664-z.
[156] C.C. Kuo, Z.Y. You, J.Y. Wu, J.L. Huang, Development and application of a conformal cooling channel with easy removal and smooth surfaces, Int. J. Adv. Manuf. Technol. 102 (2019) 2029–2039, doi:10.1007/s00170-019-03316-x.
[157] A.A. Nogueira, P.S. Pouzada, P.G. Martinho, A.S. Pouzada, A new way to produce conformal cooling channels by RPT for moulding blocks of the hybrid moulds, PMI 2010 (2010) 1–6 http://repositorium.sdum.uminho.pt/handle/1822/20527.
[158] C.C. Kuo, W.C. Xu, Effects of different cooling channels on the cooling efficiency in the wax injection molding process, Int. J. Adv. Manuf. Technol. 98 (2018) 887–895, doi:10.1007/s00170-018-2345-7.
[159] J.C. Ferreira, A. Mateus, Studies of rapid soft tooling with conformal cooling channels for plastic injection moulding, J. Mater. Process. Technol. 142 (2003) 508–516, doi:10.1016/S0924-0136(03)00650-2.
[160] C.C. Kuo, H.J. Hsu, Development and application of hybrid mold with microfeatures in micro-hot embossing, Mater. Manuf. Process. 28 (2013) 1203–1208, doi:10.1080/10426914.2013.832305.
[161] R. Cheng, X. Wu, J. Zheng, Indirect rapid manufacture of injection mould with conformal cooling channels based on SLS, Die & Mould Ind. 37 (2011) 70–75. doi:10.16787/j.cnki.1001-2168.dmi.2011.04.021.
[162] Y. Yang, S.P. Hannula, Development of precision spray forming for rapid tooling, Mater. Sci. Eng. A. 477 (2008) 63–68, doi:10.1016/j.msea.2007.09.080.
[163] X.P. Dang, H.S. Park, Design of U-shape milled groove conformal cooling channels for plastic injection mold, Int. J. Precis. Eng. Manuf. 12 (2011) 73–84, doi:10.1007/s12541-011-0009-8.
[164] Z. Shayfull, S. Sharif, A.M. Zain, R.M. Saad, M.A. Fairuz, Milled groove square shape conformal cooling channels in injection molding process, Mater. Manuf. Process. 28 (2013) 884–891, doi:10.1080/10426914.2013.763968.
[165] A.B.M. Saifullah, S.H. Masood, I. Sbarski, New cooling channel design for injection moulding, in: Proc. World Congr. Eng., London, UK, 2009.
[166] J. Huang, Y. Lu, Q. Wang, F. Lin, Design and fabrication of conformal cooling channels with vacuum diffusion bonding, Recent Patents Chem. Eng. 6 (2013) 176–183, doi:10.2174/22113347079991403311213333.
[167] A. Hughes, Method of Manufacturing a Mold With Conformal Cooling Passages and Mold Manufactured According to Said Method, US Patent Application Publication, 2013.
[168] H. Ahari, A. Khajepour, S. Bedi, Manufacturing optimization of laminated tooling with conformal cooling channels, Rapid Prototyp. J. 17 (2011) 429–440, doi:10.1108/13552541111184161.
[169] H. Ahari, A. Khajepour, S. Bedi, Laminated injection mould with conformal cooling channels: optimization, fabrication and testing, J. Mach. Manuf. Autom. 2 (2013) 16–24.
[170] S. Yoo, D.F. Walczyk, A preliminary study of sealing and heat transfer performance of conformal channels and cooling fins in laminated tooling, J. Manuf. Sci. Eng. 129 (2007) 388–399, doi:10.1115/1.2515522.
[171] R. Hölker, M. Haase, N. Ben Khalifa, A.E. Tekkaya, Hot extrusion dies with conformal cooling channels produced by additive manufacturing, Mater, Today Proc 2 (2015) 4838–4846, doi:10.1016/j.matpr.2015.10.028.
[172] S. Yoo, Design of conformal cooling/heating channels for layered tooling, in: 2008 Int. Conf. Smart Manuf. Appl., IEEE, 2008, pp. 126–129, doi:10.1109/ICSMA.2008.4505626.
[173] R.E. Williams, D.F. Walczyk, H.T. Dang, Using abrasive flow machining to seal and finish conformal channels in laminated tooling, Rapid Prototyp. J. 13 (2007) 64–75, doi:10.1108/13552540710736740.
[174] E. Sachs, E. Wylonis, S. Allen, M. Cima, H. Guo, Production of injection molding tooling with conformal cooling channels using the three dimensional printing process, Polym. Eng. Sci. 40 (2000) 1232–1247, doi:10.1002/pen.11251.
[175] M.M.A. Dewidar, Direct and Indirect Laser Sintering of Metals, The University of Leeds, 2002.
[176] S. Bobby, S. Singamneni, Conformal cooling through thin shell moulds produced by 3D printing, Aust. J. Multi-Disciplinary Eng. 9 (2013) 155–163.

[177] I. Ilyas, C. Taylor, K. Dalgarno, J. Gosden, Design and manufacture of injection mould tool inserts produced using indirect SLS and machining processes, Rapid Prototyp. J. 16 (2010) 429–440, doi:10.1108/13552541011083353.

[178] K. Dalgarno, T. Stewart, Production tooling for polymer moulding using the RapidSteel process, Rapid Prototyp. J. 7 (2001) 173–179, doi:10.1108/13552540110395600.

[179] R. Hölker, A. Jäger, N. Ben Khalifa, A.E. Tekkaya, Controlling heat balance in hot aluminum extrusion by additive manufactured extrusion dies with conformal cooling channels, Int. J. Precis. Eng. Manuf. 14 (2013) 1487–1493, doi:10.1007/s12541-013-0200-1.

[180] D. Dimitrov, A. Moammer, Investigation of the impact of conformal cooling on the performance of injection moulds for the packaging industry, J. New Gener. Sci. 8 (2003) 29–46.

[181] L. Wang, Q. Wei, P. Xue, Y. Shi, Fabricate mould insert with conformal cooling channel using selective laser melting, Adv. Mater. Res. 502 (2012) 67–71, doi:10.4028/www.scientific.net/AMR.502.67.

[182] C.G. Klingaa, M.K. Bjerre, S. Baier, L. De Chiffre, S. Mohanty, J.H. Hattel, Roughness investigation of SLM manufactured conformal cooling channels using X-ray computed tomography, in: Proc. 9th Conf. Ind. Comput. Tomogr., Padova, Italy, 2019, pp. 1–10. https://www.ndt.net/search/docs.php3?showForm=off&id=23739.

[183] S. Feng, S. Chen, A.M. Kamat, R. Zhang, M. Huang, L. Hu, Investigation on shape deviation of horizontal interior circular channels fabricated by laser powder bed fusion, Addit. Manuf. 36 (2020) 101585, , doi:10.1016/j.addma.2020.101585.

[184] K. Shin, H. Natu, D. Dutta, J. Mazumder, A method for the design and fabrication of heterogeneous objects, Mater. Des. 24 (2003) 339–353, doi:10.1016/S0261-3069(03)00060-8.

[185] G.J. Gibbons, R.G. Hansell, Direct tool steel injection mould inserts through the Arcam EBM free-form fabrication process, Assem. Autom. 25 (2005) 300–305, doi:10.1108/01445150510626433.

[186] L.E. Rannar, A. Glad, C.G. Gustafson, Efficient cooling with tool inserts manufactured by electron beam melting, Rapid Prototyp. J. 13 (2007) 128–135, doi:10.1108/13552540710750870.

[187] A. Villalon, Electron Beam Fabrication of Injection Mold Tooling With Conformal Cooling Channels, North Carolina State University, 2005, http://repository.lib.ncsu.edu/ir/handle/1840.16/2543.

[188] F. Legesse, K.P. Karunakaran, Additive manufacturing of tooling element with conformal cooling channel, J. Def. Technol. 10 (2015) 82–89.

[189] K.P. Karunakaran, S. Kapil, H. Vithasth, F. Legesse, Additive manufacturing of H13 tooling element with conformal cooling channel using MIG cladding, Int. J. Rapid Manuf. 7 (2018) 1–24, doi:10.1504/IJRAPIDM.2018.10010809.

[190] M. Soshi, J. Ring, C. Young, Y. Oda, M. Mori, Innovative grid molding and cooling using an additive and subtractive hybrid CNC machine tool, CIRP Ann. - Manuf. Technol. 66 (2017) 401–404, doi:10.1016/j.cirp.2017.04.093.

[191] R. Hölker, A.E. Tekkaya, Advancements in the manufacturing of dies for hot aluminum extrusion with conformal cooling channels, Int. J. Adv. Manuf. Technol. 83 (2016) 1209–1220, doi:10.1007/s00170-015-7647-4.

[192] D. Homar, L. Čerče, J. Kopač, Cooling simulation of conformal cooling injection mould insert produced by hybrid manufacturing, Teh. Vjesn. - Tech. Gaz. 24 (2017) 981–986, doi:10.17559/TV-20150909075338.

[193] B. Abbès, F. Abbès, H. Abdessalam, A. Upganlawar, Finite element cooling simulations of conformal cooling hybrid injection molding tools manufactured by selective laser melting, Int. J. Adv. Manuf. Technol. 103 (2019) 2515–2522, doi:10.1007/s00170-019-03721-2.

[194] M.A. Garcia, C. Garcia-Pando, C. Marto, Conformal cooling in moulds with special geometry, in: Bartolo (Ed.), Innov. Dev. Virtual Phys. Prototyp, Taylor & Francis, London, 2012, pp. 409–412.

[195] K. Boivie, S. Dolinsek, D. Homar, Hybrid manufacturing; Integration of additive technologies for competitive production of complex tools and products, in: 15th Int. Res. Conf. Trends Dev. Mach. Assoc. Technol., Prague, Czech Republic, 2011, pp. 53–56.

[196] K.W. Dalgarno, T.D. Stewart, Manufacture of production injection mould tooling incorporating conformal cooling channels via indirect selective laser sintering, Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. 215 (2001) 1323–1332, doi:10.1243/0954405011519042.

[197] X. Wang, S. Li, Y. Fu, H. Gao, Finishing of additively manufactured metal parts by abrasive flow machining, in: Proc. 27th Annu. Int. Solid Free. Fabr. Symp, 2016, pp. 2470–2472,. https://sffsymposium.engr.utexas.edu/sites/default/files/2016/197-Wang.pdf.

[198] C.-.T. Lu, C.-.H. Chen, S.-.C. Tseng, Application of conformal cooling to reduce cooling time and warpage of a U-shaped plate, AIP Conf. Proc. 2065 (2019) 030007, , doi:10.1063/1.5088265.

[199] D.G. Ahn, M.W. Park, S.H. Park, H.S. Kim, Design of conformal cooling channels for the mould of a plastic drawer of a refrigerator by analysis of three-dimensional injection moulding, Trans. Korean Soc. Mech. Eng. A. 34 (2010) 1487–1492, doi:10.3795/KSME-A.2010.34.10.1487.

[200] C.-.C. Kuo, Z.-.F. Jiang, Numerical and experimental investigations of a conformally cooled maraging steel injection molding tool fabricated by direct metal printing, Int. J. Adv. Manuf. Technol. 104 (2019) 4169–4181, doi:10.1007/s00170-019-04198-9.

[201] D.-.G. Ahn, M.-.W. Park, H.-.S. Kim, A study on the design of cooling channels of injection mould to manufacture a flat part with a partly thick volume, J. Korean Soc. Precis. Eng. 29 (2012) 824–833, doi:10.7736/kspe.2012.29.8.824.

[202] S.-.R. Han, Numerical analysis of cooling channels for injection molding cycle time improvement of plastic horn cover for an automobile, J. Korean Soc. Manuf. Process Eng. 17 (2018) 84–90, doi:10.14775/ksmpe.2018.17.5.084.

[203] N.A. Shuaib, M. Fathullah, Z. Shayfull, S.M. Nasir, M.F.M.A. Hamzas, Warpage analysis between straight and conformal cooling channels on thin shallow shell, Key Eng. Mater. 594–595 (2014) 676–685, doi:10.4028/www.scientific.net/KEM.594-595.676.

[204] X. Wu, R. Cheng, X. Liang, J. Li, C. Sun, S. Huang, W. Yang, An injection mould for local transparent thin walled part based on rapidly conformal heating and cooling, Die Mould Ind. 35 (2009) 46–49.

[205] Y.F. Lin, J.R. Wu, B.H. Liu, W.C.J. Wei, A.B. Wang, R.C. Luo, Improved contact lens injection molding production by 3D printed conformal cooling channels, in: Proc. 2017 IEEE/SICE Int. Symp. Syst. Integr, 2017, pp. 89–94, doi:10.1109/SII.2017.8279194.

[206] K.W. Dalgarno, T.D. Stewart, J.M. Allport, Layer manufactured production tooling incorporating conformal heating channels for transfer moulding of elastomer compounds, Plast. Rubber Compos. Process. Appl. 30 (2001) 384–388, doi:10.1179/146580101101541778.

[207] K.F. Liew, H.S. Peng, T.M. Jou, C.C. Wang, Investigation on the establishment and analyses of conformal cooling channel design for blow mold, in: Proc. IEEE Int. Conf. Appl. Syst. Innov. 2018, IEEE, 2018, pp. 1236–1239, doi:10.1109/ICASI.2018.8394514.

[208] K.M. Au, K.M. Yu, Conformal cooling channel design and CAE simulation for rapid blow mould, Int. J. Adv. Manuf. Technol. 66 (2013) 311–324, doi:10.1007/s00170-012-4326-6.

[209] B.I. Hussain, M. Safiulla, Comparative study of cooling systems for vacuum forming tool, Mater. Today Proc. 5 (2018) 30–36, doi:10.1016/j.matpr.2017.11.049.

[210] K. Soete, F. Desplentere, Simulation of the effects of using conformal cooling channels in SLM produced plastic extrusion calibrators, AIP Conf. Proc. 2055 (2019) 070019, , doi:10.1063/1.5084863.

[211] C. Bertoli, P. Stoll, P. Hora, Thermo-mechanical analysis of additively manufactured hybrid extrusion dies with conformal cooling channels, in: Proc. XV Int. Conf. Comput. Plast. - Fundam. Appl., Barcelona, Spain, 2019,.

[212] R. Sohmshetty, V.S. Saini, C. Chiriac, 3-D Printed Cooling Channels to Produce PHS Parts With Tailored Properties, US Patent Application Publication, 2019.

[213] V.S. Saini, 3D-printed Conformal Cooling For Hot Stamping Casted Die Inserts, US Patent Application Publication, 2018.

[214] B. Mueller, M. Gebauer, S. Polster, R. Neugebauer, R. Malek, M. Kotzian, R. Hund, in: Ressource-efficient Hot Sheet Metal Forming By Innovative Die Cooling With Laser Beam Melted Tooling components, in: High Value Manuf, Taylor & Francis Group, London, 2014, , pp. 321–326, doi:10.1201/b15961-60.

[215] A. Armillotta, R. Baraggi, S. Fasoli, SLM tooling for die casting with conformal cooling channels, Int. J. Adv. Manuf. Technol. 71 (2014) 573–583, doi:10.1007/s00170-013-5523-7.

[216] E.W. Hovig, V. Brøtan, K. Sørby, Additive manufacturing for enhanced cooling in moulds for casting, in: Proc. 6th Int. Work. Adv. Manuf. Autom, Paris, France, Atlantis Press, 2016, pp. 59–62, doi:10.2991/iwama-16.2016.11.

[217] T.N. Slavens, B.E. Snyder, Gas Turbine Engine Component With Conformal Fillet Cooling Path, US Patent Application Publication, 2016.

[218] P. Frigola, R. Agustsson, S. Boucher, A. Murokh, J. Rosenzweig, G. Travish, L. Faillace, D. Cormier, T. Mahale, A novel fabrication technique for the production of RF photoinjectors, in: Proc. EPAC08, Genoa, Italy, 2008, pp. 751–753.

[219] S. Boucher, P. Frigola, A. Murokh, M. Ruelas, I. Jovanovic, J.B. Rosenzweig, G. Travish, Inverse compton scattering gamma ray source, Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 608 (2009) 54–56, doi:10.1016/j.nima.2009.05.035.

[220] F. Siglmüller, S. Kupfer, T. Kamps, M. Schmitt, T. Lohner, G. Reinhart, K. Stahl, Efficiency of additive manufactured gears with conformal cooling, 21st TAE Int. Colloq. Tribol., Stuttgart, 2018.