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Direct rapid manufacturing of molds with conformal cooling channels

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Abstract

Purpose – This review paper aims to provide an overview of applications of direct rapid manufacturing assisted mold with conformal cooling channels (CCCs) and shows the potential of this technique in different manufacturing processes.

Design/methodology/approach – Key publications from the past two decades have been reviewed.

Findings – This study concludes that direct rapid manufacturing technique plays a dominant role in the manufacturing of mold with complicated CCC structure which helps to improve the quality of final part and productivity. The outcome based on literature review and case study strongly suggested that in the near future direct rapid manufacturing method might become standard procedure in various manufacturing processes for fabrication of complex CCCs in the mold.

Practical implications – Advanced techniques such as computer-aided design, computer-aided engineering simulation and direct rapid manufacturing made it possible to easily fabricate the effective CCC in the mold in various manufacturing processes.

Originality/value – This paper is beneficial to study the direct rapid manufacturing technique for development of the mold with CCC and its applications in different manufacturing processes.

Keywords Rapid manufacturing, Computer aided design, Computer aided engineering, Conformal cooling channel

Paper type General review

1. Introduction

The careful management of surface temperatures and heat transfer rates are required in numerous manufacturing processes, to raise production and to improve product quality. Injection molding, blow molding, die casting and extrusion are all examples of manufacturing processes that can take advantages from integrating systems of increased and balanced heat transfer within the tooling (Brooks and Brigden, 2016; Singraur and Patil, 2016). These processes are prominently used to make consumer products, engineering parts, medical devices etc., by converting the raw material form to an object of practical use (Singraur and Patil, 2016). In these methods, process cycle time is the key factor. This process cycle time depends significantly on the cooling time of the molded part, which is facilitated by the coolant flow flowing through the channels in the mold. The cooling time constitutes over 70-80 per cent of the cycle time of the molding process (Dang *et al.*, 2011; Wang *et al.*, 2011; Khan *et al.*, 2014; Marques *et al.*, 2015; Rahim *et al.*, 2016). In addition, the product quality of the molded part is highly influenced by the cooling characteristics of the mold (Ahn, 2011). The effective cooling system plays a vital role in molding processes because cooling time directly affects the productivity, mold quality and product quality. Cooling characteristics of the mold are mainly dependent on the design of the cooling channels and the thermal properties of the mold material (Ahn, 2011). Cooling channels should be designed such that:

- design variables like the size, location and layout of cooling channels should be proper;
- thermal properties, temperature and flow rate of the coolant should be appropriate;
- a careful controlling of heat transfer rates and surface temperatures should be possible;
- it must be able to remove the heat at the required rate so that the molded part can be ejected without any distortion;
- the cooling of the part should be kept as uniform and balanced so that undesired defects such as shrink marks, differential shrinkage, internal thermal residual stresses and warpage can be reduced (Zheng *et al.*, 2011; Singraur and Patil, 2016).

In previous practices, heat transfer is generally carried out through straight drilled cooling channels into the mold. The main limitations of the straight drilled cooling channels are in terms of geometry and coolant mobility. As per the part dimensional accuracy required, the drilled holes are always machined using boring tools or drilling machines in various sizes as close as possible to the actual mold cavity (Au and Yu, 2007). The freeform geometric cavity surrounded by a straight

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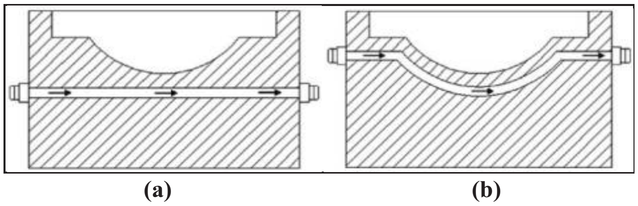
drilled cooling channel causes uneven cooling in the molded part. The uneven cooling will result in a tendency of several mold defects occurrence and increase the cooling time. It is difficult to position these cooling channels close to the surface of the cavity in such a way that it provides optimal cooling (Singraur and Patil, 2016).

To overcome these problems, an effective alternative to conventional cooling, the new technique of conformal cooling was introduced. The term conformal means that the geometry of the cooling channels follows the part surface geometry in the mold. Conformal cooling effectively transfers the heat from the mold cavity/core to the cooling channel by flowing the coolant in a pattern that closely matches with the geometry of the part being molded (Altaf *et al.*, 2013). The aim is to maintain a steady and uniform cooling performance for the molding part. Figure 1 illustrates the conventional and conformal cooling channels (CCCs) in the mold.

By using the conventional manufacturing techniques, the fabrication of CCCs in the mold is not possible. But nowadays because of the rapid advancements in the direct rapid manufacturing processes, it is easy to produce complex CCCs with any shape and configuration in the mold (Gibson *et al.*, 2005; Altaf *et al.*, 2013). Also, various optimization tools are nowadays available to optimize the design parameters of the CCC for effective cooling.

In this paper, a systematic review of the literature was conducted, based on the use of direct rapid manufacturing techniques for the fabrication of mold with effective CCCs in various manufacturing processes. The article is organized as follows: "Direct rapid manufacturing of mold with CCC" and "Technical problems in direct rapid manufacturing processes" has been described in Section 2 and Section 3. "Selection of direct rapid manufacturing technique for fabrication of mold with CCC" and "Use of direct rapid manufacturing assisted mold with CCC in various manufacturing processes" have been presented in Section 4 and Section 5. Section 6 describes a case study taken from the open literature. This includes the application of direct rapid manufacturing assisted mold with CCCs in various manufacturing processes. Various aspects related to direct rapid manufacturing assisted mold with CCCs have been discussed in Sections 7. The last section concludes this comprehensive review study and outlines the future directions for manufacturing of the mold with CCC and its applications in various manufacturing processes.

Figure 1 Cooling channels



(a) (b)

Notes: (a) Conventional; (b) conformal
Sources: Altaf *et al.* (2013), Khan *et al.* (2014)

2. Direct rapid manufacturing of mold using conformal cooling channels

Generalized standard methodology for the development of the mold with CCC using direct rapid manufacturing technique is illustrated in Figure 2. The fabrication of mold with CCC using direct rapid manufacturing technique is divided into three phases:

1 design of part, mold and CCC;
2 optimization of CCC design; and
3 direct rapid manufacturing of mold with CCC and post-processing.

2.1 Design of part, mold and conformal cooling channels

The first step of direct rapid manufacturing of mold with CCC is design of the part and mold using various softwares (Table I). Initially, the design of the CCC is performed using analytical approach. In analytical method, initial configuration of CCC including pitch, depth and diameter is finalized. Even though this step is called initial design, its result tends to come up to the optimal design because the analytical method has been reported to be applicable for simple molded part. Next step is modeling of the CCC using various design software (Table I).

2.1.1 Different structures of conformal cooling channels' design

As advances in computer-aided design (CAD) modeling and rapid manufacturing techniques, designing and fabrication of CCC in different complicated shapes is possible easily. Various authors have developed and studied the feasibility of different structures of CCC in the mold, to obtain the uniform cooling and to reduce the cycle time. The cooling system has an important role in the molding process to improve the productivity, quality and to reduce the mold-making cost. The structures of CCC design can be categorized by:

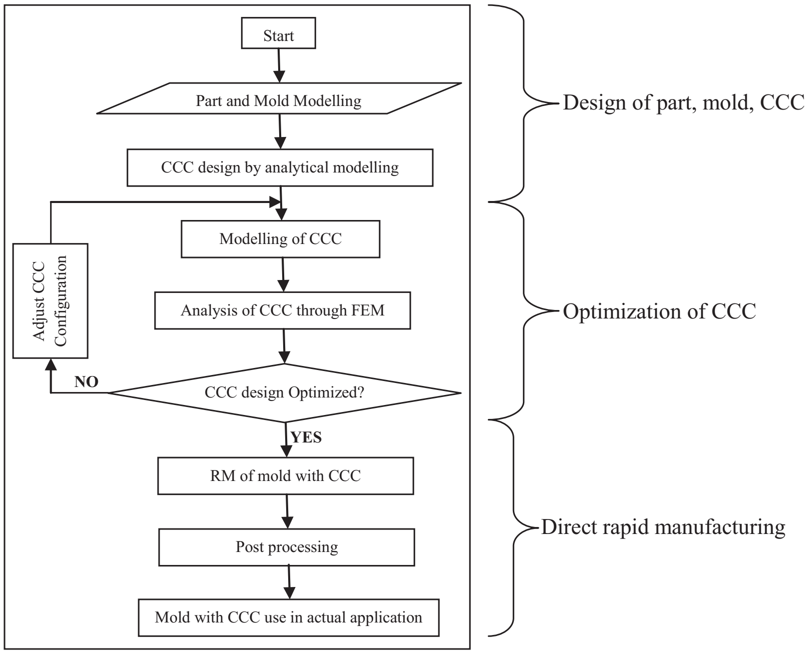
- Cross-section wise: circular, square, profiled, finned.
- Layout wise: an array of baffles, series, parallel, spiral, scaffolding, lattice, porous, voronoi.
- Positioning with respect to cavities wise: fixed or variable distances.

2.1.1.1 Cross section wise. Saifullah and Masood (2009) describe a new square sectioned CCC system for injection molding dies for an industrial part, a plastic bowel and compared with the circular sectioned CCC [Figure 3(a and b)]. The simulation and experimental results showed 35 per cent reduction in cooling time and 20 per cent reduction in total cycle time for the plastic part using square sectioned CCC.

Altaf *et al.* (2013) presented a profiled CCC and compared with circular CCC [Figure 3(c)]. In a profiled CCC, the cross-sectional shape is so designed that the flat face surface of the channel facing the cavity follows the profile of the cavity. Experimental analysis for temperature measurement for the molded part with injection molding process showed that mold with profiled CCC has required less cooling time than mold with circular CCC.

Hearunyakij *et al.* (2014) introduced a new concept to increase cooling efficiency of circular CCC by adding the fins in cross section [Figure 3(d)]. The fin helps to increase the cooling channel perimeter. From the simulation results, author concluded that when number of fins increases in the CCC then

Figure 2 Generalized standard methodology for the development of the mold with CCC using direct rapid manufacturing technique



Sources: Dang and Park (2011); Park and Dang (2012)

Table I Software can be used for CAD modeling and simulation of mold with CCC

Dedicated CAD and simulation software	General simulation software	General CAD software
Moldex3D	COSMOS/Works	Creo
C-Mold	ANSYS POLYFLOW	Catia
Cadmold	Aaccuform B-Sim	Solidworks
Moldflow Insight	Abaqus/Explicit	Solidedge
MoldFlowAdvisor	LS-DYNA	
Pro/Molddesign		

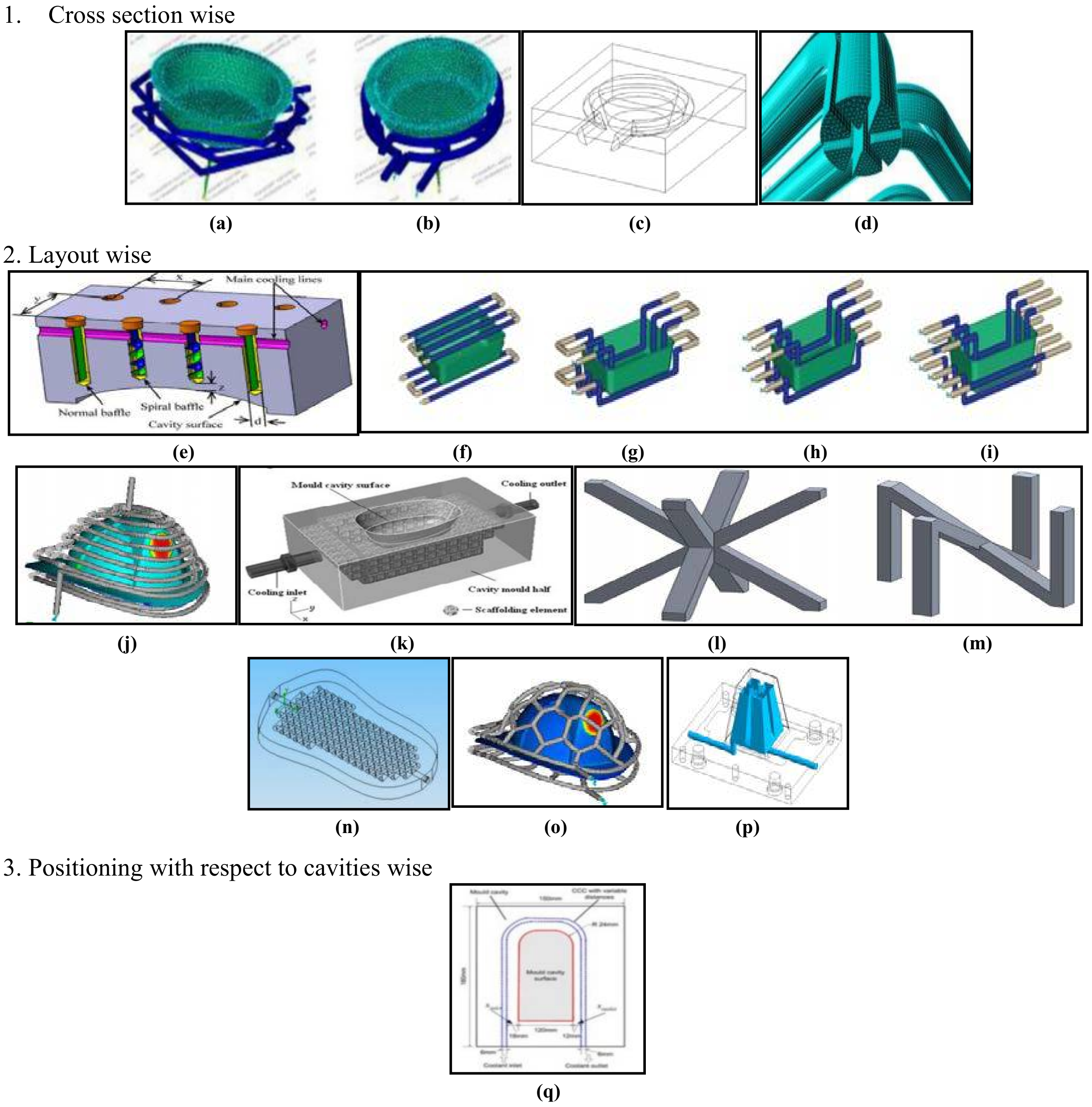
cooling time decreases. The CCC with fins provided faster coolant velocity than that of the CCC with no fins. CCC with fins was able to release the heat from molten plastic to injection mold better than the CCC with no fins because of the heat convection principle. The change in hydraulic diameter that was a proportion between peripheral and cross section area resulted in the increase in the coolant velocity and cooling heat flux.

2.1.1.2 Layout wise. Park and Dang (2010) proposed a CCC with an array of baffles for obtaining uniform cooling over the entire free-form surface of molded parts. CCC with the array of baffles leads to a more efficient and uniform control of mold temperature distribution. CCC with the array of baffles drilled perpendicular to a main cooling line with a thin plate separating the drilled hole into two semicircular channels. The plate forces the coolant to flow down on one side and up on the other side [Figure 3(e)]. CCC with the array of baffles is effective for a medium and large-sized mold for molded part with a complex shape or free-form surface. The author noted that the coolant pressure drop and pump power are larger than other methods, but the high cooling effect and the low mold making cost are the important advantages of the proposed cooling channels. Results show that CCC with the array of baffles increases the molding quality, reduces cooling time and manufacturing cost in injection molding industry.

Khan *et al.* (2014) described the analytical study of cooling analysis of different types of cooling channel designs. In this study, the time to reach ejection temperature (time required to reach the ejection temperature, which is measured from the start of fill), time to reach part ejection temperature (time required by the part to freeze), volumetric shrinkage at ejection and the temperature variance of the part have been studied by simulation method for four different cooling channels, that is, conventional cooling channel design [Figure 3(f)], series CCC design [Figure 3(g)], parallel CCC [Figure 3(h)] and CCC with additive cooling lines [Figure 3(i)], respectively. The obtained results showed that CCC with additive cooling lines is the most efficient and suitable cooling system for the case study part among other cooling channels. It has lower time to reach ejection temperature, lower time to reach part ejection temperature, lower volumetric shrinkage and lower temperature variance (i.e. minimum warpage because of more uniform cooling); thus, it will lead to a better part quality with minimum cycle time.

Wang *et al.* (2015) introduced a new algorithm to generate spiral CCC for complex shaped parts using boundary-distance maps [Figure 3(j)]. In this study, the cooling efficiency of the spiral CCC developed by boundary-distance maps algorithm is compared with the voronoi diagram-based CCCs generated by Wang *et al.* (2011) for a molding of toy helmet using ABS material. Simulation result shows that boundary-distance maps based spiral CCC gives better results than centroidal voronoi diagram-based CCC.

Figure 3 1. Cross section wise



Notes: (a) Circular-sectioned CCC and (b) squared-sectioned CCC (Saifullah *et al.*, 2009); (c) profiled cross-sectional CCC (Altafet *al.*, 2011); (d) CCC with fins (Hearunyakij *et al.*, 2014); 2. Layout wise: (e) array of baffle CCC (Park and Dang, 2010); (f) conventional cooling channel design, (g) series CCC, (h) parallel CCC and (i) CCC with additive cooling lines (Khan *et al.*, 2014); (j) spiral CCC (Wang *et al.*, 2015); (k) scaffolding architecture (Au and Yu, 2007); CCC with lattice structure: (l) cross type and (m) N type (Brooks and Brigden, 2016); (n) CCC with multi-connected porous structure (Au and Yu, 2011); (o) voronoi diagram based CCC (Wang *et al.*, 2011); (p) bubbler CCC (Eiamsa-ard and Wannissorn, 2015); 3.Positioning with respect to cavities wise: (q) variable distance CCC (Au and Yu, 2014)

Cooling time has been shortened from 42.73 s to 37.91 s. The cooling also occurs more uniformly. The temperature variation between 28.69°C and 60.47°C has been reduced to the range between 26.90°C and 53.10°C. It is clear that centroidal voronoi diagram-based CCC leads to poor flow rates and Reynolds numbers resulting in non-uniform cooling in the tool. Reserchers also noted that, the spiral CCC helps to keep a stable turbulent flow rate through the entire length and enables the heat to be transferred more effectively. Moreover, by having simple connectivity, these spiral channels can be fabricated by copper duct bending instead of expensive direct rapid manufacturing technique.

Au and Yu (2007) proposed a novel model of porous scaffold architecture for an injection mold for the design of a more conformal and hence more uniform cooling channel [Figure 3(k)]. CAD model for constructing the scaffolding structure is examined and cooling performances are validated by computer-aided engineering (CAE) and computer fluid dynamics (CFD) analysis. In the simulation results, the cooling performance indicates that the scaffold cooling technique can offer a more uniform thermal distribution with minor in-cavity residual stresses occurrence than the conventional method. Uniform cooling performance can be obtained without severe mold shrinkage. Injection mold defects such as thermal stress or warpage can be avoided. This increases productivity and hence reduces the time to market.

Brooks and Brigden (2016) introduced a new concept, that is, CCC filled with self-supporting repeatable unit cells that form a lattice throughout the CCC [Figure 3(l) and (m)]. CCC with self-supporting lattices constructed from simple unit cells is found easy to build using direct rapid manufacturing technique and capable of providing efficient and balanced heat transfer. These types of CCC with lattices increase fluid vorticity which improves convective heat transfer. The results showed that CCC with lattice structure reduces cooling time by 26.34 per cent over conventional circular cooling channels because of increased interfacial surface areas and fluid vorticity.

Au and Yu (2011) proposed an alternative design method based on the duality principle for a conformal cooling passageway with multi-connected porous characteristics, that is, uniform decomposition and the octree-based decomposition [Figure 3(n)]. The proposed methods allow an efficient coolant flow within the mold plate. The coolant flow within the multi-connected porous cooling passageway is in multiple directions from the coolant inlet to the coolant outlet. For the proposed cooling passageway design, the cooling surface provides a more uniform heat transfer from the mold surface to the cooling passageway than the conventional CCC designs as the cooling covers the whole model surface.

Wang *et al.* (2011) presented an automatic method for designing complex CCC in three dimension especially for a product with freeform surfaces [Figure 3(o)]. In this method first, the conformal surface that will be used to locate the center of cooling channels is computed by an offset surface generation method. Then the centroidal voronoi diagram is computed on the conformal surface, where the boundary of centroidal voronoi diagram will be used as the central lines of cooling channels. The obtained results showed that the cooling circuits constructed by this method can effectively reduce the cooling time and control the uniformity of temperature and volumetric shrinkage.

Eiamsa-ard and Wannissorn (2015) proposed bubbler CCCs in plastic injection molding. Experiments were conducted to confirm the normal temperature distribution over the mold surfaces for 5-mm-thick polypropylene (PP) part design. Experimental study shows that bubbler CCC can be possible to manufacture using hybrid manufacturing and help to reduce the cycle time and the energy consumption.

2.1.1.3 Positioning with respect to cavities. Au and Yu, 2014 proposed a novel adjustment method for distance modification between the existing CCC and its cavity (or core) surface in the cooling design for the rapid tool [Figure 3(q)]. The proposed method can compensate the increase in the coolant temperature from the coolant inlet to the coolant outlet during the cooling process. A more effective heat removal between the cavity (or core) surface and the variable distance CCC can be achieved than the existing CCC design. In this study, the cooling channel distance modification relies on two adjustment attributes:

1. the adjustment direction; and
2. the adjustment amount, between the mold cavity (or core) surface (terrain) and the cooling channel axis (polyline) after the linearized approximation.

The simulation results showed that, the cooling performance of the variable distance CCC is better than the convectional CCC design. The maximum part temperature performed by the variable distance CCC is smaller than the contemporary CCC. Besides, the cooling time and the volumetric shrinkage performed by the variable distance CCC are also smaller than the contemporary CCC and the injection molding cycle time can be reduced. The compensation of the coolant temperature at the coolant outlet, performed by the variable distance CCC, can offer an effective heat removal during the cooling process.

2.2 Optimization of CCC design

Once the design of CCC is finalized by analytical approach, then the next step is, import the mold with CCC to simulation software (Table I) for analysis and optimization of CCC design. The main purpose of optimization of CCC design is to obtain the target mold temperature; reduce the cooling time and cycle time; minimize the non-uniformity of the part surface temperature distribution and to reduce mold making cost. Because once the cooling channels cut, they could not be reconfigured or adjusted as other factors (Au *et al.*, 2007; Park and Dang, 2010; Dang and Park, 2011). Before proceeding with optimization method, it is necessary to understand thoroughly the reaction of the thermal behavior of the mold to cooling channels' configuration physically and mathematically (Ahn, 2011; Dang and Park, 2011). The different types of optimization techniques are: direct numerical technique, exploration technique, expert system, direct penalty method and multi-objective exploitive technique (Park and Dang, 2010). Optimization techniques have been well-studied in literature, and it is beyond the scope of this study. Selection of optimization technique depends on problems and individual choices of mold designers.

Simulations for mold cooling have received more and more attention from researchers since the early 1980s when the scientific analysis was introduced into the molding industries (Eiamsa-ard and Wannissorn, 2015). Nowadays with the advancement of both computer's hardware and CAE software, three-dimensional (3D) computation of heat transfer and flow simulation in molding is widely used in mold design engineering. To determine the optimal process parameters, CAE simulation is widely used and is recognized as one of the powerful tools available (Kitayama *et al.*, 2016). In cooling simulation by analyzing the temperature of all elements of CCC design, confirm whether the CCC design is optimized or not. The target mold temperature and the uniformity of temperature between the top and bottom faces of molded part are reached after a few iterations by adjusting the different variables. These steps are repeated (iterations) until the optimal conditions are satisfied. Proper constraints have to be enforced upon all design variables in the form of equality or inequality constraints to keep the design optimization realistic from the design and manufacturing point of view. Furthermore, according to the manufacturers' viewpoint, the diameter and shape of the CCCs is finalized by considering the availability of manufacturing technique and its capability to manufacturing intricate shape of CCC. The determination of design optimization issues are constrained by following parameters.

2.2.1 Design for conformal cooling condition

The conformal cooling condition must be applied throughout the mold to provide the good control of the temperature at the surface of the mold. To satisfy this condition, the mold designer can increase the channel diameter, decrease the distance between the CCCs, increase the heat transfer coefficient and the mold wall or choose mold material with a high thermal diffusivity. Also, part thickness, location, arrangement and structure of the CCC in the mold play a vital role to fulfill the conformal cooling criteria.

2.2.2 Design for coolant pressure drop

The allowable pressure drop of the coolant in the CCC is constrained by the available pumping pressure of the chiller. The objective of the optimized CCC design for pressure drop is to find a proper combination of the coolant flow rate, the CCC diameter and length so that the resulting total pressure drop is smaller than the given pressure budget. The fluid mechanics of the incompressible flow can be used to predict the coolant pressure drop that is a function of the CCC length, the CCC diameter and the coolant flow rate.

2.2.3 Design for coolant temperature uniformity

The objective of the optimized CCC design for the coolant temperature uniformity is to check and make sure that the coolant temperature drop is maintained within a certain range. To decrease the coolant temperature drop, the mold maker can use a coolant with large thermal mass, enhance the coolant flow rate, reduce the pitch distance between two adjacent CCCs or decrease the length of the CCC.

2.2.4 Design for sufficient cooling

With the concept of conformal cooling, adequate cooling can be provided throughout the mold. The steady cycle averaged mold temperature can be obtained by maintaining the proper part ejection temperature and the cycle time.

2.2.5 Design for uniform cooling

The "uniform cooling" in the mold has both the global and the local meanings. The global uniformity means the cooling rate variation over the entire mold. It can be obtained by maintaining the uniform coolant temperature. The local cooling uniformity means the variation of the mold surface temperature within the individual CCC. The local cooling uniformity is defined by the difference in the cycle averaged temperatures on the mold surface right above the CCC and at the middle of the two adjacent CCCs.

2.2.6 Design for mold strength and deflection

CCC should be designed in such a way that less stress and deformation occurs in the mold. Commonly circular-shaped CCCs are used to obtain much smaller stress and deflection in the mold. In various studies, the numerical simulation shows that the stress concentration is reduced by over 50 per cent if round-shaped CCCs are used in the mold.

2.2.7 Design for mold manufacturability

The emerging rapid manufacturing techniques for freeform fabrication of molds place a new challenge to the mold design and analysis strategy because of the increased complexity in CCC geometry. The CCC design should be complex enough to manufacture easily using direct rapid manufacturing technique.

2.3 Rapid manufacturing of conformal cooling channels

Once the optimized design of mold with CCC is obtained, the next step is a fabrication of mold with CCC using direct rapid manufacturing technique. In this step, suitable direct rapid manufacturing technique is used for fabrication of mold with CCC. Because mold cooling is one of the limiting factors in the molding cycle, effective CCC design in the mold, as well as its fabrication, is very important for controlling the production time and quality. Rapid tooling promotes the advantages of CCC in molds and cuts down production time. Ahn (2011) and Karunakaran *et al.* (2012) explains the direct rapid manufacturing techniques for fabrications of metallic objects. Direct rapid manufacturing is an effective tool for rapid tooling, by which free form fabrication of CCCs in the mold can be possible easily (Saifullah and Masood, 2007). There are currently a number of direct rapid manufacturing techniques commercially available in the market based on special techniques such as subtractive, additive and hybrid methods. The selection of exact direct rapid manufacturing technique depends on their availability, cost and time. Also, it depends on their advantages and disadvantages such as accuracy, surface finish, the visual appearance of internal structure and strength and the most important are the material and their mechanical properties needed for the particular application (Rahmati, 2014). The main advantage of direct rapid manufacturing technique is to create complex, intricate, freeform shapes of CCCs as well as minor details such as undercuts, voids and contours available on the mold geometries. Direct RM techniques can be divided into the following three groups for fabrication of molds with CCC in metal:

1. Subtractive manufacturing: (CNC machining).
2. Additive manufacturing: (Rapid prototyping techniques – selective laser sintering (SLS), selective laser melting (SLM), direct metal laser sintering (DMLS)s and electron beam melting (EBM).
3. Hybrid manufacturing: (subtractive plus additive).

In rapid prototyping technique, CAD model of the mold with CCCs in STL format is used for the direct fabrication of mold with CCC. Hybrid manufacturing combines the additive and subtractive technique to combine the benefits of the both routes. The advantages and disadvantages of various direct rapid manufacturing techniques which are commercially

Table II Direct rapid manufacturing techniques, which are commercially available for fabrication of the mold with CCC

Process	Techniques	Advantages	Disadvantages
Subtractive	CNC machining (Milling)	Different materials can be used for mold fabrication Most suitable for medium-sized and large-sized molded part with the free-form surface High-speed machining is possible Suitable for all kinds of popular mold material (Dang and Park, 2011) Using CNC milling CCC pattern can be designed freely to avoid interfering with other features in the mold such as ejector pins or other components (Dang and Park, 2011). Optimal combination of various parameters like initial setup of CNC machine, CAM software, advanced machine tools and cutting tools will provide best direct rapid manufacturing process in terms of cost, quality and time (Karunakaran *et al.*, 2012; Rahim *et al.*, 2016)	Not flexible than additive manufacturing (Dang and Park, 2011). The cost of initial setup, CAM software, advanced machine tools and cutting tools is very high
Additive	SLS	Can produce parts with accuracy ±1mm (Rahmati, 2014) No support structures needed Having ability to mold large quantities of parts. The finished mold is capable of producing up to 50,000 final products via injection molding with the functional material before breaking down Well suited for manufacturing of molds with complex CCCs in the injection moulding and die casting	High costs and the abrasive surface finish of sintered models To achieve the required accuracy and surface finish some machining and finishing operations can be required like Milling using high-speed or carbide cutting tools Welding/brazing Electro-discharge machining (EDM) Chemical etching and plating
	DMLS	Can produce metallic parts directly in a single process (Rahmati, 2014) Able to develop molds in a variety of materials like bronze, steel, SS316L, titanium, or Al-30% Si (Rahmati, 2014). The bronze molds can be used for more than 10,000 injection-molding cycles, and steel molds made by this process could withstand as high as 100,000 shots (Dolinsek, 2005). Can produce 95% dense part so no need of further sintering. DMLS has the ability to produce fine features and thin walls, with good accuracy, resolution, and mechanical properties of the finished parts. Capable of producing complex, fully functional metal parts and molds, small geometrical features that would be difficult to produce by conventional machining Best method for fabrication of molds with complex structure CCCs in injection molding, blow molding, extrusion, die casting (Běhálek and Dobránsky, 2009; Rahmati, 2014) To avoid the post-processing, the self-supporting can also be provided	It requires support structure Parts may require a variety of post-processing including heat treatment, support removal, shot peening, etc.
	SLM	Speedy and automatic process Uses a high power density fiber laser beam to selectively melt and fuse accumulating layers of metallic powder together to form a 3D physical model in a single operation (Au and Yu, 2013; Mazur *et al.*, 2016) In SLM, a mold can be built directly without any additional process such as sintering or firing for mechanical strength enhancement Direct fabrication of metallic mold is possible The stainless steel (AISI P20) material can be used for mold making which is commonly used in the all molding processes (Au and Yu, 2013)	SLM process often requires support structures to achieve required build geometry The use of support material can increase surface roughness and compromise part functionality when manual removal is constrained by access, as is the case in cooling channels and lattice structures (Thomas, 2010)

(***continued***)

Table II

Process	Techniques	Advantages	Disadvantages
	DMD	Metal parts produced using closed-loop feedback control to achieve high-dimensional resolution (Muzumder *et al.*, 2000) The characteristically rapid cooling of DMD results in a fine material microstructure which is necessary for molding applications (D'Souza, 2001; Muzumder *et al.*, 2000; Mazumder, 1999) It is capable of building 100% accurate and dense metallic molds from metal powders maintaining quality mechanical and metallurgical properties and without creating engineered scrap (Mazumder *et al.*, 1997; D'Souza, 2001) The DMD process can produce a thermally conductive mold with CCCs and the embedded chiller block (Morrow, 2007)	It is a viable process, which has been underutilized until recently
	EBM	Capable of direct rapid manufacturing of molds through layer-wise EBM of metal powder (Arcam, 2005) Presently, two different steels suitable for injection molds are available, Arcam Low Alloy Steel and Arcam H13 Tool Steel The EBM method is well suited for a variety of materials. High reflective materials such as aluminium can also be used in EBM process (Taminger and Hafley, 2002). EBM also offer CCCs in hard steel tooling (Gibbons and Hansell, 2005) EBM method is able to create molds with virtually no porosities and with full interlayer bonding (Cormier *et al.*, 2004) The EBM process is capable of creating fully denser mold structures without any binding agents	The EBM process has limitations regarding small features, such as diameters, radii, etc., but most possibly, further improvement of the cooling efficiency could be achieved with new types of cross sections
	LOM/LST	Can fabricate complex geometric molds with CCC in high-dimensional accuracy Material costs are very low Different metals with different chemical and mechanical properties for a variety of applications can be processed by LOM LOM is well suited for complex and large parts The build speed is very fast, but a lot of effort is needed for decubing, finishing and sealing the parts (Liu *et al.*, 2006; Noorani, 2006)	Molds are used only for low-melting thermoplastics and are not appropriate for the injection-molding process with thermosetting plastics or high-temperature glass fiber
	3DP	Good fabrication speed and low material cost Unbound powder temporarily supports unconnected portions of the component, allowing fabrication of complex geometrical shapes, e.g. overhanging partitions inside cavities, undercuts and internal volumes to be created, without artificial support structures (Negi *et al.*, 2014; Sachs *et al.*) Direct rapid manufacturing of mold with CCCs in metals such as stainless steel (316L) powder can be possible (Sachs *et al.*)	Disadvantages include surface finish, moderate strength, hand-free post-processing and availability of materials (Negi *et al.*, 2014)
Additive + Subtractive	Hybrid	Hybrid machining reduces time and cost of the fabrication of the mold (Sreenathbabu *et al.*, 2005; Mognol *et al.*, 2007; Simhambhatla and Karunakaran, 2015) The base part is typically fabricated from conventional and high-speed CNC machining. Then guide slots are generated on the top surface of the base part using additive manufacturing Can create the final external contours and the finely detailed shapes of the mold through the post-processing (Ahn, 2011)	In hybrid manufacturing, joining characteristics between base parts and deposited molding parts is the main problem which is the most important cause of leakage

available for the fabrication of the mold with CCC are summarized in Table II. The detail specification and features of commercially available direct rapid manufacturing techniques and materials which can be available for fabrication of mold with CCCs are mentioned in Table III. Figure 4 represents examples of mold incorporating with the CCC fabricated using various direct rapid manufacturing techniques.

2.3.1 Materials

In the case of molding applications, the direct rapid manufacturing assisted mold with CCCs can be fabricated with a variety of materials, and the selection of material directly depends on availability, suitability and cost of the rapid manufacturing technique. These materials should have the property to sustain the high pressure, forces, static and cyclic stresses generated

Table III Features of commercially available direct rapid manufacturing techniques for fabrication of mold with CCC

Direct rapid manufacturing techniques (commercially available since)	Process	Layer thickness (μm)	Accuracy (μm)	Maximum part dimensions (mm^3)	Scan speed (mm/s)	Materials used in direct RM technique for fabrication of mold with CCCs
CNC (1967)	Subtractive	–	±2	1016 x 508 x 635	–	All types of mold materials
SLS (1991)	Sintering of powders	76	±51	330 x 380 x 425	0.001-0.008	P20, P21
3DP (1998)	Ink-jet printing	177	±127	355 x 457 x 355	0.005-0.007	SS316L
SLM (1995)	Sintering of metal powders	20-100	±20-50	600 x 400 x 500	50-320	SS316L, H13
DMLS (1995)	Sintering of metal powders	20	±100	250 x 250 x 185	50-175	Cobalt chrome alloys, structural steel
EBM (2007)	Melting metal powder	50-200	±40	200 x 200 x 180	100	Ti-6Al-4V, H13
DMD (1993)	Melting and deposition of metal powder	200-800	±127	–	10	H13, Al
LOM (1990)	Metal sheet lamination	76-203	±127	813 x 559 x 508	508 (cutting speed)	Steel sheets
Hybrid (2002)	Additive + Subtractive	–	–	1016 x 508 x 635	–	Materials of additive and subtractive process

during the molding processes. Also, materials are capable enough to provide suitable stability and strength in the molds with CCCs in various applications. Fabrication of molds with highly conductive material such as nickel/copper CCC (copper layered) led to productivity improvements of about 70 per cent when compared to a similar mold made using conventional steel with conventional cooling channels (Dimla *et al.*, 2005). So materials should be highly conductive to facilitate high heat transfer. The strength of the mold material should be enough such that it can sustain the ejection force required to push the molding from the mold; otherwise, tensile failure takes place (Hopkinson and Dickens, 2000). Molds must have a good mechanical strength to withstand injection and hold pressures. Also, they must exhibit a surface hardness high enough to ensure a good wear resistance to the abrasive effect of reinforced materials (Karapatis *et al.*, 1998).

2.4 Post-processing

Direct rapid manufacturing techniques were first initiated into mold making by considering manufacturing of entire shape of molds without any additional post-processing (Karapatis *et al.*, 1998). After fabrication of mold with CCC using direct rapid manufacturing technique, post-processing is the next important step. To overcome the limitations of direct rapid manufacturing technique induced because of the width of sintering, melting or cladding beads and stair steps on the external surface of the mold, post-processing is needed for precise shaping of fine details and improvement of surface roughness. Post-processing helps to remove the support material (if needed) and to provide necessary reinforcement. Many direct rapid manufacturing techniques required support structures while building the mold with CCCs. These support structures have to be cleaned manually. But because of this, they left back rough surfaces which are responsible for reducing the accuracy of surface finish of CCCs and the mold. The qualities of direct rapid manufacturing assisted molds are also dependent on the mold geometry and build orientation. Because of the layered by layered manufacturing of molds, the accuracy of curved surfaces is limited by stair-stepping effects which depend on layer thickness and surface orientation.

Because of limitations of direct rapid manufacturing technique, mold designers preferred hybrid manufacturing for fabrication of mold with CCC (Ahn, 2011). In hybrid manufacturing generally, the post-processing includes high-speed machining, electro-discharge machining (EDM), conventional machining, etc., to obtain the fine details and thin walls (Ahn, 2011). Finally, lapping, polishing and surface treatments are performed to improve the surface roughness and the corrosion characteristics of the mold. In hybrid manufacturing to perform proper post-processing in the deposition part of molding, external contours of the mold are offset by a proper depth in the normal direction (Mognol *et al.*, 2007). To evaluate the joining characteristics of the joined region between base part and molding deposition part, leakage and the microstructures in the vicinity of the joined region are observed using leakage testing devices and scanning electronic microscopy (SEM) (Ahn, 2010).

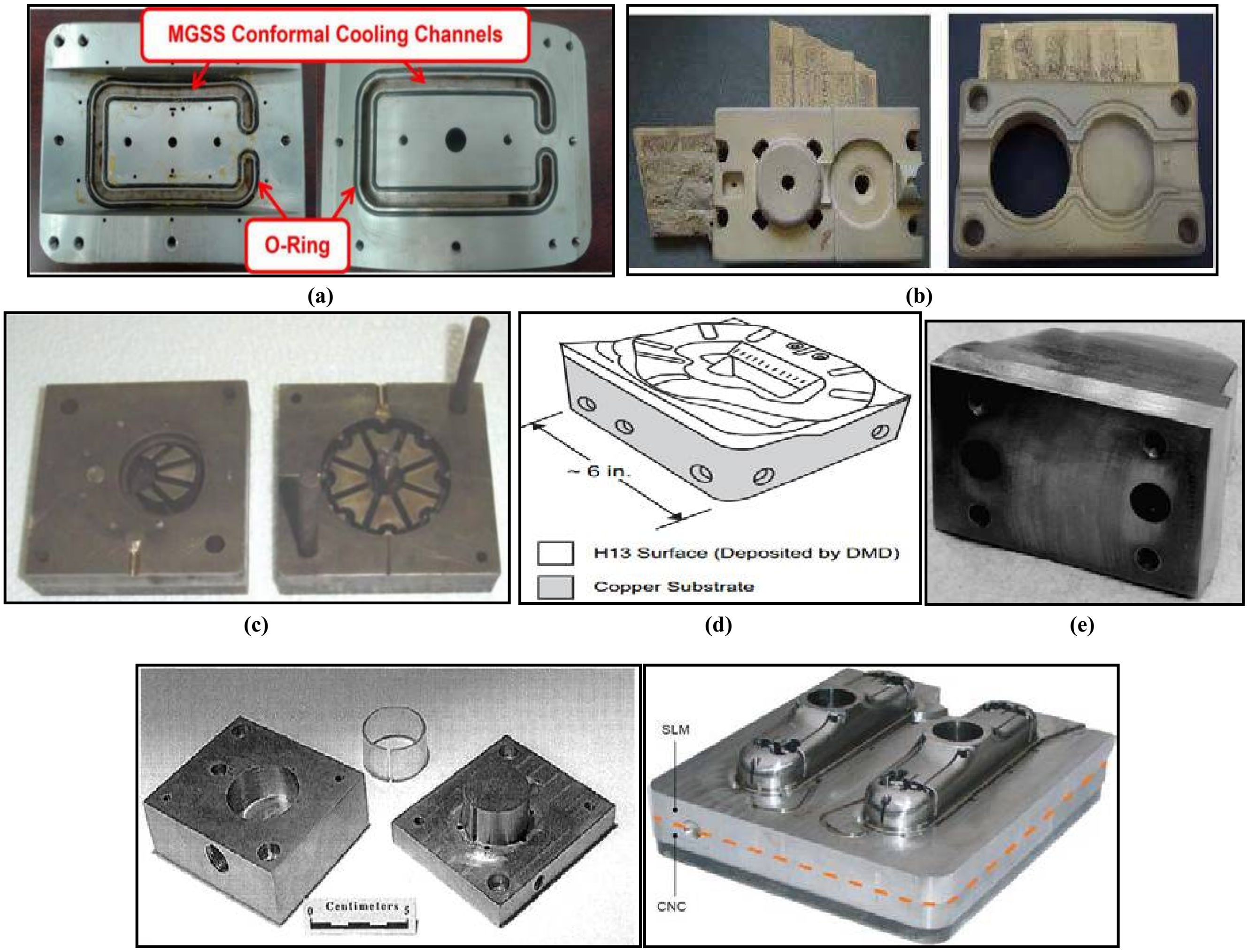
The mold fabricated using SLS and DMLS processes have to perform the heat treatment to improve the hardness of the mold. Molds, which are manufactured from SLM, DMD and DMT processes, contain a sufficient hardness of the molds because of the rapid melting and cooling of the deposited material. However, the molds, which are produced by the melting and cladding processes, occasionally need a tempering process to remove residual stresses in the molds (Ahn, 2011).

3. Technical problems in direct rapid manufacturing processes

3.1 Powder removal

In SLS process mold, weight is an important factor that has to be considered while manufacturing CCCs in the mold. In SLS process, clearing of powder from CCCs is much easier where

Figure 4 Mold with CCC fabricated using direct rapid manufacturing technique



(a) (b)

(c) (d) (e)

(f) (g)

Notes: (a) CNC milling (Rahim *et al.*, 2016); (b) SLS (Ilyas *et al.*, 2010); (c) DMLS for hub gear (Nagahanumaiah and Ravi, 2009); (d) mixed-material mold: H13 tool steel deposited on a copper substrate using the DMD (Morrow *et al.*, 2007); (e) EBM in the modular tool (Rannar *et al.*, 2007); (f) 3DP (Sachs *et al.*, 2000); (g) hybrid machined die for die casting (Armillotta *et al.*, 2014)

the green part of the mold is of a weight which allows it to be manipulated by hand and can become difficult when the weight of a component exceeds that which can be lifted by one person (Dalgaro *et al.*, 2001).

3.2 Manufacturability

The support structures used in direct rapid manufacturing process hinders the manufacturing of complex CCC and small diameter CCCs in the mold. This problem can be avoided by creating self-supporting structures and proper build orientation (Mazur *et al.*, 2016).

3.3 Clogging

Generally, the optimal diameter of CCC should be designed between 4 mm and s12 mm (depending on the size and shape of the product). These values are preferred values to be used in ideal cases; in practice, sometimes molds are too slim to exactly follow this rule (e.g. a closely placed pair of ejector pins, thin walls and so on). In cases of complex geometrical conditions, it can be necessary to design much smaller diameters, for example, when eliminating a hot spot. To avoid this problem, processes such as DMLS play a vital role. In that powder bed, fusion can build CCCs down to 1 mm in diameter. In such cases, specially treated fluids are used to avoid clogging in the CCC (Mayer, 2009).

3.4 Structural integrity

Various researchers reported the sources of inaccuracies in direct rapid manufacturing assisted fabrication of mold with CCC at various stages of manufacturing which affects the structural integrity:

- creation and removal of support structures;
- stair-step effects;
- build orientation;

- laser diameter;
- laser path;
- the thickness of the layer;
- finishing; and
- mathematical modeling for surface finish.

3.5 Porosity

Mold manufactured using the RapidSteel (SLS) process would have residual interconnected porosity. Generally, the amount of residual porosity is to be 2-5 per cent by volume. To ensure that the cooling fluid stayed confined to the CCC, molds are infiltrated with a high-temperature resin to seal the tool surfaces (Dalgaro *et al.*, 2001).

3.6 Leakage

In hybrid manufacturing, joining characteristics between base parts and deposited molding parts is the main problem which is the most important cause of leakage (Ahn, 2011).

4. Selection of direct rapid manufacturing technique for fabrication of mold with conformal cooling channels

The selection of the best rapid manufacturing technique for the fabrication of the mold with CCC generally depends on the available direct rapid manufacturing technique and its factors associated with these techniques including mold geometry, design complexity of CCC, accuracy of the technique, size of the mold, post-processing, mold materials (strength and durability), production volume, fabrication time and fabrication cost.

4.1 Mold geometry and design of the complex conformal cooling channels

Mold geometry and design of the complex CCC constraints are the important parameters for the selection of the best rapid manufacturing technique for development of mold with CCC. Because of these constraints, only those processes that are capable of generating the desired geometry can be considered. It underlies the decision because each technique that is favorable for developing the desired geometry will also be more or less suited for producing particular features or aspects of the mold and CCC geometry. Deciding on the right direct rapid manufacturing technique for particular mold geometry and CCC structure is therefore very dependent on the mold maker's experience and judgment. For example, most experienced mold makers can look at a part and immediately determine that DMLS is the best fabrication method or that laminated object manufacturing (LOM) would not work well. The mold maker does this by noting specific features of the mold geometry and CCC structure and then mentally filtering the possibilities based on learned experience. This mental evaluation is the "essence" of the selection of the suitable rapid manufacturing technique. The mold maker must understand the critical features of the mold and CCC so that an optimal technique is chosen based on the design of the mold with CCC and its application.

4.2 Post-processing

Post-processing is necessary for most direct rapid manufacturing techniques for fabrication of mold with CCC. It generally includes two aspects: removing the support structure and finishing the surface of the mold and CCC. The amount of post-processing work required to achieve a level of surface finish differs widely among the different direct rapid manufacturing techniques. For example, it may be very difficult to remove the support materials from an internal cavity of an LOM mold with CCC, while the same task may be relatively easy for the SLS or 3DP methods.

4.3 Materials (strength and durability)

There are a variety of materials used in different direct rapid manufacturing techniques (Table III). Because different materials demonstrate different mechanical strength and durability, the material will eventually affect the mold life and accuracy. To select the appropriate technique, the mold maker needs to know the production volume in a particular application, as it will influence tool life and tool wear.

4.4 Production volume

The mold material selected and the molding approach used depends to a large extent on the production volume, which is the number of molded parts to be produced over the lifetime of the mold. If a large number of molded parts are to be produced, then the mold material and approach is likely to differ from that used for a short production run. For example, if only a few moldings are to be produced «10), then any direct rapid manufacturing technique may be acceptable. If moderate production volumes (10-300) are anticipated, then some direct rapid manufacturing techniques cannot be used only because of material strength and durability limitation. For large production volumes (>300), few direct rapid manufacturing techniques can be used. For example, the DMLS can produce highly durable metal molds.

4.5 Time, cost and accuracy

Time, cost and accuracy are dependent factors that affect the selection of the suitable direct rapid manufacturing technique for development of the mold. This is particularly true because of the nature of different techniques of direct rapid manufacturing. The mold maker needs to evaluate the trade-offs between these factors to find the best or most acceptable combination.

5. Use of direct rapid manufacturing assisted mold with conformal cooling channels in various manufacturing processes

Numerous researchers have reported the influence of direct rapid manufacturing technique for the fabrication of mold with CCCs in the field of various molding processes such as injection molding, blow molding, hot extrusion and die casting. As per the previous research work given in Table IV, it can be concluded that direct rapid manufacturing technique is being tremendously used in the injection molding process for the manufacturing molds with CCC. Also, selective laser melting (SLM) technique is being used the most for direct rapid manufacturing of molds with CCC

Table IV Use of direct rapid manufacturing techniques for fabrication of mold with CCC in various manufacturing processes

Sr. No.	Researcher	Types of CCC	Material		Direct RM technique	Application	Results
			Part	Mold			
1	Mazumder *et al.* (2000)	Simple	–	H13 steel	DMD	Injection molding	Cycle time reduced by 40%
2	King and Tansey (2003)	Simple	–	P20	SLS	Injection molding	CCC are able to be designed and fabricated with SLS
3	Rannar *et al.* (2007)	Straight with baffle	POM	H13 tool steel	EBM	Injection molding	Cycle time and warpage of molded part with CCC is shorter than conventional cooling channels
4	Ahn *et al.* (2010)	Simple	ABS + 20% glass fiber	P21 steel	DMT	Injection molding	Cooling time reduced 35% and cycle time reduced 25.7% using CCC as compare to conventional cooling channels
5	Ilyas *et al.* (2010)	Simple	PP	Steel	SLS	Injection molding	Significant productivity improvements and reduction of energy use are possible through the implementation of CCC in injection molding
6	Dang and Park (2011)	Simple	Noryl GTX979	P20 Steel	MG CNC	Injection molding	Warpage improved by 15.7% with the CCC compared to straight cooling channels
7	Au and Yu (2013)	Simple	–	H13 steel	SLM	Blow molding	SLM process explored and recommended for the direct and rapid fabrication of blow mold integrating CCC in a single operation in this study
8	Hölker *et al.* (2013)	Simple	Aluminum	H13 steel	SLM	Hot extrusion	Decreases the profile's exit temperature and to avoid thermally induced surface defects, such as hot cracks, raise the productivity in hot aluminum extrusion
9	Armillotta *et al.* (2014)	Simple	Zink alloy	H13 steel	Hybrid (CNC + SLM)	Die casting	Improves the surface quality of die casted parts and reduces the cycle time and part porosity
10	Rahim *et al.* (2016)	MGSS	ABS	–	MG CNC	Injection molding	Warpage reduced in both x and y directions by 14-54% and cooling time by 65%
11	Wu *et al.* (2015)	Simple	PP	Structural steel	DMLS	Injection molding	Improved thermal performance
12	Eiamsa-Ard and Wannissorn (2015)	Bubbler	PP	–	Hybrid (CNC + MDT)	Injection molding	Uniform temperature distribution and increases the production rate
13	Mazur *et al.* (2016)	Latice structured	–	H13 steel	SLM	Injection molding	SLM process applied for designing CCC and lattice structure for increasing thermal performance

in H13 steel material in various manufacturing processes. Some researchers (Armillotta *et al.*, 2014; Eiamsa-Ard and Wannissorn, 2015) have proved that hybrid manufacturing is the best method for fabrication of molds with CCC, but very less work has been done in this field, and lot of research is still required to minimize the mold fabrication time and cost. The different direct rapid manufacturing techniques used by different researchers in various manufacturing processes are summarized in Table IV. The overall results show that the mold with CCC fabricated using direct rapid manufacturing technique helps to improve the results in terms of warpage, cycle time, cooling time as compared to conventional cooling channels in various applications. Examples of mold with CCC manufactured by different direct rapid manufacturing techniques in various manufacturing processes are given in Figure 5.

6. Case report

In this section, a case report on "Manufacturing of an injection mold with CCC for rapid and uniform cooling characteristics for the fan parts using a hybrid manufacturing" from the open literature has been considered for discussion, which presents application of direct rapid manufacturing technique for the development of mold with CCC. Ahn *et al.* (2010) represented a case study to manufacturing an injection mold with a pair of

Figure 5 Examples of mold with CCC manufactured by different direct RM technique in various manufacturing processes

(a) (b) (c)

Notes: (a) injection molding (Muzumder *et al*., 2000); (b) blow molding- golf ball (Es-Tec, DemoCenter); (c) hot extrusion- mandrel of an extrusion die with CCC manufactured by SLM (Hölker *et al*., 2013).

CCCs in each blade of the mold for a plastic fan part via direct rapid manufacturing technique to acquire both rapid and uniform cooling characteristics. A dual CCC structure was used in each blade of the mold to allow effective controlling of heat transfer characteristics in each blade of the mold through the variation in spaces of cooling channels.

Step 1- Mold design with CCC

- First, the initial design of mold and CCC are designed in the CAD software [Figure 6(a)].

Step 2- Optimization of mold design with CCC using virtual simulation

- 3D injection molding analyses are performed to acquire a proper arrangement of the CCCs. The influence of the design of the CCCs on the qualities of the molded product and the variation of temperature in the mold was examined via injection molding analysis [Figure 6(b)].
- From the results of the injection molding analysis, the proper channel spacing and the cooling distances of the cooling channels were determined as D2 (α = 11.3 mm and β = 25.3 mm) and 6 mm, respectively.

Step 3- Direct rapid manufacturing of mold with CCC by hybrid manufacturing

- To reduce the fabrication time of the mold, hybrid type of rapid tooling process combining machining process with laser-aided direct metal rapid tooling (DMT) process was adopted [Figure 6(c)].

Step 4- Post-processing

- Post-processing was added to improve the surface roughness of the molding part [Figure 6(c)].
- Through the observation of the microstructures in the vicinity of the joined regions, it was shown that the deposited P21 material is completely joined to the supporting part without defects in the joined region. Final completely fabricated mold with CCC is shown in Figure 6(d).

Step 5- Application of mold in injection molding and experimental analysis

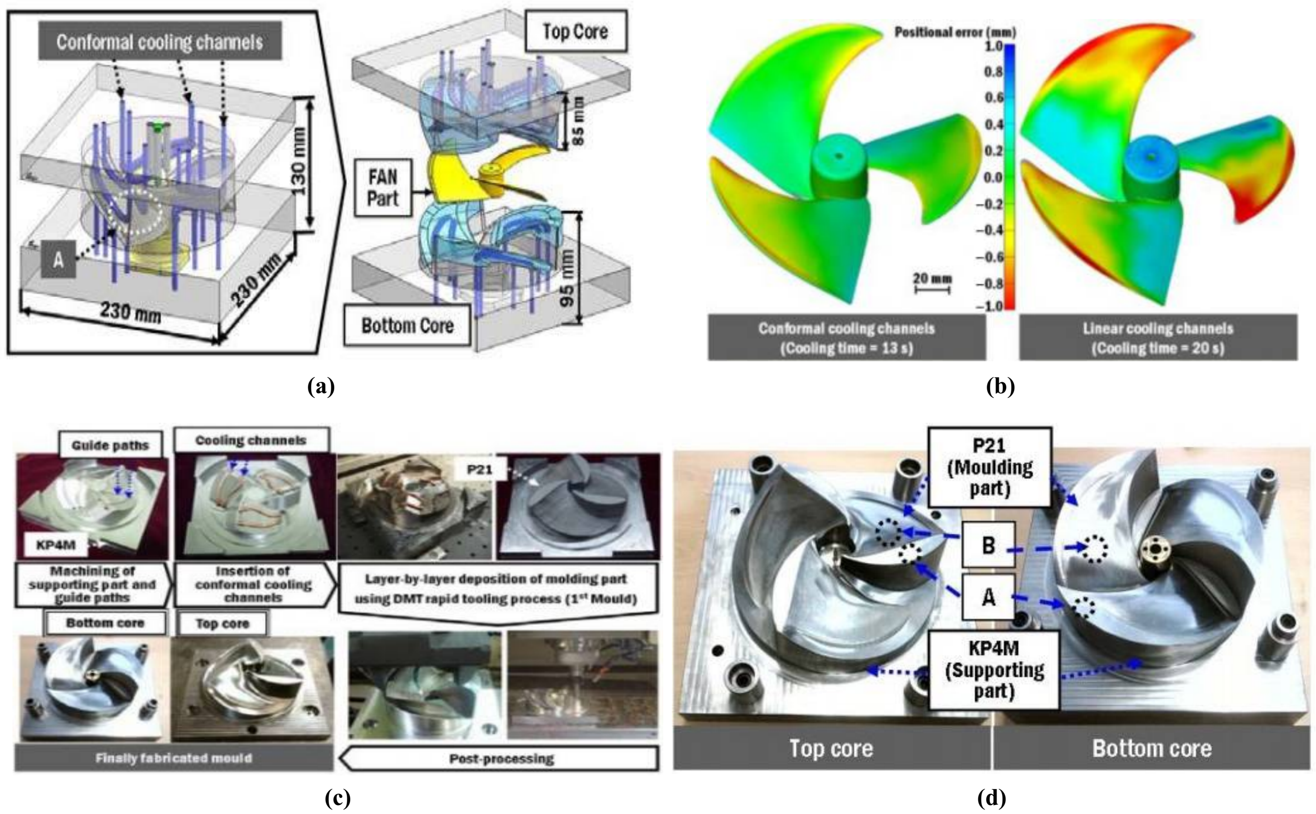
- To investigate the practical applicability of the fabricated mold and the influence of the cooling time on the qualities of the molded product injection molding experiments are carried out.
- From the results of the experiments, it was observed that the positional error distributions in the molded product, the mean error of the product thickness and the eccentricity of the molded product are minimized when the cooling time is 13 s. From the results of the experiments, the optimum cooling time for the designed mold is selected.
- The experimental results showed that the designed mold can remarkably reduce the positional error distributions and the eccentricity of the molded product as compared to the mold with conventional cooling channels.
- In addition, it was shown that the cooling and cycle times of the designed mold can be shortened to 35.0 per cent and 25.7 per cent of those of the conventionally designed mold, respectively.

7. Discussion

Cooling system plays an important role in the molding process in terms of not only productivity and quality but also mold-making cost. The insertion of the CCC into the mold is restricted by the relatively simple cooling channel configurations imposed by the limitation of the fabrication technology used to make the mold. The direct rapid manufacturing technique allows the fabrication of CCCs in the mold directly in metal form. Fabrication of mold with CCC using direct rapid manufacturing technique making noteworthy results in the various manufacturing processes with a variety of applications and its potential has also been demonstrated in several case studies. The results obtained in various case studies available in the literature noted that mold with CCCs fabricated using direct rapid manufacturing technique reduces the cooling time and improve the part quality. Past researchers have proved that direct rapid manufacturing technique is a viable method for the direct production of the mold with CCCs to increase and balance the heat transfer within the mold for injection molding, blow molding, hot extrusion and die casting purposes in various day-to-day applications.

Various investigators have developed and analyzed the different structures of CCCs design in the mold. In CCC structure design, a lot of work has been performed in layout wise CCC design, but very little work has been done in the area of cross section wise and positioning with respect to cavity wise

Figure 6 (a) Design of mold with CCCs; (b) injection molding analyses; (c) manufacturing procedure of the mold with CCCs using DMT; (d) completely fabricated mold with CCC



(a) (b) (c) (d)

Source: Ahn *et al*. (2010)

CCC structure design. The efficiency and performance of various structures of CCCs in mold proved superior in terms of uniform cooling, quality of molded part, reduction of cooling and cycle time. The designing of different CCC structures is quite easy but the actual fabrication of all that type of CCC structures in the mold using any fabrication technique is not still possible because of limitations in direct rapid manufacturing techniques. Also, previous literature is unable to decide which CCC design is best for a particular part in the particular manufacturing process. Most of the researchers only focused on simulation works and still lack support and verification from real experimental data. Research only based on the simulation work could not fully solve the actual problems in real production. As per the previous research, it can be concluded that cross section wise and positioning with respect to cavity wise CCC design may be well suited for regular and simple parts. Conversely, layout wise CCC structure design may give better results in complex shaped part.

In addition, advanced direct rapid manufacturing technique allows fabrication of complex CCCs in the mold. However, direct fabrication of highly complex structured CCC in the mold is difficult because of limitations of the direct rapid manufacturing technique. The review showed that the efficiency and performance of direct rapid manufacturing assisted fabrication of mold with CCCs is much superior in terms of the uniform thermal distribution, improvement in parts deflection, reduction in cooling time and cycle time. However, comparison of different direct rapid manufacturing technique was not performed by any previous researchers, so the selection of exact direct rapid manufacturing technique for fabrication of mold with complex CCC for any particular application is only based on availability of the technique. Also, the selection of suitable CCC structure depends on the manufacturability of available direct rapid manufacturing technique for the various molding process. Additive manufacturing techniques have the capability to fabricate CCC inside the mold, but this technique is still expensive, especially for a large-sized mold. Also, the choice of mold material with appropriate thermal and mechanical properties for making CCCs in the mold by rapid prototyping is limited. These issues hinder the popular use of rapid prototyping technique for making a large-sized mold (Dang and Park, 2011). Generally, when the SLS and DMLS processes are selected for the fabrication of mold with CCC, most of the shape is created directly in a layer-by-layer deposition of the metal bead. However, in when SLM, DMD and DMT processes are chosen to create the mold with CCC, it is desirable to use the hybrid manufacturing technique to reduce the manufacturing time and cost (Ahn, 2011).

The mold making process is a huge expenditure mostly when the complex and precise products are required. In product design and development, time is a main important factor. No mold making company would ever afford to take a risk to attempt a new structure of CCCs without justification through experimental study. Even though direct rapid manufacturing technique provides a lot of benefits and potentials in producing complex CCC structures in the metallic mold, the complete establishment of rapid manufacturing process at industrial level is not accomplished yet; also, molds formed by current rapid manufacturing technique are still not suitable for real industry uses. Furthermore, direct rapid manufacturing technique cannot be used in regular fabrication process because of some issues such as suitable material, fabrication time and the high cost of the fabrication procedure. Even though fabrication of CCCs using direct rapid manufacturing techniques is faster and more flexible than tedious conventional methods, it is neither fast enough nor cost-effective to cater for molds with very complex structures of the CCC in desirable material. At least, a few hours to some days may be required to fabricate mold with CCCs because of designing, optimization, and manufacturing procedure. Time and cost issues restrict the use of direct rapid manufacturing technique for fabrication of mold with CCCs. Moreover, the required time and cost is high in the fabrication of all the direct rapid manufacturing assisted molds with CCCs, even though it seems to be acceptable in complex CCC development as compared to the use of conventional manufacturing methods which are very tedious and costly and unable to develop the complicated structure of CCCs. Nowadays because of exploration and growth of direct rapid manufacturing techniques, mold development time has reduced by around 50 per cent or more (Levy *et al.*, 2003). However with high initial investment, specialized maintenance and substantial material cost, direct rapid manufacturing technique for fabrication of mold with CCC in metal is about 50 per cent more expensive than traditional machining processes (Wu *et al.*, 2015). As a result, the use of hybrid manufacturing technique is more desirable for the reduction of mold fabrication time and cost.

These issues imply that extensive experimental research is needed to support the molding industries for improving the effective method of mold with CCC fabrication and to produce better quality of plastic parts. Future studies are required to focus on the possibility of applying the exact structure of CCCs in the mold for reducing the cooling time using particular direct rapid manufacturing technique for various applications. Also, the comparison should be done between the molded parts produced from different rapid manufacturing techniques in particular application. Thus, mold makers can see clearly the advantages and disadvantages of using different direct rapid manufacturing techniques for the fabrication of mold with proper structure of CCC, so that this information can be used as a guideline in selecting the best combination of CCC structure in the mold and fabrication technique to produce cost- and time-effective molds to increase productivity and to reduce cycle time.

8. Conclusions

In this paper, a review of a direct rapid manufacturing of the mold with CCC is proposed with the integration of CAD, CAE simulation and direct rapid manufacturing technique to improve the cooling performance of the mold during the various molding processes. The outcomes based on literature review and case study, discussed in this paper, strongly suggest that direct rapid manufacturing assisted mold with CCCs might become part of the standard protocol in various manufacturing processes in the near future. After an elaborate scrutiny of the published research, main conclusions can be summarized as follows:

- CAE simulation and direct rapid manufacturing techniques contribute to reduce the cooling time and the cycle time in the molding processes by effective heat removal between the mold surface and the CCC. These techniques help to increase the productivity and quality of the molded parts.
- Complex-shaped CCC structures are studied by various researchers using simulation technique but manufacturing of such a complex shaped CCC is still the main hurdle even though a lot of advanced direct rapid manufacturing techniques are available.
- The exact selection of CCC structure and direct rapid manufacturing technique for particular manufacturing process (injection molding, blow molding, die casting, hot extrusion) for fabrication of desired part is not well established in previous literature, so further research is required to overcome this problem.
- Also, further research is required to reduce the overall cost and time (caused by CAD, simulation, optimization, direct rapid manufacturing technique and post-processing) to fabricate direct rapid manufacturing-based mold with CCCs so that it can be used in regular manufacturing processes for fabrication of mold with CCCs in desired material.

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