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CONFORMAL COOLING FOR MOLDS PRODUCED BY ADDITIVE MANUFACTURING: A REVIEW

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ABSTRACT

The present research study demonstrates a critical review on the permanent molds used for injection molding, pressure die casting and investment casting has one common task of dissipating the heat from the mold effectively for better production, longer tool life and better surface quality of the components being produced. Conventional method of keeping the mold cooler during the casting process is achieved by drilling the cross holes and then attaching to the coolant media. This follows the straight line profile owing to the process limitation and creates non-uniform cooling for a contoured surface. Hence the effectiveness of the cooling compromised where the cavities or punches are having more curvilinear surfaces. The method of making the cooling channels to follow the contour of parts is called conformal cooling. Earlier it was very difficult to produce such cooling channels, but with the invention of additive manufacturing, last few decades has witnessed a lot of experimentation and advancement in the field of conformal cooling.

Key words: Conformal cooling, Rapid tooling, Additive manufacturing, molds.

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1. INTRODUCTION

The invention of the first injection molding machine in 1872 by John Wesley Hyat, the complexity of the plastic components and the quality requirement has changed many folds. The development of the injection molds for better mechanical and thermal properties and increased production rate is the need of the present time. Every day lots of new models of cars, mobiles, Television, refrigerator, A/Cs and many other products are being launched in the market, all these products use plastic parts, means a pressure to generate more efficient tools in shortest possible lead time. The injection molding cycle mainly depends upon filling of the cavity, solidification of the component and ejection of the component. The cooling or the solidification time is the major contributor of the total cycle time (Fig 1.).

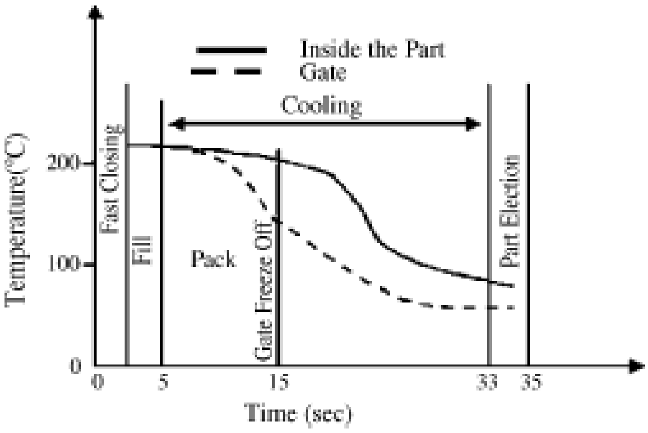

Figure 1 Temperature history during injection molding [1]

The cooling time remains up to 50% to 70% of the total time, depending upon the size and the surface texture quality requirements. To reduce the cycle time many different methods and techniques have been developed. The development has happened in both the hardware and software for productive, predictable and economical mold generation. In the hardware side of the apart from straight cooling channels , different methods such as helical channels, baffled hole system, spiral plug system and heat pipes have been developed for the uniform and efficient cooling of the part [2]. Other method of milling of cooling channels layer by layer such as stacking slices was used to manufacture the tool by Luling M.[3]. Jacobs [35] used highly conductive material Nickel and copper to manufacture an injection mold tool using electroforming with conformal cooling channels for the increase in the productivity in comparison to conventional cooling. The additive manufacturing process developed during 1990s provided a new dimension to the development of in built cooling channels conforming to the surface of the mold. The computational development of analysis tools during late 70s provided a further direction to optimize the design of the cooling channels to tackle the quality pertinent issues such as residual stress , warpage and shrinkage to improve strength and productivity The rapid heating of the mold is also desired in some cases such as in micro molds or where the thickness of the surface is so less as compared to the total volume of the component that instead a premature cooling freezes the flow of the polymer. A number of attempts were also made to impart the required heat rapidly in to the mold followed by the cooling of the mold. Among all the available heat generation technologies, electrical resistive heating is the most widely used mechanism for mold rapid heating. It is usually accomplished by passing direct or alternating current in the cartridge heaters or in thin electrical conductive layer [4]. Another approach to thermally cycle the mold surface temperature consist of in circulating a hot and a cool fluid in alternate sequence in the cooling channels [5].

2. ADVANCEMENTS OF THE CONVENTIONAL COOLING CHANNELS

The polymer injected in to the mold at temperature above the melting point though the gate, the melted polymer then loses heat to the mold surface in contact and conduct the heat through the mold body to lower the temperature for final solidification of the part. For reducing the cooling cycle time the heat transfer is increased in mold through the external cooling media flowing in to the holes created near the mold surface. These holes are termed as cooling channels or water lines. Traditionally the cooling channels are made by drilling straight holes either parallel to each other or at the maximum at some inclination to the base surface or at an angle to each other in a plane. These cooling systems works efficiently for the simple flat and uniform depth of core and cavity. The sufficient cooling channels are relatively easy to place in the cavity (limited by ejector system), but cooling channels for core are problematic as the core is extruded away from the base surface fig. 2 and conventional cooling in the core itself is not advisable.

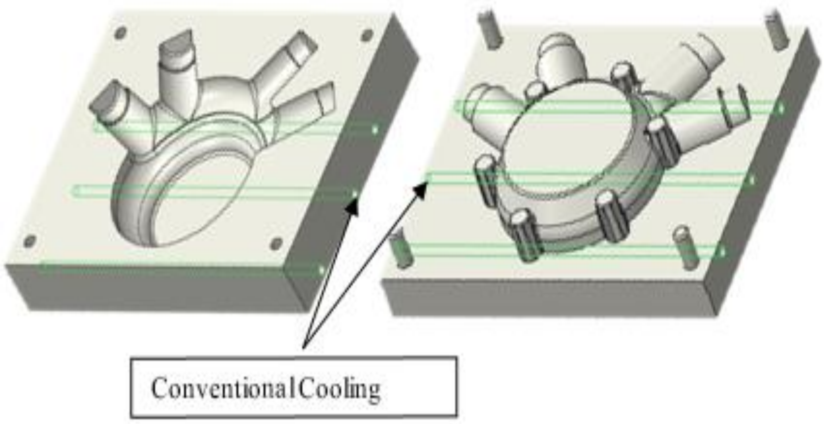

Figure 2 Core and cavity with conventional cooling channels of injection molding

The excessive high temperature in the core must be dropped to a specific temperature before the component can be successfully ejected. The unequal heat distribution creates mold stress and the possibility of component warping. An improperly cooled core along with a longer cooling time are both uneconomical and wasteful. It is usually desirable and sometimes necessary to supply cooling inside core pins .Several different techniques are designed for cooling cores and cavities depending upon their size and construction: baffle system, bubbler cooling, angled hole, stepped hole, spiral cooling, heat rods, heat pipes and beryllium copper cores and cavities. Baffle System is a simple means of cooling smaller-sized cores, although arrays of baffles can be used in bigger cores. A hole is bored into the core and a strip of copper is placed in it. Figure 3 shows a conventional multiple baffle structure inside a big core. The drilled whole can also be fixed with a bubbler cooling system instead of a baffle as shown in figure 4. This provides a much more uniform temperature control over the complete molding surface in comparison to the baffle system.

Kunnyat and kittinat [8] used hybrid system of layer by layer deposition and CNC machine to create and compare conformal bubbler and baffle cooling system. Sometime angled hole (fig 5) and steeped holes (fig 6) are drilled in to the mold core for as cooling channels. The angled holes are limited to 150mm depth only owing to the problems of intersection of the holes to the full diameter due to the tendency of the drill to wander off path. Steeped hole are simpler method for toolmakers to produce compared with the angled hole design, because it is not too difficult to match up the drilling. Wherein drilled holes break through into the punch surface they need to be plugged followed by brazed or welded over. A trouble linked with this method is that as a result of the injection pressure and persisting cyclic expansion and contraction, the plugs in many cases are likely to leak. This method can result in problems where the product is of a very important visual aspect. A mark can often be seen on the component where the plugs are positioned. For bigger cylindrical cores above 50 mm diameter, spiral cooling designs produce more uniform and effective cooling permitting quite suitable temperature control. A number of different designs can be utilized depending on the sizes of the cores and the space available. The elementary design makes use of a channel which is machined down the outside of a centrally inserted tapered diameter and adheres to the pathway of a helix (Fig 7). When space allows, a dual helix are useful to provide two cooling channels that operate beside one another. The single-channel and double-channel solutions are extremely resembling a single-start and double start screw thread respectively. The remaining wall portion of the core should also be heavy enough to endure the pressure developed during the course of injection of the polymer. Cooling channels also need to be far enough far away from the core area to reduce unnecessary chilling of the polymer very fast. Where ever due to the size of the cores or core pins it is difficult to install any of the above discussed cooling system, the heat pipe or heat rod can be inserted in to the core pin or core. Highly thermal material such as copper can be used as heat rods to dissipating the heat away from the core to the coolant flowing in to the channels. A heat pipe contains a copper tube closed at both ends with a fine ‘wick’ streaming along the length of the inside wall of the tube. The tube is filled either with water or with a low-boiling-point alcohol. The fluid vaporizes mainly because it accumulates heat from the molding and moves to the further, cooler, end of the tube which is positioned in the flow of a cooling fluid. The vapor at the cool end of the tube condenses back into fluid which is drawn back up to the hot end by capillary action. The performance of the heat pipe is directly related to the orientation of the wick structure. Loh et al. [9], did a comparative investigation on heat pipe capabilities with various wick structures confronted with different orientations. They testes three different wick structure groove, mesh, and sintered metal powder for three different diameters 4, 5 and 6mm. The evaporator block tested at three different inclinations as 0^0,30^0 and 60^0 for different temperature differentials. Due to the strongest capillary action the sintered metal powder wick was least affected by the heat source generation. For biggest pipe diameter i.e. 6 mm, the groove heat pipe has a better performance in comparison to the other two.

Apart from these pulse heating and cooling technique for better control of mold temperature [10] and various novel process such as injection compression molding, lost core molding and co injection molding have been developed for further improvement of the process quality and variety [11]. Kim and Suh [12] reported the development of a low thermal inertia mold for isothermal filling. The mold was constructed by placing multiple layers of woven graphite, silicon rubber, Teflon and zirconium oxide on the surface of the mold base. The rapid switch of the heating circuit fires the graphite fiber and warms up the mold surface in very short time so that the isothermal filling occurs. The experiments with low thermal inertia molding showed significant improvement in the part residual stress and molecular orientation. Other advantages of the low thermal inertia molding include lower barrel plastic temperature, lower injection pressure, slower injection rate and short shot eliminated part and uncoupled scheme for mold flow and cooling design analysis. Kim and Wadhawa [13] designed a mold which uses thermoelectric devices for rapid heating and cooling.

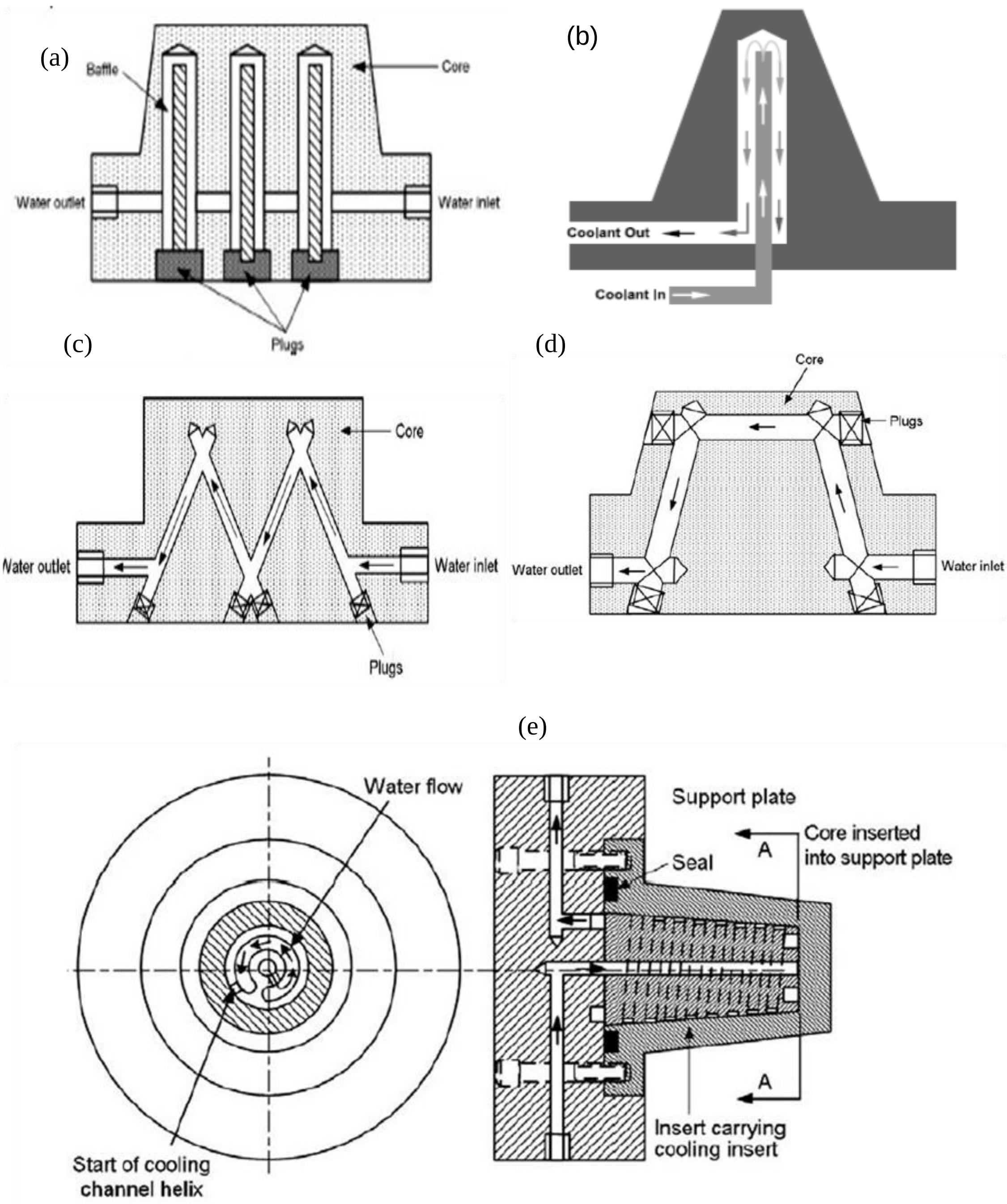

Figure 3 Moulding design: (a) Baffle Design, (b) Bubbler cooling for mold core, (c) Angled hole for mold core, (d) Stepped hole for mold core, (e) Spiral cooling insert design [7]

3. CONFORMAL COOLING CHANNELS

As discussed above, there are a number of efforts being made to enhance the cooling of the molds, but all system discussed are difficult to fabricate due to the limitation of conventional tools. The emergence of additive manufacturing systems offered mold designers a new way to tackle the problems related to the cooling system design. Typical additive manufacturing processes includes fused deposition modeling, selective laser sintering, streolithography, laminated object manufacturing and 3D printing etc. These processes has been developed over the year to give a near net and accurate shape and size of virtually any project. The materials range available with these processes varies from polymer to metal and powder to liquids and lot of new materials are being developed by the researchers. The capability to fabricate 3D features with close to arbitrary complexity has made these processes significant for manufacture complex cooling channels inside the molds as a way to improve the uniformity of cooling [6], these types of cooling channels have been fabricated to follow the contour of the mold, hence called conformal cooling channels .Sachs et al. [14] presented progress of conformal cooling, dimensional control, surface finish and hardness for direct 3D printed metal tooling. Tooling inserts tested with a variety of patterns of conformal cooling shows a reduction in the cycle time up to 15 % and reduction in the part distortion up to 37 %, conformal cooling with chevron patterns found to be best for heat transfer. Xu et al. [15] presented a systematic modular approach to the design of conformal cooling channels for complex injection molding tool. The work proposed builds a synthesis software tool instead of analysis tool used in the work prior to this work, taking into consideration the advantage of additive manufacturing. The analytical expression for the time period as suggested in [15], depends directly on the thermal diffusivity of the mold and to the square of the distance of the cooling channel from the surface of the mold. The model thus suggested to be based upon transient heat transfer calculations and also, geometry of the cooling channels is found to be more important than the material properties. The approach of dividing the whole geometry into small regions as cooling cells eliminates the complexity of the geometry, thus making this modular approach suitable for any shape of the surface. Sachs et al. [16] experimentally compared the conventional cooling channels with the conformal cooling channels manufactured using 3D printing process for powdered materials of ink jet style printer. The 316 L stainless steel 60 μm spherical powder and Acrysol binder was used to print the part with 60% packing density. The excess powder was removed using water before putting the part for sintering and debinding, leaving final density of the part as 64% of theoretical. The cavity generated with 3D printer has two different circular conformal cooling channels 3.18 mm apart and 8.0 mm underneath the cavity surface, while the core generated with torus shaped cooling channels. The conventional mold with straight cooling channel was made of 303 stainless steel to match up in properties with the 3D printed part. Both the tools were subjected to similar injection molding process parameters such as, melt temperature 2150C, injection clamping pressure 1000psi and injection speed 1.8 in /sec. Mold surface temperature measurements were taken using various thermocouple installed in the molds having conformal cooling and straight channels keeping the coolant temperature of 110C and cycle time of 11 s for all the experiments. The data presented revealed a constant temperature of about 20 0C was maintained by the mold in case conformal cooling during the production of 25 parts, while the conventional cooling channels shows an continuous increase in the temperature of the mold surface from 11 0C to 60 0C for the same production rate as shown in fig 8. Thus the uniform cooling in case of conformal cooling channels resulted in lower residual stresses and faster production.

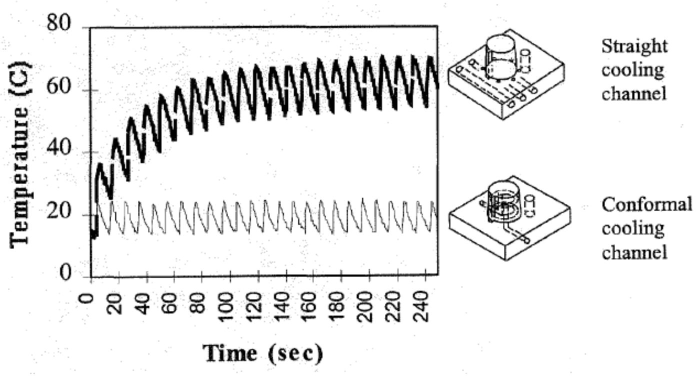

Figure 4 Comparison of mold surface temperature for conventional and conformal cooling [8]

Ferreira and Mateus [17] created the soft mold for small batch production on injection molding with conformal cooling to control the sink marks on the components during molding process due to poor thermal conductivity Dimla et al. [18] used FEA and thermal heat analysis to optimize the gate location and design of cooling channels to increase the production rate of injection molding components. The analysis of CAD models established the fact that there was substantial reduction in the cycle time and enhancement in the surface finish of the components with conformal cooling channels in comparison to the conventional cooling channels. Saifullah and Massod [19] determined an optimum design for conformal cooling channels of an injection molded part using finite element analysis and thermal heat transfer analysis. Cooling channels have been designed keeping the design rule of minimum distance between cooling channels and cavity surface as well as channels itself. Diameter of the cooling channels was 12 mm. Using Ansys software steady state and transient analysis was done on the mold to evaluate the thermal responses over the period of time. The results presented in the work clearly shows more uniform cooling in the case of conformal cooling with low average temperature as compared to the conventional cooling. The cycle time also found to be reduced to 9s from 13s a saving of 20% in time. Eva [34] designed a conformal cooling system for injection mold and manufactured using direct metal laser sintering, also confirmed the improvement in the dimensional stability and increase in the productivity.

Li and Li [21] addressed the less explored area of layout design for the cooling channels taking in to consideration the mold components such as ejector pins, sprue puller, and guiding pins etc. A special technique to compute configuration space and storage in 3D was developed for cooling system design. A simple genetic algorithm was implemented and integrated with configuration space representation to automatically generate candidate layout design. In the configuration space design the whole mold is divided in to two regions as blocked region and free region, the free regions are the one suitable for layout of cooling channels. The resolution in the configuration space representation was 0.15 mm, which does not make substantial difference in the cooling rate. This method overcomes the limitation of relying on specific heuristics to generate the layout design and can be used as stand-alone system. The limitation of this work is that it has not integrated the process parameters such as coolant flow rate, cooling time and ejection time etc. for the design of cooling channel layout. Au et al. [22] developed a methodology called visibility-based cooling channel generation for automatic preliminary cooling channel design for rapid tooling. The mold surface was approximated to polyhedral followed by facet classification and then normal offsetting, the point light source was used to fit the cooling axis and finally the cooling channel was constructed by the developed software. The application of this methodology resulted in to a better design of cooling channel in shorter time similar to the optimal CAE results. Wang et al. [23] generated an automatic design algorithm for design of conformal cooling circuit for interacted 3D shapes without any decomposition step in between, as observed in the previous works. The developed algorithm works as five step process, first the CAD model is generated, then the surface to be cooled is offset to the required value, the offset surface is then isolated as conformal surface, then the centroidal Voronoi diagram (CVD) is computed on the conformal surface. Finally the CVD was used as the centre lines of the cooling channels. The method proposed can generate the conformal cooling channels automatically after selecting type of coolant, the diameters of channels and the injection time. The optimized solution is an iterative process for the injection time for the best cooling channels. Agazzi et al [25] introduced the concept of controlling the temperature of the mold and the plastic part by the cooling surface depending upon the morphological concept. Two stage method of optimal distribution of coolant temperature and location of cooling channels along the cooling surface was approached for the design of the cooling system. From the optimal solution, thermal field in the mold was analyzed and optimal regulation surfaces were extracted according to the shapes of some isotherms located in the quasi-stationary thermal zone of the mold. This led to the transition from a continuous distribution of the coolant fluid temperature to a distribution of discrete cooling channels. Au and Yu [28] proposed a design to counter the heat energy absorption differential at the inlet and outlet of the cooling channels. As the cooling medium entering the cooling channel has less temperature than at the outlet, the proposed model tried to optimize the temperature gradient by variable distance conformal cooling channels (VDCCC) form the cavity/core surface moving from inlet to outlet. From the Moldflow plastics insight analysis results, the cooling performance of the VDCCC was better than the conventional conformal cooling channel (CCC) design. The maximum part temperature performed by the VDCCC was smaller than the contemporary CCC. Besides, the cooling time, and the volumetric shrinkage performed by the VDCCC were also smaller than the contemporary CCC one. The injection molding cycle time can be reduced. The compensation of the coolant temperature at the coolant outlet performed by the VDCCC can offer an effective heat removal during the cooling process. Wu et al. [29] used numerical simulation to design a die with conformal cooling for foreseen cycle time, component quality and tooling life. An algorithm for optimum thermos- mechanical topology was design for better weight control and thermal behavior of the mold. The stress and temperature distribution along with optimal density distribution were also presented in the work. The findings of the work highlighted that the materials between the cavity surfaces and cooling channels can be reduced without hampering the performance of the mold. As a future extension of the work it was suggested to include flow in the channels, volumetric shrinkage, cooling time and total cycle time to be explored with the inclusions of conformal cooling in to the molds. The topology optimization model developed for 2D needed to be further taken for 3D models.

Lucchetta et al. [24] developed a technology for rapid heating and cooling of injection molds for the improvement in the micro features and moldings appearance. Furthermore, the mold cavity heating combined with the fast cooling of the molded part significantly contributed to contrast the development of surface defects, such as weld lines, which were due to stress relaxation. The study of structural and thermal behaviour verified that the metallic-foam inserts largely increases the heat exchange rate w.r.t. the conventional cooling channels. The process has produced the components with sharp features even at thinnest section and without any weld line, but the work is required to be done to reduce the cycle time for more cost effectiveness of the process. Devrim and Can [20] compared the performance of dense copper and copper coated electrodes with internal cooling channels formed with SLA technique. Four different electrodes viz solid copper, copper coated SLA electrode without cooling channels, two copper coated SLA electrodes with different cooling styles name as type I and type II. The SLA electrodes were made conductive using electroless coating of palladium oxide and finally coated with copper. The paint based activation was avoided as it leads to delamination of the coating for thick coatings. A coating of 1.2 mm thickness was achieved within 24 hours at 20 A/dm2 current density. The interface of SLA epoxy and cooper was cooled with circulating water inside the electrodes to delay the heat build-up. The MRR values of coated SLA electrode found to be close to the solid copper along with 10-15% more deeper machining. The Surface finish was found to be better in case of solid copper, but the value produces by coated SLA electrodes were still acceptable. Armillotta et al. [26] used metal additive manufacturing process to fabricate the die casting mold with conformal cooling to compare the benefits and limitations for the application in contrast to the most of work which was done in plastic molds. The tool produced by selective laser melting process was used to die cast Zn alloy casting with different variations in the process parameters. Initially the thermal analysis of ejector die and cover die, made of H13 hot work steel material with conventional cooling channels using Flow 3D software was done. The observations indicated a clear temperature differential up to 1000 C in the thinner and thicker sections of the door handle. In the second stage the ejector die impression block was redesigned with conformal cooling system, with no change in the cover die half. The ejector die was manufactured by selective laser melting process from powders of AISI H11 hot work steel. The production tests on this die system yielded encouraging results as the increase in the cooling rate allowed the reduction in the lubrication spray, hence avoiding premature freezing. Further the work was suggested to analyse the die set with wider set of variables related to both part design and process conditions. Wang et al. [27] developed a rapid heating/cooling system for injection molding of an automotive interior part. They have conducted experimental as well as numerical simulation to analyse the effects of different temperatures and cycle time for weld marks free glossy surface of the product. It was shown that with the traditional straight line heating/cooling channels, the desired temperature for high quality product was more than the desired cycle time. They designed a baffle based heating/cooling channel system for the uniform and rapid heating and cooling across the surface of the cavity, the temperature difference of the whole cavity surface was decreased between 10-300C. The mold time constant reduced by 50% and the thermal efficiency of the system increased by 27%. It was also established that for the concerned part the critical level of temperature for surface gloss was about 1100C and the weld mark on the part was almost eliminated at the critical temperature of approximately 1300C. The simulation results and experimental results were found to be into sync. Hu et al. [30] reported the results of numerical modelling of several cooling design such as straight, longitudinal, transversal, parallel and serpentine conformal cooling channels for their cooling performance for hot stamping dies. For uniform cooling at low cost the longitudinal conformal cooling was found to worth for further application. The longitudinal design is optimized for a Bi pillar tool and a novel manufacturing method was also introduced for hot stamping tools[31]. Park and Dang [32] developed an additional idea which utilized and connected an array of baffles to attain conformal cooling. Schieck et al. [33] have experimented with two different cooling channels fabricated using additive manufacturing for shell structure and casting to cast in the cooling channels.

4. CONCLUSIONS

It has been established by various researchers that the conformal cooling is a viable and better solution to improve upon the quality of the final product for appearance, for controlling the residual stresses and thermal stresses and for cycle time reduction. The following relevant conclusions can be taken from the reviewed research work on conformal cooling.

- The cycle time with conformal cooling can be reduced by 15% to 20 % with proper design of cooling channel spacing, pipe diameter and coolant flow rate.
- The conformal cooling brings down the average operating cycle temperature by about 30^0C to 40^0C.
- The conformal cooling is feasible with almost all the additive manufacturing process.
- The conformal cooling can be employed into injection molds, pressure die casting tools, EDM electrodes and hot stamping tool etc.
- Automation and analysis of conformal cooling has gone up to a level that feature based optimization and consideration of the elements of mold such as gate, ejector pins sprue puller, and guiding pins etc can be predicted with the analytical software .

The uniform cooling due to conformal cooling ensured good surface quality, no weld lines, low residual stresses and improved productivity

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