Experimental analysis of milled groove conformal cooling in injection molding

Mahesh S Shinde[1], Dnyaneshwar S Malwad[2,*], Sandeep Kakade[3]

[1]Department of Mechanical Engineering, VilasraoDeshmukh Foundation Group of Institutions, Latur-413531, Maharashtra, India
Email: maheshsshinde@ymail.com

[2]Department of Mechanical Engineering, All India Shri Shivaji Memorial Society's College of Engineering, Pune- 411001, Maharashtra, India
* Email: dsmalwad@gmail.com

[3]Department of Electronics and Telecommunication Engineering, VilasraoDeshmukh Foundation Group of Institutions, Latur-413531, Maharashtra, India
Email:kakadesandeep2000@gmail.com

Abstract

Conformal cooling channels have been proposed as a promising alternative to traditional cooling channels. The objective of this paper is to introduce a novel method of producing milled groove conformal cooling channels for injection molding using hard tooling. An experimental investigation was carried out by comparing the conventional cooling channel approach with conformal cooling channels to optimize the cooling time. The study focuses on a specific case study of an "enclosure part" from a medium-scale industry (Mold Craft Engineers Pvt. Ltd. in Pune). The injection mold tools for this part used straight drilled cooling channels, which resulted in uneven cooling and longer cooling times. The milled groove conformal cooling channels was designed to improve the cooling time and reduce cycle time, to conform to the shape of the cavity. The fabrication of the mold with conformal cooling channels was performed using CNC machining. Milled grooves were sealed with a fitted plate and O-rings to prevent leakage. Temperature measurements were recorded using RTDs embedded near the cavity surface under controlled molding conditions. The experimental analysis, which involved temperature measurement of the molded part during the injection molding process, revealed that the mold with milled groove conformal cooling channels exhibited shorter cooling times than the mold with straight cooling channels. Cooling time was reduced by 73.33% compared to the conventional cooling system.

Keywords: Injection mold, Milled groove conformal cooling channels, Cooling time, Hard tooling.

1. Introduction

Various manufacturing methods are used to produce plastic parts; among them, the injection molding process is one of the most extensively used. A characteristic of this process is that it is cyclic in nature and is used for mass production. Filling, packing, cooling, and ejection are the steps of injection molding. The process cycle time depends on these stages. The predominant factor is cooling time because cooling requires 50–60% of the cycle time [1–6]. The geometry of cooling channels is an important criterion for the calculation of cooling time. Straight drilled-type conventional cooling channels are used frequently in the industry. The drawbacks of these cooling channels are longer cooling time and non-uniform cooling. Due to these problems, conformal cooling channels (CCC) came into existence. Conformal cooling channels (CCC) are cooling channels designed to follow the contour of the part being produced. CCC has been shown to offer several benefits, including a significant reduction in cooling time and more uniform cooling compared to traditional cooling channels. Previous research has demonstrated that the use of CCC leads to higher production rates and improved accuracy of the molded part when compared to conventional cooling channels.

Traditional cooling channels, or CCs, consist of straight drilled cooling lines that surround the complex shape of the mold cavity. This results in non-uniform cooling due to variations in the distance between the surface of the mold cavity and the cooling lines [7]. In contrast, CCCs are designed to perfectly match the contour of the mold cavity, maintaining a consistent distance between the cooling lines and the mold cavity. This results in superior and even temperature distribution within the molded objects as compared to traditional CCs.

Rapid prototyping (RP) is considered the preferred method for fabricating conformal cooling channels (CCC) in molds. Although CNC milling is an alternative technique for CCC development, it does not offer significant advantages over RP. However, CNC milling has the advantage of being capable of producing complex CCCs from any material. The machining time can be reduced by utilizing high-speed CNC machining and techniques that enable high material removal. The milled groove (MG) technique can be used to design freeform CCC patterns that prevent interference with other parts of the mold, such as ejector pins. Research has demonstrated that CCCs offer higher efficiency in rapid tooling than conventional cooling channels. Consequently, researchers are increasingly focusing on developing CCCs in hard tooling for injection molding. However, the design and development of CCC using hard tooling poses significant challenges due to limitations in CNC machining techniques.

Sun et al. [8] investigated the use of milled groove conformal cooling channels (MGCCC) as an alternative to traditional cooling channels in hard tooling for injection molding. They conducted a simulation study in Abaqus software, utilizing steel as the mold material, ABS as the part material, and normal water at 30ºC as the coolant. Results showed that the use of MGCCC significantly improved thermal distribution by reducing the cooling time by 54.2% compared to conventional cooling channels. In their study, In their study, Dimla et al. [9] utilized Moldflow software to optimize the gating system and design cooling channels in order to achieve a uniform temperature distribution. Their findings suggested that the use of conformal cooling channels (CCCs) could result in optimal cooling time.

In a study conducted by Saifullah and Masood [10], the effectiveness of conventional cooling channels (CCs) and conformal cooling channels (CCCs) was compared using normal water at 25ºC as the coolant. The results indicated that the use of CCCs reduced the cooling time by 20%. Another research by Saifullah and Masood [11] involved the development of a mold for plastic canisters made of polypropylene (PP) material with CCCs. Ansys software was used to compare the efficiency of CCCs and conventional CCs, considering normal water at 25ºC as the coolant. Their design optimization led to a significant 40% reduction in cooling time and a 35% reduction in cycle time.Saifullah et al. [12] investigated the effectiveness of square section CCCs in injection-molding processes for plastic bowls and circular plastic components, comparing them to conventional straight drilled CCs. They performed experiments only on simple circular shaped plastic parts and designed and fabricated the mold with square section CCCs using CNC milling in mild steel. Their results, supported by Moldflow simulations, showed that using square section CCCs with PP and ABS as plastic materials and normal water at 25ºC as a coolant reduced the cooling time by 35% and cycle time by 20% compared to conventional CCs. The extent to which the cycle time can be reduced is heavily reliant on the adaptability of the cooling channels and the intricacy of the component. When using a cooling channel system that is limited to a specific area, there is a potential for a 30% decrease in cycle time [13].

Park and Pham [14] devised a comprehensive CCC structure for car component injection molds with polyamide (PA06) material, utilizing a set of smaller CCC subsets. They compared the efficacy of CCCs and traditional CCs with Moldflow simulation software, discovering that the temperature distribution was reduced by 75%, from 6 to 1.5ºC, with the implementation of CCCs. In a separate study, Park and Dang [15] designed a mold for a radiator grill using CCCs and an array of baffles, utilizing P20 steel to produce parts in ABS 750 material. Moldflow simulation software revealed that the temperature distribution in the CCC mold with an array of baffles was found to be more consistent than that in a conventional CC mold.. Additionally, in another experiment, the same researchers employed a CC with an array of baffles for a plastic cover molded with Amoco 1046 (crystalline polymer). Moldflow analysis demonstrated that the CC with the array of baffles improved the temperature distribution by 49.41% (from 8.3°C to 4.3°C). Moreover, Dang and Park [16] created a U-shaped MGCCC for a car fender mold, utilizing P20 steel for the mold insert to mold parts in Noryl GTX979. Moldflow simulation software showed that the mold with the U-shaped MGCCC reduced component warpage by 15.7%.

Furthermore, Altaf et al. [17] introduced a profiled conformal cooling channel (PCCC) and evaluated it against the circular conformal cooling channel. Their experimental findings revealed that the PCCC mold necessitated lesser cooling time than the circular CCC. In another study, Saifullah et al. [18] put forward an MG square section conformal cooling channel for the front panel housing. Through Autodesk Moldflow Insight (AMI) 2012 simulation software, it was demonstrated that the MG square section CCC resulted in a 6 to 8% decrease in cooling time and a 12 to 50% enhancement in the uniformity of thermal distribution when compared to the conventional cooling channel.

Several studies have explored the use of CCC structures in plastic injection molding, focusing on their design and development using hard tooling. In particular, Shinde and Ashtankar [19] conducted a review of rapid prototyping-assisted CCC in the mold, highlighting their ability to reduce cooling and cycle times, improve thermal distribution, and minimize part deflection. Moreover, they conducted a comparison between straight drilled conventional cooling channels (CC) and MGCCC, utilizing Autodesk Moldflow Insight (AMI) 2016 software. They presented a case study on the enclosure part to examine the reduction in cycle time and enhancement in quality. According to the simulation results, the use of MGCCC led to a significant 32.1% reduction in cooling time and a 9.86% reduction in warpage as compared to conventional cooling. [20]. In the milled groove technique, the shape of the cross-section is determined by the milling tool used, which can vary from square and rectangular to U-shaped. However, certain unconventional machining methods like electrical discharge machining can be utilized as supplementary processes to machine challenging geometries such as corners or other complex shapes that may be difficult to achieve solely through milling [21].

Jahan and EI-Mounayripresented systematic approach for including confirmal cooling channels into injection molding dies using additive manufacturing process. The limitations of conventional straight drilled channels were overcome by placement of with3D printed CCC. The numerical thermal model was experimentally validated by authors to evaluate cycle time and cooling performance. Direct Metal Laser Sintering significantly reduced the cycle time and improved efficiency. This study has demonstrated the potential of rapid prototyping for CCC for industrial injection molding applications [22]. Furthers Hen et. al. investigated conformal cooling cavities (CCC) produced through 3D printing. This novel approach to conformal cooling reinforced with structurally optimized lattice architecture. Authors evaluated the key industrial performance metrics through experimentally validated numerical simulations. Cooling time, temperature uniformity and pressure drop were considered during the evaluation of performance of CCC. The study reported improved thermal performance and superior manufacturability were reported with 3D printing compared to conventional CCC designs [23].

Previous studies on molds with CCs have mostly relied on simulation work, with little experimental research performed to validate the effectiveness of CCCs compared to conventional CCs in plastic injection molding. Relying solely on computer simulation software may not solve actual industry-based problems. Real experimental approaches are needed to solve live industry-based problems related to CCs in injection molding. The process of mold making can be costly and time-consuming, particularly for complex products that require precise production. Without experimental analysis of the new CCC design, mold-making companies may not support manufacturing molds with CCCs. Such results are not advantageous for injection molding industries. This paper presents experimental analysis to assist molding companies in minimizing cooling time and increasing production quality.

Milled Groove Conformal Cooling Channels (MGCCC) offer a practical and cost-effective alternative to conventional straight-drilled channels.Small and medium-scale industries cannot adopt advanced additive manufacturing–based cooling solutions. Straight-drilled cooling channels are still widely used in many Indian industrial settings. This leads to non-uniform heat removal and longer cooling and cycle times. This study focuses on designing, fabricating, and experimentally evaluating MGCCC. ABS plastic components are manufactured using the MGCCC arrangement. The milled grooves sealed with a plate can be effectively implemented in existing mould manufacturing infrastructure. Improved cooling performance and significant reductions in cycle time without compromising part quality is demonstrated successfully.

2. Methodology

The fabrication process of milled groove CCC can be divided into three phases: the first phase involves design and CAD modeling, the second phase involves physical fabrication through CNC, and the third phase involves testing and experimentation. Fig. 1 illustrates the standard process for the development of milled groove CCC and its application in the injection molding process.

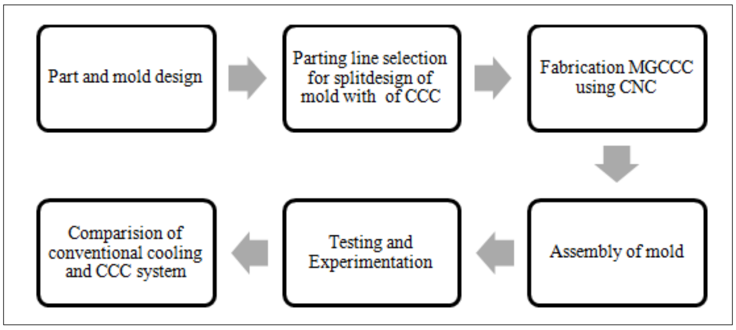
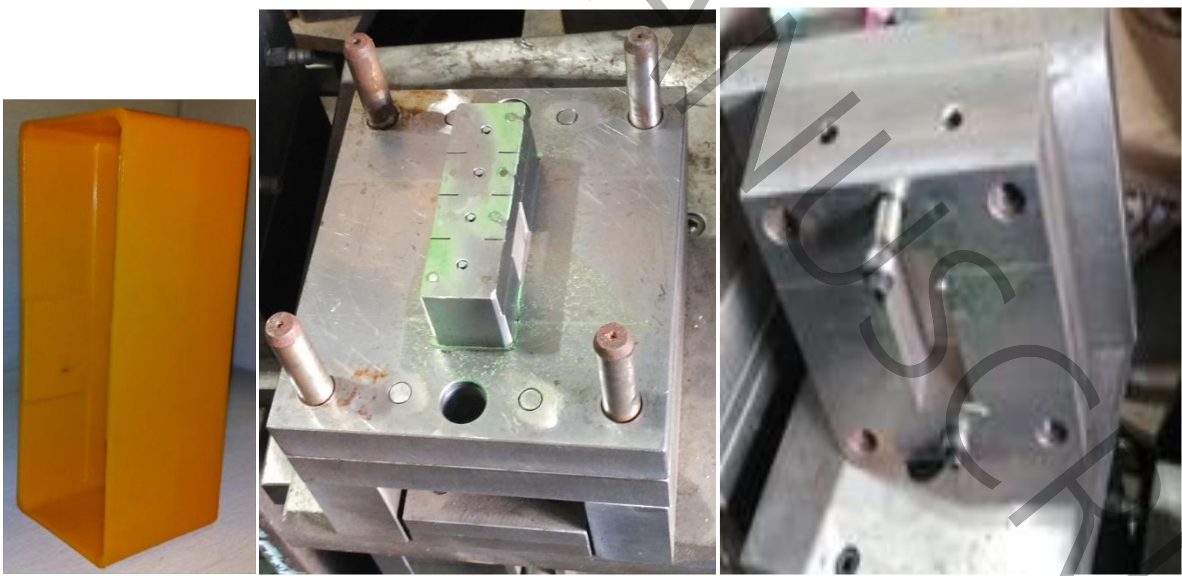


Fig. 1. Generalized standard procedure for development and use of milled groove CCC in injection molding

2.1 Case study

A case study was conducted on a plastic component to improve the cooling system, using Mold Craft Engineers Pvt. Ltd Pune, a medium-scale industry, as a reference. The plastic enclosure made of ABS thermoplastic material and manufactured via injection molding was selected for the experimental work depicted in Fig. 2 (a). The industry had an available mold with straight drilled cooling channels for this part, as shown in Fig. 2 (b) and (c). The cooling time required for the part using the available mold was 30 seconds, and the cycle time was 40 seconds. The 3D CAD design of the plastic component, which had a length of 112.5 mm, a width of 40 mm, a height of 40 mm, and a thickness of 1.5 mm, is presented in Fig. 3(a).

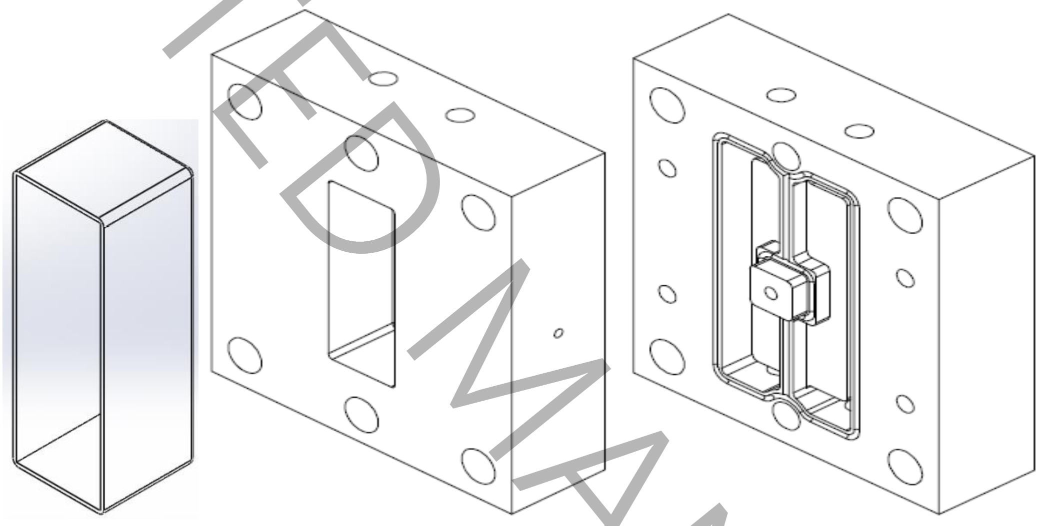


(a) **(b)** **(c)**

Fig. 2. (a) Enclosure part, (b) core plate, (c) cavity plate available in the industry

2.2 Milled groove CCC design

To design the MGCCC, the cavity is taken as a reference point, and the outline and profile of the CCC are considered during the design phase. The cavity plate was split into two plates in order to prevent interference with other mold components, such as sub-inserts, spurs, runners, and ejector pins. This allowed for the opening of cooling channels from one side. CCC can then be manufactured through the milled groove method. Choosing the parting line between the two split plates is crucial and varies from one part to another. Figure 3 illustrates the design of the milled groove CCC for the enclosure part, where the cooling channel is located 8mm away from the part cavity and has a rectangular shape with dimensions of 8x55 mm from the bottom side.



(a) (b) (c)

Fig. 3. (a) part model (b) front view of Cavity plate (c) rear view of cavity plate with milled groove CCC

2.3 Fabrication of milled groove CCC

For the fabrication of MGCCC in the cavity insert for the enclosure part, D2 steel was used as the raw material, which was the same as that of the available cavity plate. Two plates, with dimensions 205×185×70 mm and 205×185×12 mm were taken with machining allowance. The CAD model was then imported into "Mesh CAM" software for generating the CNC program. The required tools for the operation were listed out and the blocks were mounted on the Vertical Milling Center (VMC) where the program was sent for machining. After the machining process was completed using the required tools, the assembly of the two plates was done using 4 CSK screws (as shown in Fig. 4). It was important to ensure that the coolant did not leak during the experimentation. Therefore, O-rings or gaskets were used to seal the grooves. Fig. 5 illustrates the MGCCCs that were milled directly on the cavity insert and sealed by the O-ring to prevent coolant leakage. This process was important for the successful implementation of the MGCCC in the injection molding process, as it allowed for better cooling and improved production rates.

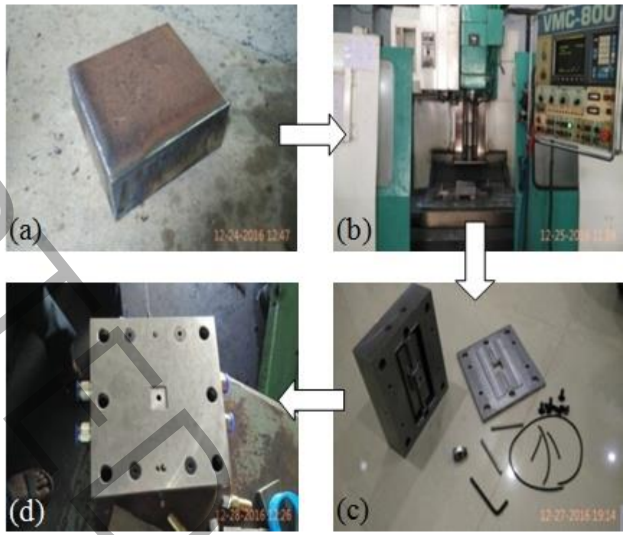


Fig. 4. Fabrication of milled groove CCC (a) raw material, (b) VMC machining, (c) macchied mold with milled groove CCC, (d) assembly of mold with cooling channel connectors

2.4 RTD embedded inside the mold cavities for measurement of temperature

RTD were employed to measure the temperature of the part throughout the injection molding process. The thermocouples were fixed in place by drilling a 6 mm hole through the CC. Sleeves were then inserted into the holes, and a RTD was fitted inside each sleeve. The thermocouple bead was placed at the centre of the mold cavity to ensure accurate temperature measurement. This process was done for both conventional and CCC mold cavities. By embedding the thermocouples in the mold cavities, the temperature distribution inside the mold during the injection molding cycle could be accurately monitored and analysed. Fig. 5 illustrates this process, with the thermocouples embedded in the mold cavity and the sleeves in place.

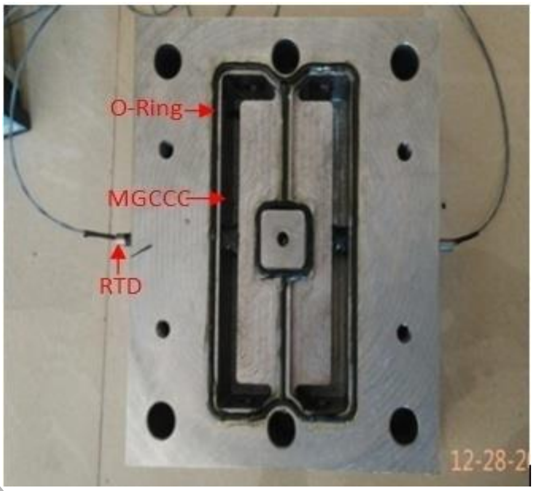


Fig. 5. MGCCC with resistance temperature detector and sealing

Some amount of uncertainty is unavoidable in any experiment after knowing all errors and influencing factors. Measuring environment, precision of instrument and repeated readings influence on the uncertainty in the final outcome. Uncertainty in the temperature measurement is determined from the Eq. 1 [24]

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + ... + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{1/2} \quad (1)$$

Repeatability, accuracy (±0.3ºC), data logger calibration and insertion errors are considered for calculation of uncertainty in temperature measurement. Combined uncertainty in temperature measurement due to error in Resistance temperature detector (RTD) and data logger is ± 0.38ºC.

3. Experimentation

Horizontal injection molding machine was used for the experimental study as shown in Fig. 6. Injection mold with CCC were placed in the injection molding machine. Resistance temperature detector (RTD)was used for temperature measurement.

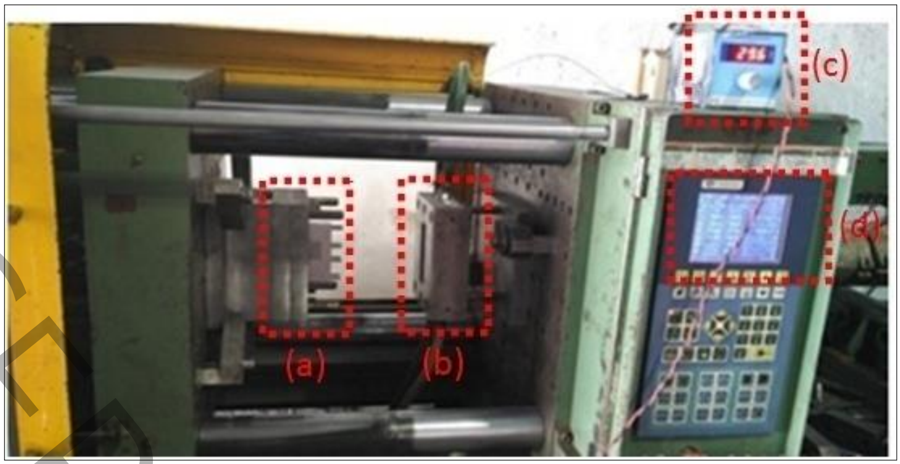


Fig. 6. Experimental set up (a) core plate (b) cavity plate (c) temprature disply (d) parameter setting

3.1. Injection molding parameters

ABS is a commonly used thermoplastic material with good impact resistance, dimensional stability, and heat resistance.Melt temperature is the temperature at which the plastic material is melted and injected into the mold. ABS typically has a melt temperature range of 200-250 [°C]. D2 steel is a high-carbon, high-chromium tool steel that is commonly used for injection molding tools. It has good wear resistance, toughness, and heat resistance. Filling time is the time it takes for the molten plastic to completely fill the mold cavity. The filling time can affect the quality and consistency of the part.After the mold cavity is filled, packing pressure is applied to compress the plastic material and ensure that it fills all the voids in the mold. The packing time can affect the part's strength, surface finish, and dimensional accuracy. Packing pressure is the pressure applied to the plastic material during the packing phase. The packing pressure can affect the part's strength and dimensional accuracy.Initial mold temperature is the temperature of the mold at the start of the injection molding process. The initial mold temperature can affect the part's cooling time, warpage, and shrinkage.Initial coolant temperature is the temperature of the coolant (water) that circulates through the mold to remove heat from the plastic material. The initial coolant temperature can affect the cooling time and the final part dimensions.Water is a common coolant used in injection molding. Other coolants, such as oil or air, can also be used depending on the application. The coolant type can affect the cooling time, part shrinkage, and surface finish.

The information of parametrs that affects on injection molding process as follows:

- Part material = ABS
- Melt temperature = 230 [°C]

- Mold material= D2 steel
- Filling time = 1.5 [s]
- Packing time = 10 [s]
- Packing pressure = 45 [MPa]
- Initial mold temperature = 29.6 °C
- Initial coolant temperature = 25 °C
- Coolant type = water

3.2 Experimental procedure for injection molding

By considering both i.e. conventional and CCC moldsexperiment on injection molding was performed. 29.6 °C starting reference mold temperature was considered for experimentation.Through molding trials of mold with conventional CCthe mean ejection temperature was recorded as 32°C. Then temperatures were taken at the cavity wall for 40 sec cycle time after taking 5 trials.

Same procedure were carrid out for CCC mold by setting different cycle times. Temperature measurements were taken from starting mold temperature to the ejection temperatureby setting different cycle time.

Temprature distribution for injection molding experiments was carried out.Total five experiments of each cycle time was carried out and mean ejection temp found out. Same procedure was fallowed upto mean ejection temperature reaches upto 32°C.

4. Results and discussion

4.1 Temperature distribution during experiments

Table 1. Experimental results for ejection temperature

Sr. No.	Cycle time (sec)	Mold Mean ejection temp (°C)
1	40 Conventional	32
2	40 CCC	29.7

3	35 CCC	30.2
4	30 CCC	30.9
5	25 CCC	31.2
6	22 CCC	31.4
7	20 CCC	31.8
8	18 CCC	32.1

As per industrial data cycle time required for manufacturing of enclosure part using conventional mold was 40sec. Experimental analysis (Table 1) shows that the mold ejection temperature reaches 32°C in 40 sec cycle time for conventional mold.Same experiments carried out on CCC mold for different cycle times 40,35,30,25,22,20, and 18 sec which obtained mean ejection temperature 29.7, 30.2, 30.9, 31.2, 31.4, 31.8, 32.1°C respectively as shown in Table 1. Cycle time was reduced step by step to increase the ejection temerature to the temperature obtained in the conventional mold.The shortest tested cycle time of 18 seconds results in an ejection temperature of 32.1°C, which is almost equal to the conventional value.Across all cooling cycles, the mold temperature shows a consistent pattern. Mold initial temperature begins at 29.5 °C and rised rapidly during injection stage. The temperature increase attains peak of 34.5 °C around 12 seconds, which is the maximum thermal load during the cycle. After highest peak temperature dropping to 32 °C.

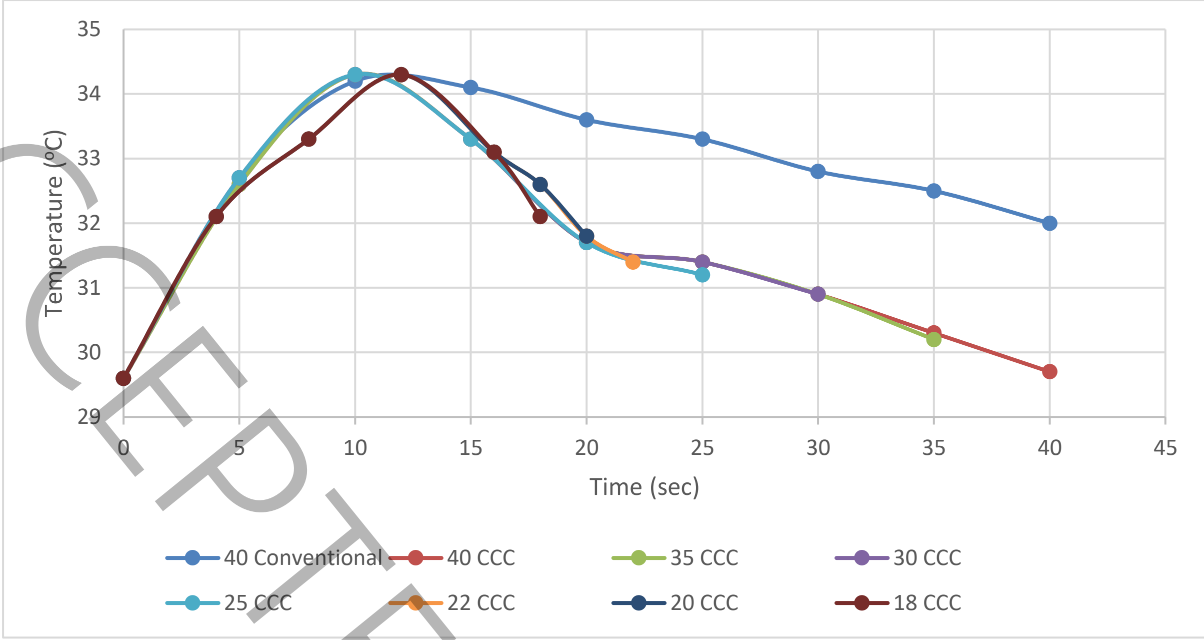


Figure 7: Temperature vs cooling time for different cycle time

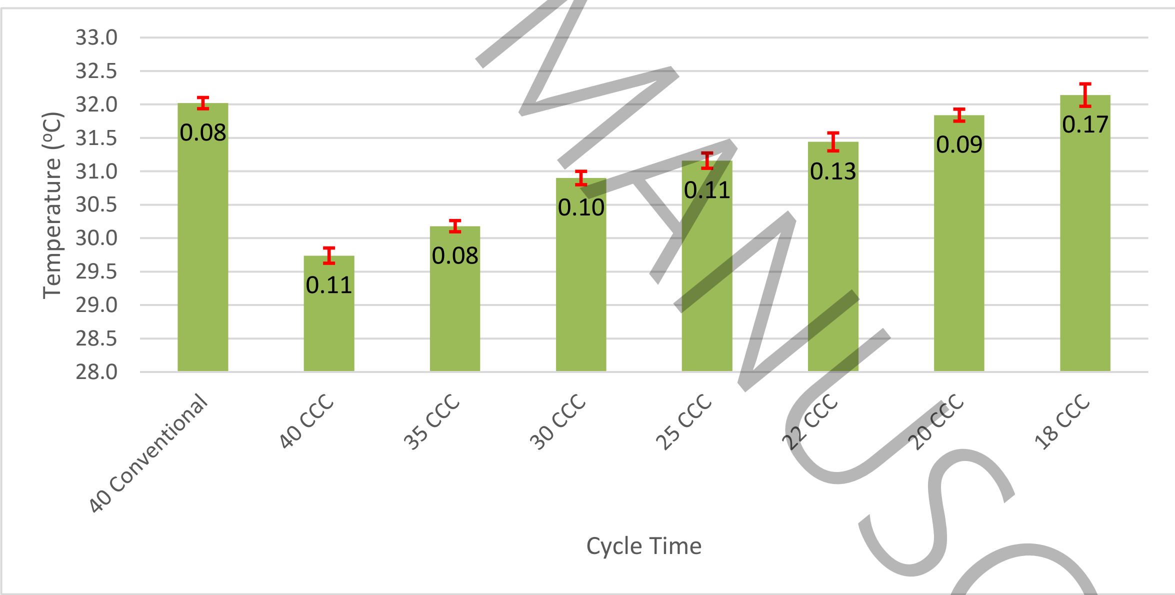


Fig. 8. Comparative results of mean ejection temperature for different cycle time with standard deviation

MGCCC is characterized by superior cooling properties due to two key factors. Firstly, the surface area of CCC is increased as compared to conventional CC, through the design modification of flow channels. This allows for a more efficient heat transfer by decreasing the distance through which heat is released. Secondly, heat transfer enhancement is achieved by modifying the pathway for heat conduction as per requirements. MGCCC follows the contour of the cavity, leading to a more even and reduced depth of heat transmission from the mold. The adoption of MGCCC also enhances the convection of the coolant and the conduction of the mold, resulting in improved heat dissipation from the molded part to the heat sink. Furthermore, the circulation of coolant through the MGCCC enhances the efficiency of heat transfer from the mold material to the coolant.

Experimental analysis demonstrated that MGCCC led to relatively lower mold temperature deviation, as indicated by the mold temperature vs. cooling time graphs (Fig. 7). Rapid heat flow facilitated faster cooling of the part, reducing cooling time from 30 sec to 8 sec and cycle time from 40 sec to 18 sec. MGCCC resulted in a total reduction of cooling time by 73.33% and cycle time by 55% as compared to conventional cooling.The error bars in the Fig. 8 represent ± one standard deviation obtained from five repeated measurements for each condition. The standard deviation valuesindicated above each bar. Standard devation values remain low (approximately 0.08–0.17 °C) which shows confirming good repeatability and reliability of the experimental measurements.

5. Conclusions

The findings of this study lead to the following conclusions.

- In the injection molding process, MGCCCs have the potential to provide better thermal distribution and reduce cooling time as compared to conventional CC.
- The use of MGCCC in injection molding results in a 73.33% reduction in cooling time as compared to conventional cooling.
- Cycle time is reduced by 55% when MGCCC is used as compared to conventional cooling.
- Implementation of MGCCC technique can lead to a reduction in cycle time and improvement in production rate.
- Future research should focus on improving the design of MGCCCs to further enhance the production rate.

References

[1] K. Eiamsa-Ard, K. Wannissorn, Conformal bubbler cooling for molds by metal deposition process, Computer-Aided Design, 69 (2015) 126-133.

[2] K. Au, K.M. Yu, A scaffolding architecture for conformal cooling design in rapid plastic injection moulding, The International Journal of Advanced Manufacturing Technology, 34(5) (2007) 496-515.

[3] H. Brooks, K. Brigden, Design of conformal cooling layers with self-supporting lattices for additively manufactured tooling, Additive Manufacturing, 11 (2016) 16-22.

[4] M. Khan, S.K. Afaq, N.U. Khan, S. Ahmad, Cycle time reduction in injection molding process by selection of robust cooling channel design, International Scholarly Research Notices, 2014(1) (2014) 968484.

[5] Y. Wang, K.-M. Yu, C.C. Wang, Y. Zhang, Automatic design of conformal cooling circuits for rapid tooling, Computer-Aided Design, 43(8) (2011) 1001-1010.

[6] S.Z.A. Rahim, S. Sharif, A.M. Zain, S. Nasir, R. Mohd Saad, Improving the quality and productivity of molded parts with a new design of conformal cooling channels for the injection molding process, Advances in polymer technology, 35(1) (2016).

[7] S. Feng, A.M. Kamat, Y. Pei, Design and fabrication of conformal cooling channels in molds: Review and progress updates, International Journal of Heat and Mass Transfer, 171 (2021) 121082.

[8] Y. Sun, K. Lee, A. Nee, Design and FEM analysis of the milled groove insert method for cooling of plastic injection moulds, The International Journal of Advanced Manufacturing Technology, 24(9) (2004) 715-726.

[9] D. Dimla, M. Camilotto, F. Miani, Design and optimisation of conformal cooling channels in injection moulding tools, Journal of Materials Processing Technology, 164 (2005) 1294-1300.

[10] A.B. Saifullah, S. Masood, Finite element thermal analysis of conformal cooling channels in injection moulding, in: Proceedings of the 5th Australasian congress on applied mechanics, Engineers Australia Brisbane, Qld., 2007, pp. 337-341.

[11] A. Saifullah, S. Masood, Cycle time reduction in injection moulding with conformal cooling channels, (2007).

[12] A. Safullah, S. Masood, I. Sbarski, Cycle time optimization and part quality improvement using novel cooling channels in plastic injection moulding, Society of Plastics Engineers, (2009).

[13] H.-S. Park, X.-P. Dang, Development of a smart plastic injection mold with conformal cooling channels, Procedia Manufacturing, 10 (2017) 48-59.

[14] H.-S. Park, N.H. Pham, Design of conformal cooling channels for an automotive part, International Journal of Automotive Technology, 10(1) (2009) 87-93.

[15] H.-S. Park, X.-P. Dang, Structural optimization based on CAD–CAE integration and metamodeling techniques, Computer-Aided Design, 42(10) (2010) 889-902.

[16] X.-P. Dang, H.-S. Park, Design of U-shape milled groove conformal cooling channels for plastic injection mold, International Journal of precision engineering and manufacturing, 12(1) (2011) 73-84.

[17] K. Altaf, A. Majdi Abdul Rani, V.R. Raghavan, Prototype production and experimental analysis for circular and profiled conformal cooling channels in aluminium filled epoxy injection mould tools, Rapid Prototyping Journal, 19(4) (2013) 220-229.

[18] Z. Shayfull, S. Sharif, A.M. Zain, R.M. Saad, M. Fairuz, Milled groove square shape conformal cooling channels in injection molding process, Materials and Manufacturing Processes, 28(8) (2013) 884-891.

[19] M.S. Shinde, K.M. Ashtankar, Additive manufacturing–assisted conformal cooling channels in mold manufacturing processes, Advances in mechanical engineering, 9(5) (2017) 1687814017699764.

[20] M.S. Shinde, K.M. Ashtankar, Cycle Time Reduction in Injection Molding by Using Milled Groove Conformal Cooling, Computers, Materials & Continua, 53(3) (2017).

[21] X.-P. Dang, H.-S. Park, Design of U-shape milled groove conformal cooling channels for plastic injection mold, International Journal of precision engineering and manufacturing, 12(1) (2011) 73-84.

[22] S.A. Jahan, H. El-Mounayri, Optimal conformal cooling channels in 3D printed dies for plastic injection molding, Procedia Manufacturing, 5 (2016) 888-900.

[23] S. Shen, B.B. Kanbur, C. Wu, F. Duan, Three-dimensional printing conformal cooling with structural lattices for plastic injection molding, Frontiers in Heat and Mass Transfer, (2024).

[24] R.J. Moffat, Describing the uncertainties in experimental results, Experimental thermal and fluid science, 1(1) (1988) 3-17.