

Cycle Time Reduction in Injection Molding by Using Milled Groove Conformal Cooling

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Abstract: This paper presents simulation study on Milled Grooved conformal cooling channels (MGCCC) in injection molding. MGCCC has a more effective cooling surface area which helps to provide efficient cooling as compared to conventional cooling. A case study of Encloser part is investigated for cycle time reduction and quality improvement. The performance designs of straight drilled are compared with MGCCC by using Autodesk Moldflow Insight (AMI) 2016. The results show total 32.1% reduction of cooling time and 9.86% reduction of warpage in case of MGCCC as compared to conventional cooling.

Keywords: Injection mold, conformal cooling channels, cooling simulation, rapid tooling.

1 Introduction

Injection molding technique is widely used for manufacturing of plastic parts. This cyclic characteristic process mainly utilized for the mass production. The cycle time of this process is mainly depended on filling, packing, cooling and ejection. Cooling time is the predominant factor because total 50-60% of cycle time required for cooling process [Eiamsa-Ard and Wannissorn (2015); Au and Yu (2007)]. Basically, cooling time of the process depends on geometry of the cooling channels used. More frequent use of straight drilled type of cooling channels in the industry results into more cooling time, no uniform cooling and defect prone. Due to these factors Conformal Cooling Channel (CCC) comes into existence. Cooling channel in shape of the part is called as CCC. The main advantages of CCC are, it reduces cooling time significantly and provide uniform cooling. Previous studies proved that CCC gives higher production rate and the accuracy of the molded part as compare to the conventional cooling channel (CC) [Brooks and Brigden (2016); Khan, Afaq and Khan et al. (2014); Wang, Yu and Wang et al. (2011); Rahim, Sharif and Zain et al. (2016)].

In conventional CC, the intricate shape of cavity in the mold is enclosed by straight drilled cooling lines. Due to variation in the distance between the surface of the mold cavity and cooling line causes non-uniform cooling. On the other hand, CCCs exactly

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matches with the surface of mold cavity by maintaining the unvarying distance among the mold cavity and cooling lines. Also, as compare to conventional CC, CCC provides superior even temperature distribution in the molded objects.

Rapid prototyping (RP) is the gold standard technique for the fabrication of the CCC in the mold. Also, development of CCC in the mold using CNC milling is another important technique however it is not that much advantageous than the RP technique. But the main advantage of the CNC milling is that it can be used for making complex CCCs in the mold of any material. Also by using high speed CNC machining and high material removal techniques machining time can be reduced. Free form CCC patterns can be designed using milled groove (MG) technique which helps to avoid the interference with another part available in the mold like ejector pins or other components. It is proved that CCC gives better efficiency in the rapid tooling than in the conventional CC. So nowadays researches have started working on the CCCs in hard tooling for injection molding. But design and development of CCC by hard tooling is the big challenge due to limitations in CNC machining techniques. [Sun, Lee and Nee et al. (2004)] used the MGCCC as an alternative in the hard tooling for injection molds and compared the results with the conventional CCs. Simulation study performed in the Abacus software. Steel is used as a mold inserts material to mold the ABS household iron and normal water at 30 °C as a coolant. The CCC was found better in terms of thermal distribution by reducing cooling time 54.2%.

[Dimla, Camilotto and Miani (2005)] used Moldflow software for optimizing the gating system and designing of cooling channels for uniform temperature distribution. The obtained result shows optimum cooling time using CCCs.

[Saifullah and Masood (2007)] have compared the efficiency of conventional CC and CCC by considering normal water as a coolant at 25 °C. The cooling time reduced by 20% by using CCC. In another study [Saifullah and Masood (2007)] has developed mold with CCC in polypropylene (PP) material for plastic canister. CCC and conventional CC was compared using Ansys software by considering normal water as a coolant at 25 °C. This optimization in design results 40% saving in cooling time and 35% saving in cycle time. In 2009 again [Safullah, Masood and Sbarski (2009)] investigated square section CCC in an injection-molding process for a plastic bowl and circular plastic parts and compared with conventional straight drilled CCs. The experiments were carried out only on uncomplicated circular shaped plastic parts. The mold with square section CCC was designed and fabricated using CNC milling in mild steel. Moldflow simulation results supported with the actual experimental results. The results revealed that with PP and ABS as the plastic materials and normal water at 25 °C as a coolant helps to reduce the cooling time by 35% and cycle time 20% with square section CCC as compared to conventional CCs. [Park and Pham (2009)] developed a group of small subs sets of CCCs to make the complete CCC structure for the injection mold for car parts with polyamide (PA06) material. The efficiency of the CCC and conventional CC were compared using Moldflow simulation software. The results showed that temperature distribution reduced by 75% i.e. from 6 to 1.5 °C using CCC.

In another study [Park and Dang (2010)] developed CCC for a radiator grill by using an array of baffles in the plastic injection molds. Steel P20 was used as the mold insert to obtain parts in ABS 750 material. Moldflow simulation software shows that the temperature distribution

in CC with an array of baffles was more unvarying as compared to conventional CC. Some researchers again performed the experiment in that CC with array of baffles used for plastic cover molded with Amoco 1046 (crystalline polymer). In that Moldflow analysis revealed that CC with array of baffles enhanced 49.41% temperature distribution variation (i.e. 4.3 from 8.3 °C). [Dang and Park (2011)] established U-shape MGCCC in the mold for car fender. Steel P20 used for the fabrication of mold insert to mold parts in Noryl GTX979. For simulation cooling time considered was 6.3sec and normal water at 25 °C as a coolant. Moldflow simulation software showed that U shaped MGCCC reduced warpage of the molded parts by 15.7%. [Altaf, Raghavan and Rani (2013)] presented a profiled CCC (PCCC) and compared with circular CCC. Experimental results showed that PCCC mold require less cooling time than the circular CCC. Saifullah et al. [Shayfull, Sharif and MohdZain et al. (2013)] proposed milled groove square section (MGSS) CCC for the front panel housing. Autodesk Moldflow Insight (AMI) 2012 simulation software showed that reduction by 6 to 8% in cooling time and 12 to 50% improvement in the variation of thermal distribution in case of MGSS CCC as compared to conventional CC. [Shinde and Ashtankar (2017)] reviewed RP assisted CCC in the mold for different manufacturing processes which shows CCC helps to reduce cooling time and cycle time, improve part deflection, and provide uniform thermal distribution. To determine the optimal process parameters CAE simulation is widely used and is recognised as one of the powerful tools based on Finite Element method (FEM) [Wei, Chen and Chen et al. (2016); Panthi and Saxena (2012); Shiah, Lee and Wang (2013); Essam, Mhamed and Thamar (2015); Ma, Sato and Takada (2015)].

In this paper the performance designs of straight drilled CC are compared with MGCCC by using Autodesk Moldflow Insight (AMI) 2016 software. A case study of Enclosure part is investigated for cycle time reduction and quality improvement. The simulation results show 32.1% reduction of cooling time and 9.86% reduction of warpage in case of MGCCC as compared to conventional cooling. MGCCC has a more effective cooling surface area which helps to provide efficient cooling as compared to conventional cooling.

2 Physical and mathematical modelling

Physically, heat transfer during the cooling phase in the injection molding process represents a complex problem. Thus, some assumptions are applied to simplify the mathematical model. After several cycles, the molding process reaches a steady state at which the average temperature of the mold is constant. This average temperature is used for the mold and transition analysis of the molded parts. A heat balance is reached when the heat flux from the molten plastic, which is transferred to the mold, equilibrates with the heat flux from the mold. The heat balance is expressed by the following equation

$$Q_m + Q_c + Q_e = 0 \quad (1)$$

Where Q_m , Q_c and Q_e are the heat flux from the molten plastic, the heat flux exchange with coolant, and environment, respectively. The heat from the molten plastic which transferred into a mold is taken away by coolant circulation (forced convection), transferred into the mold plate (conduction), and environment (convection and radiation). The heat loss through the mold exterior surfaces in the real application is less than 5%,

and thus these faces can be treated as adiabatic. By neglecting the heat lost to the surrounded environment, the equation of energy balance can be simplified as

$$Q_m + Q_c = 0 \quad (2)$$

The heat flux transferred into the coolant from the molten plastic can be calculated as

$$Q_m = 10^{-3} [(T_M - T_E) C_p] \rho_m \frac{s}{2} x \quad (3)$$

Where T_M is the melt temperature, T_E is the ejection temperature, C_p is the specific heat of the plastic material, ρ_m is the melt density, s is the part thickness, and x is the pitch of the cooling channels.

The cooling time t_c , which is the time of heat flux from the mold exchanges with coolant, is expressed as

$$Q_c = 10^{-3} t_c \left(\frac{1}{10^{-3} \alpha \pi d} + \frac{1}{k_{st} S_e} \right)^{-1} (T_W - T_C) \quad (4)$$

Where α is the heat transfer coefficient of water, k_{st} is the thermal conductivity of the mold steel, T_W is the mold temperature, and T_C is the coolant temperature.

The effect of the cooling channels position on the heat conduction is considered by applying shape factor, S_e

$$S_e = \frac{2\pi}{\ln \left[\frac{2x \sinh\left(\frac{2\pi y}{x}\right)}{\pi d} \right]} \quad (5)$$

Where x is the pitch of the cooling channels, y is the distance from center of the cooling channels to the mold surface, and d is the diameter of the cooling channels.

The heat transfer coefficient of water is calculated by

$$\alpha = \frac{31.395}{d} R_e^{0.8} \quad (6)$$

The Reynolds number, R_e is defined as

$$R_e = u \frac{d}{\nu} \quad (7)$$

Where u is the velocity of the coolant, and ν is the kinematic viscosity of the coolant.

The cooling time of the molded part in the form of plate is calculated as

$$t_c = \frac{s^2}{\pi^2 \alpha} \ln \left[\frac{4}{\pi} \left(\frac{T_M - T_W}{T_E - T_W} \right) \right] \quad (8)$$

Where,

$$\alpha = \frac{k_m}{\rho_m C_p} \quad (9)$$

With α is the thermal diffusivity, and k_m is the thermal conductivity of the plastic material.

By combining Eqs. (2) to (9), the cooling time, t_c is calculated iteratively from the heat balance, $Q_m = Q_c$

$$\frac{[c_p(T_M - T_E)]\rho_m \frac{x}{2} \left\{ \frac{1}{2\pi k_{st}} \ln \left[\frac{2x \sinh\left(\frac{2\pi y}{x}\right)}{\pi d} \right] + \frac{1}{0.03139\pi R_e^{0.8}} \right\}}{T_W - T_C} = \frac{\rho_m c_p S^2}{\pi^2 K_m} \ln \left[\frac{4}{\pi} \left(\frac{T_M - T_W}{T_E - T_W} \right) \right] \quad (10)$$

$$t_c = \frac{[c_p(T_M - T_E)]\rho_m \frac{x}{2} \left\{ \frac{1}{2\pi k_{st}} \ln \left[\frac{2x \sinh\left(\frac{2\pi y}{x}\right)}{\pi d} \right] + \frac{1}{0.03139\pi R_e^{0.8}} \right\}}{T_W - T_C} \quad (11)$$

It is important to understand the reaction of thermal behavior physically and mathematically in injection mold. The cooling time of the molded part in Eq. (8) shows that the cooling channels configuration does not directly affect the cooling time. However, it affects the mold surface temperature, indirectly affecting the cooling time. Equation (11) expresses the relationship between cooling time and the variables related to the cooling channels configuration which are pitch of the cooling channels x , distance from the center of the cooling channel to the mold surface y , and diameter of the cooling channels d . So, in order to improve the cooling time, the configuration of cooling channels needs to be improved. Equation (11) is only suitable in calculating the cooling time at merely one point. In this study, Eq. (8) is used to calculate the cooling time for Encloser part as a reference to compare the results from simulation

3 Methodology

3.1 Part and mold design

Case study was taken from medium scale industry “mold craft engineer’s pvt. Ltd pune” for improvement of the cooling system applied to a plastic part. The component selected for the study work is an injection molded plastic enclosure in ABS thermoplastic. Cooling time taken for this part with the available mold in the industry with conventional CC is 30 sec and cycle time 40 sec. Figure 1 shows the 3D CAD design of the plastic component having length 112.5mm, width 40mm, height 40mm and 1.5mm is the thickness of the part.

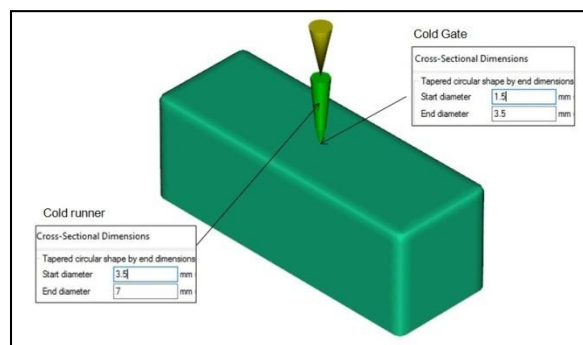


Figure 1: Part model with feed system

3.2 Milled groove CCC design

The shape of MGCCC can be designed by considering cavity as a reference. The main

aspects that required to be considered during the design stage are the profile and outline of CCC. The CCC should be design in such a way that it avoids the interference with other mold components like sub-insert, sprue, runner, and ejector pins. The cavity plate split into two plates so that cooling channels opens from bottom side so through milled groove method CCC can be manufactured. In this case selection of parting line between two split plates is important and this parting line differs from part to part. Distance between cooling channel and part cavity was taken 8 mm and dimension of cooling channel which is rectangular milled groove was 8×55 mm from bottom side. Figure 2 shows conventional CC and MGCCC used for analysis.

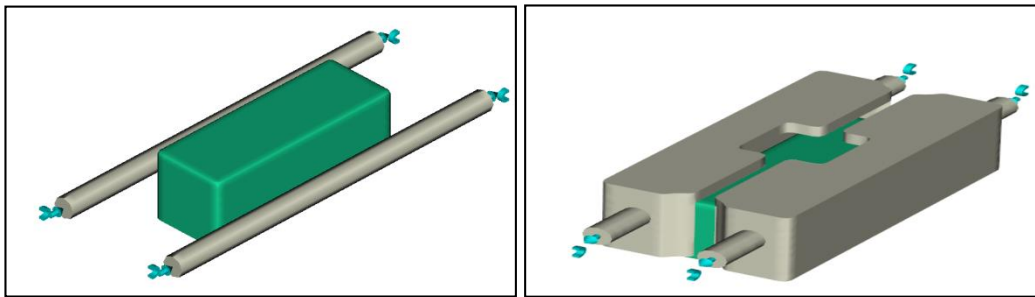


Figure 2: Types of cooling (a) Conventional (b) conformal cooling channels (CCC)

3.3 Moldflow analysis for plastic injection molding

In this study, simulation was performed in the injection molding software, Moldflow given in the Figure 3. For the cooling analysis a uniform initial temperature (i.e. the melt temperature) was assumed for the melt of polymer. In order to estimate cooling time of part model, auto set cooling time command in Moldflow Insight 2016 was applied for cool (FEM) analysis. The following injection mold conditions were set for analysis.

- Part material = ABS
- Mold material = D2 steel
- Melt temperature = 230 °C
- Filling time = 1.5 sec
- Packing time = 10 sec
- Packing pressure = 45 MPa
- Initial mold temperature = 25 °C
- Initial coolant temperature = 25 °C
- Coolant type = water

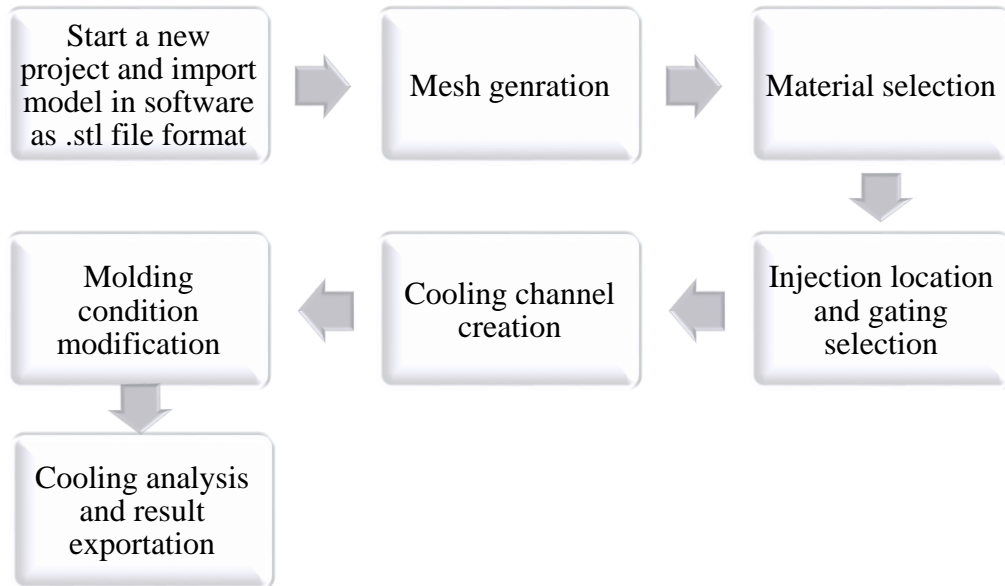


Figure 3: Steps of plastic part analysis in Moldflow Insight software

4 Results

4.1 Cooling time

Cooling time result is produced by a cool analysis which shows the time required to reach the ejection temperature, which is measured from the start of the cycle. At the start of the measurement, the part is assumed to be filled with material at its melt temperature (T_M). The cycle time increases due to more time require for cooling. For this study the cooling time for the conventional CC was obtained as 9.583 sec and for the MGCCC was 6.506 sec (Figure 4).

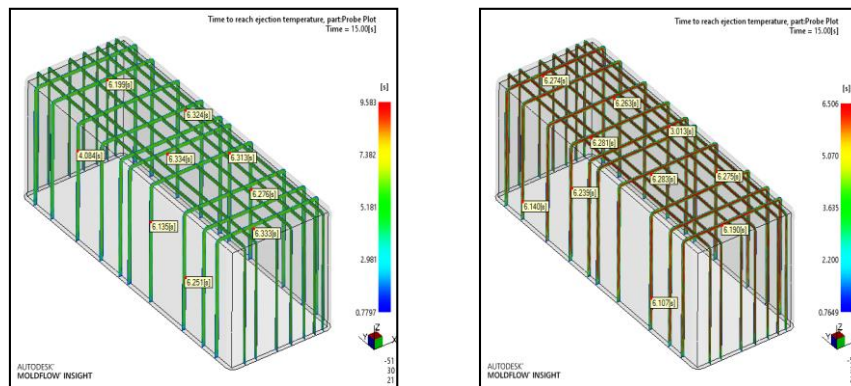


Figure 4: Results of cooling time with: (a) conventional and (b) MGCCC

4.2 Cooling circuit temperature

The mold-circuit interface temperature (averaged) result is an elemental result over the cycle, calculated using the finite element method (FEM). This result shows the temperature of the metal cooling circuits. The temperature distribution should be evenly distributed on the cooling circuits. The temperature will increase when the circuit nears to the part, and these hotter regions will also heat the coolant. The cooling circuit temperature achieved for conventional cooling channel was 26.23 °C and for the CCC was 30 °C respectively (Figure 5).

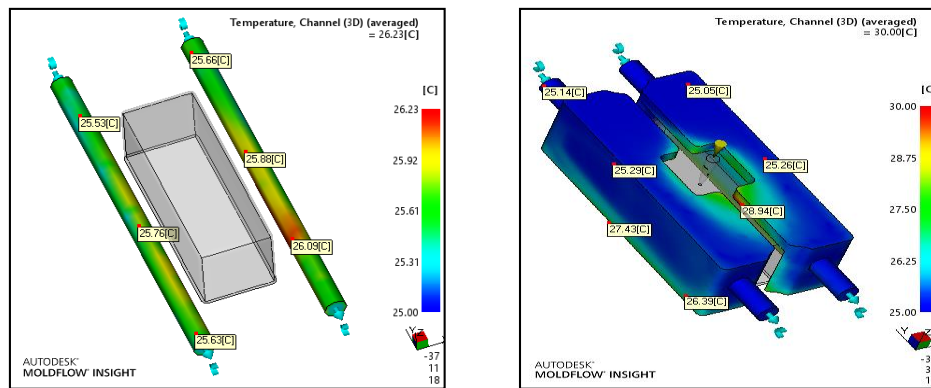


Figure 5: Results of cooling circuit temperature with: (a) conventional and (b) MGCCC

4.3 Mold interface temperature

The mold-cavity interface temperature (averaged) is the cycle averaged temperature of the mold, at the mold-cavity interface, calculated using the FEM. The mold interface temperature for conventional cooling channel was found 62.92 °C and for the CCC was 61.48 °C respectively (Figure 6).

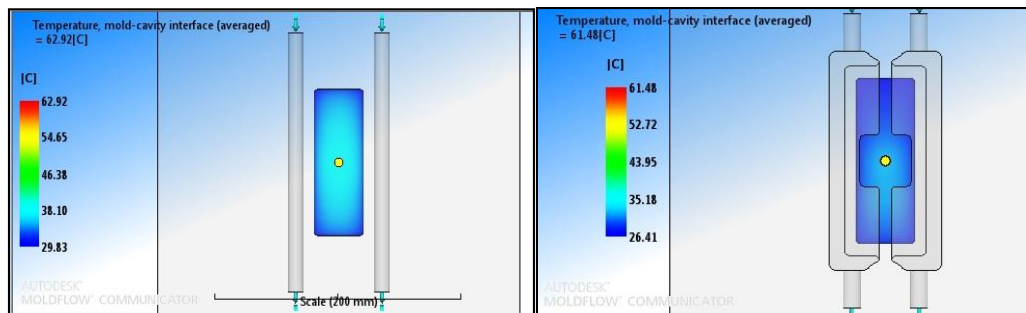


Figure 6: Results mold interface temperature with: (a) conventional and (b) MGCCC

4.4 Warpage analysis

The deflection at each node of the part is calculated using Warp or Stress analysis. In warpage analysis results are calculated by a best fit technique, where the original geometry and the deformed geometry are overlapped in such a way that they best fit together and obtained error

is considered as warpage. In this study warpage from all direction for conventional cooling channel was found 1.520 mm and for the MGCCC was 1.370 mm respectively (Figure 7).

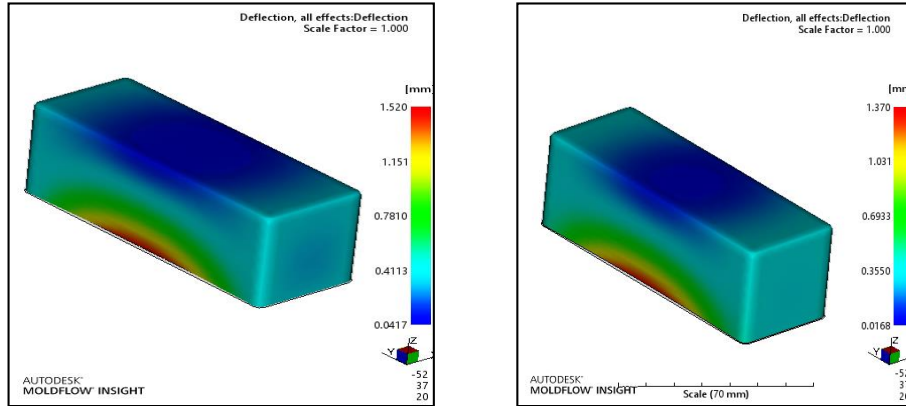


Figure 7: Results of warpage in all directions with: (a) conventional and (b) MGCCC

5 Discussion

MGCCC can be explained with better cooling features, based on two important factors. The first factor is the surface area of CC. The conventional CC has the least surface area. Any modification from the conventional CC to CCC increases the surface area. The design modification of flow channel facilitates to decrease the distance through which heat is to be released. The second factor of CC is heat transfer enhancement. In MGCCC the pathway for heat conduction can be modified as per requirement to obtain better results. The MGCCC follows the contour of the cavity which results more uniform and shorter the heat transmission depth from the mold. Heat discharge from the molded part to the heat sink can be improved by improving the convection in the coolant and conduction in the mold. The better heat transfer from the mold material to the coolant can be possible by, passing coolant through the MGCCCs due to improvement in the heat conduction path. In this analysis it is found that the more rapid heat flow ends to more faster cooling of the part. The comparative simulation result shows that MGCCC provide better results as compared to conventional CC as context to cooling time, cooling circuit temperature, mold interface temperature and warpage in all direction (Table 1). Presently in the industry cooling time used for conventional CC was 30 secs and from analysis cooling time for conventional CC obtained 9.583 sec and for MGCCC 6.506 sec. MGCCC reduces warpage from 1.520 mm to 1.370 mm as compared to conventional CC.

Table 1: Comparative results of all parameters of conventional CC and MGCCC

Parameters	Conventional CC	MGCCC
Cooling time	9.583 sec	6.506 sec
Cooling circuit temperature	26.23 °C	30 °C
Mold interface temp	62.92 °C	61.48 °C
Warpage all directions	1.520 mm	1.370 mm

6 Conclusion

According to the results obtained in the analyses conducted in this study, the following main conclusions can be drawn

- MGCCC gives better results as compared to conventional cooling CC.
- Total 32.1% reduction of cooling time obtained in case of MGCCC as compared to conventional CC.
- Total 9.86% reduction of warpage obtained in case of MGCCC as compared to conventional CC.
- MGCCC improves productivity as well as quality of the parts produced from injection molding.

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