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ORIGINAL ARTICLE

Thermal–structural analysis of bi-metallic conformal cooling for injection moulds

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Abstract In injection moulding process, cooling time greatly affects the total cycle time. As thermal conductivity is one of the main factors for conductive heat transfer in cooling phase of IMP, a cooling channel made by higher thermal conductive material will allow faster extraction of heat from the molten plastic materials, thus resulting in shorter cycle time and higher productivity. The main objective of this paper is to investigate bi-metallic conformal cooling channel design with high thermal conductive copper tube insert for injection moulds. Thermal–structural finite element analysis has been carried out with ANSYS workbench simulation software for a mould with bi-metallic conformal cooling channels and the performance is compared with a mould with conventional straight cooling channels for an industrial plastic part. Experimental verification has been carried out for the two moulds using two different types of plastics, polypropylene (PP) and acrylonitrile butadiene styrene, in a mini injection moulding machine. Simulation and experimental results show that bi-metallic conformal cooling channel design gives better cycle time, which ultimately increases production rate as well as fatigue life of the mould.

Keywords Bi-metallic conformal cooling · Injection moulding · Copper tube · Cooling time · Finite element analysis

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1 Introduction

Injection moulding is one of the most important manufacturing processes available in plastic manufacturing industries. With the broader use of plastics parts for consumer products, the injection moulding process (IMP) has been renowned as the most widely used mass manufacturing process. The moulding cycle of IMP consists of mould closing, injection/holding, cooling, mould opening and product removal stages. In any injection moulding cycle, cooling stage is the dominant component, and generally accounts for 50% to 70% of the moulding cycle time [1]. Thus the production rate is generally affected by the cooling channel design in the mould. In a typical mould, cooling channel design is the most complex as well as vital factor for economical performance of injection moulding. The cooling system of an injection mould can be divided mainly into three categories, cavity cooling, core cooling and sometime cooling of the stripper plate. There are many types of cooling channels that have been invented by mould designers and researchers since the invention of injection moulding. Among all types of cooling channels, straight-drilled cooling channel (SDCC) system is the cheapest and the most popular cooling method the injection moulding companies are using. Figure 1 shows the cross-sectional view of an injection mould with the location of SDCC around a plastic part cavity.

SDCCs are also used as baffles and bubblers for cooling of cores in the injection moulds. These cooling channels are also machined using drilling or boring [2, 3]. They have a straight flow path and a circular cross-section. Baffles are used for cooling of cores with highly convex geometry [4]. In baffle design, holes are first bored to the rear face of the core, and the lower end of each hole is plugged. The borings are then interconnected by another hole drilled from a side

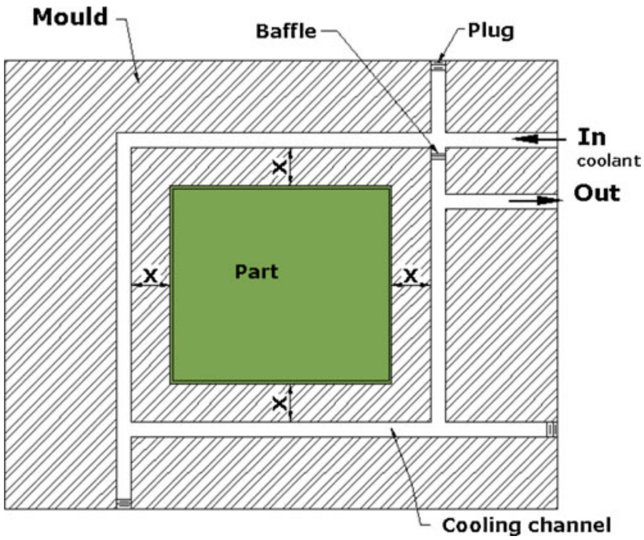

Fig. 1 Sectional view of SDCC layout in a mould cavity

face. To ensure that the coolant flows into each hole, blades are fitted in each hole and act as baffles to divert water to the top of each hole. To achieve more efficient cooling, twisted baffle are applied in practice. Bubbler is another popular method used in the core cooling. Bubblers are similar to baffles, but instead of flowing from one side to the other, the incoming coolant passes through a tube fitted in the centre of the hole and returns to the outlet through the passage in between the tube and the hole. But, it is more expensive [1].

There has been significant improvement of cooling channel design since the innovation of CAD/CAM/CAE and Rapid Tooling (RT) technology. Since early 1980s, mould cooling simulation provided substantial attention with different methods to predict the temperature distribution of the mould and part in injection moulding process [5–9]. In 1999, Jacobs [10] described the use of conformal cooling channels in an injection mould insert. In that study, channels were built by electroformed nickel shells, and finite element simulation shows that the conformal cooling channel formed by copper duct bending can increase the uniformity of mould temperature distribution. It can also decrease the cycle time and part distortion. As common injection moulding materials, such as steel, have not been included in his research, the application is only restricted to copper or nickel duct bending. Xu et al.[11] in 2001 applied the 3D printing process to fabricate injection moulds with conformal cooling channels inside. Cha and Park [12] in 2007 described some conformal cooling methods, with direct metal laser sintering and spray-formed tooling process. However, the increase in complexity of part geometries hinders the realization of conformal cooling layout fabrication in some RT processes. Therefore, it is worthwhile to investigate further other effective approaches in order to obtain better cooling performances. One such approach is to use materials with higher thermal conductivity in injection moulds. Copper is a well-known material with higher thermal conductivity than steel while its strength is generally lower than steel. Attempts have been made by some researchers to use copper or high strength copper alloys in dies to allow faster extraction of heat to reduce cycle time. Kelly et al. [13] in 2011 have investigated the performance of high strength copper alloy mould tool materials in injection moulding with regard to cycle time, part quality and energy consumption in comparison with tool steel. They concluded that copper alloy tooling can achieve significant reduction in cycle time without affecting process or part quality. Beal et al. [14] in 2007 have used the concept of functionally graded materials to develop tooling inserts made of copper and steel using selective laser melting technique. They observed that as copper was added to tool steel, it provided more efficient heat transfer but it had less capacity to absorb steel.

This research work presents a novel cooling system design involving bi-metallic cooling channels in injection moulds, with high thermal conductive copper tube insert (CTI) used to replace conventional straight cooling channel (CSCC). It is expected that a copper tube insert in the channel will further enhance heat transfer process during cooling time of injection moulding. Bi-metallic cooling with CTI can also be used for baffles and bubblers, but it may be more suitable for plastic parts that do not have curved surface other than round or fillet, and as a result such cooling channel will maintain equidistance from the cavity surface as shown by distance x, in Fig. 1. According to Fourier's law of conduction of heat transfer, the distance that heat is conducting through is inversely proportional to the total conduction of heat transfer energy. As a result, uniform heat transfer will take place in the moulding process. In this paper, the performance of bi-metallic straight cooling channel (BSCC) and bi-metallic conformal cooling channel (BCCC), with two different thicknesses of CTI, have been investigated for a cavity mould and core mould with bubblers, through thermal–structural finite element analysis, supported by experimental verification.

2 Design of bi-metallic cooling channels

The part chosen for this study is an injection moulded plastic canister (0.5 L) made of polypropylene (PP) thermoplastic. Actual mould for this part is of six cavities mould, but only single cavity type has been considered for this investigation. Figure 2 shows the CAD model of the plastic part, which has outer dimensions of 160, 120 and 48 mm with wall thickness of 2 mm and the weight of the part is 69.5 g. Note that the part has curved surfaces at the corners.

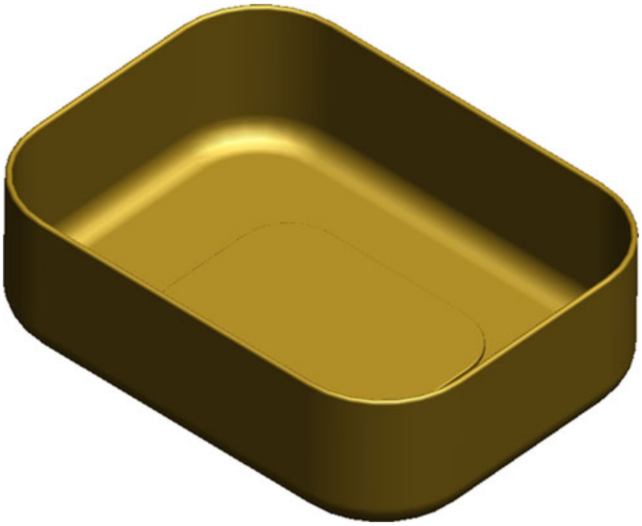

Fig. 2 CAD model of plastic canister

Figure 3 shows the cavity and core moulds for the plastic part with CSCC including bubbler cooling in the core. Figure 4a shows the design of BSCC with CTI fitted. Figure 5a shows the design of BSCC with CTI fitted. CTI has also been used for bubbler system of core in both cases. Two different thicknesses, 2 and 3 mm of CTI, have been used for BSCC and BCCC. The difference between BSCC and BCCC design is that in case of BSCC, the channels are straight with no curved corners as shown in Fig. 4b, while in case of BCCC, the channels have curved shape corners, which are conformal with the plastic part corners, and as a result, these cooling channels maintain same distance from surfaces of the plastic part as shown in Fig. 5b. Table 1 gives the names and abbreviations of five types of cooling channels that will be used in this study. The outer dimensions of the single cavity mould are height of 232 mm, diameter of 300 mm and the inner diameter of cavity and core cooling channels are 12 and 15 mm, respectively.

3 Thermal–structural finite element analysis

Thermal–structural FEA of the proposed bi-metallic cooling channel moulds has been carried out with ANSYS workbench simulation software to demonstrate that such mould can extract faster heat from molten plastic material in injection moulding process, as well to check the robustness and longevity of the mould with such bi-metallic channels. In the analysis, the mould material was taken Stavax Supreme (SS), a stainless steel tool alloy, as recommended by a local mould manufacturer, and the cooling channel insert material was high thermal conductive beryllium–copper (BC) alloy, which is capable of transferring heat at a higher rate than steel. Table 2 shows a comparison of the physical properties of SS and CA.

ANSYS workbench simulation software is capable of simulating both the steady state and transient behaviour when subjected to different structural and heat loads. In this simulation, transient analysis has been used because in injection moulding, mould experiences variable temperature, pressure and forces. Automatic meshing (elements that are automatically created depending on the physical structure) with tetrahedral elements have been used. Fine relevance centre and medium smoothing has been applied in the meshing.

In the simulation process first, the transient thermal analysis has been carried out in the mould assembly and then thermal analysis results have been coupled with transient structural analysis, to calculate equivalent stress (von Mises) in thermal loading conditions. In the moulding process of thermoplastics, three types of heat transfer take place:conduction through mould, convection in the cooling medium and outer surface of the mould, and finally, radiation heat transfer, which is of very negligible amount. In this analysis, radiation heat transfer has been neglected. For thermal analysis, conduction and convection heat flux (heat energy per unit area) have been used as a boundary condition.

Conduction heat transfer energy, which is of vital importance in IMP, has been calculated by Eq. 1, as described in [15]. This equation which is suitable for steady-state one-dimensional heat transfer process has been derived from Fourier conduction heat transfer equation for composite material. Though Eq. 1 has been used to calculate conduction heat flux values as an input boundary condition, tabular values of heat flux for different timing of the moulding cycle have been used rather than constant

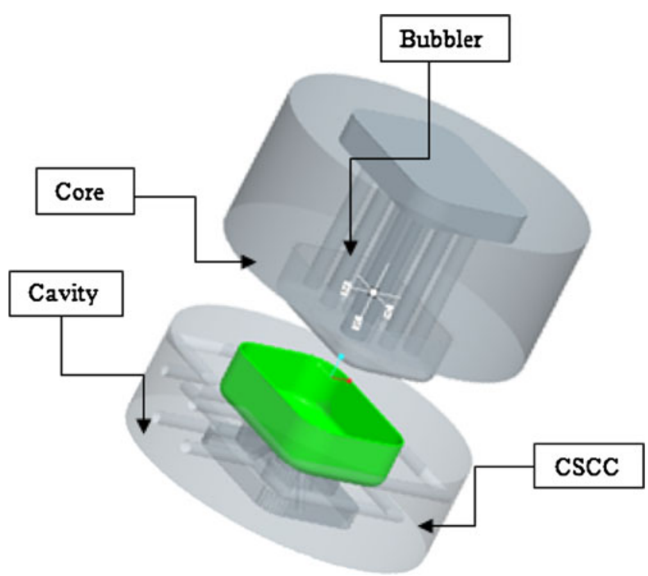

Fig. 3 Cavity and core with conventional straight cooling channel (CSCC)

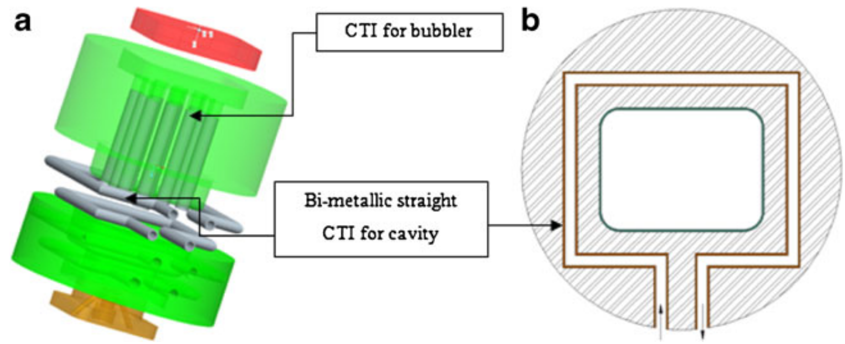

Fig. 4 **a** Bi-metallic straight cooling channel (BSCC) with copper tube insert (CTI) in core and cavity; **b** sectional top view of cavity mould, showing the orientation of BSCC in the mould

values to get the transient heat transfer effect in the simulation process.

$$\text{Conduction heat energy, } Q_C = \frac{Ti - Tw}{\frac{l_s}{k_s A} + \frac{l_c}{k_c A}} \quad (1)$$

where,

- k_s Thermal conductivity of SS
- k_c Thermal conductivity of CTI
- A Cross-sectional area through heat is transferring
- T_W Inside surface temperature of CTI.
- T_i Temperature of cavity or core surface interface with plastic
- l_s Distance from cavity or core surface to corresponding CTI outer surface
- l_c Thickness of CTI

Similarly, Eq. 2 [13] has been used to calculate convective heat transfer energy inside the cooling channels surface.

$$\text{Convective heat energy, } Q_h = h_c A (T_W - T_C) \quad (2)$$

where,

- A Surface area of the cooling channels in contact with flowing fluid
- T_w Average temperature of the inside surface of CTI
- T_C Average temperature of the coolant
- h_c Convection heat transfer coefficient

The convection heat transfer coefficient h_c, has been calculated using Eq. 3, based on Dittus-Boetler [16] correction equation for forced convective heat transfer by turbulent flow in a circular pipe. These coefficients were calculated to be 5,397 and 5,709 watt/m^2 °C for core and cavity cooling channels respectively.

$$h_c = 0.023 \frac{k}{D} \mathrm{Re}^{0.8} \mathrm{Pr}^{0.4} \quad (3)$$

$10{,}000 < \mathrm{Re} < 120{,}000$ and $0.7 < \mathrm{Pr} < 120$

where,

- h_c Heat transfer coefficient
- k Thermal conductivity of coolant (water)
- D Diameter of the cooling channels
- Re Reynolds Number
- Pr Prandtl Number

Other thermal boundary conditions are the natural convection on the side surface of the cavity mould which is exposed to the air and the channel around the sprue bush, in which, air has been passed for additional cooling of sprue bush. This additional cooling of sprue bush is necessary as it carries the hot molten plastic material for injection into the mould cavity. Convection co efficient has been used as boundary conditions in these cases, and the values for these are 5×10^{-6} Watt/mm^2 °C and 6.083×10^{-3} Watt/mm^2 °C as recorded by local mould manufacturer. So altogether, eleven input boundary conditions have been used for thermal

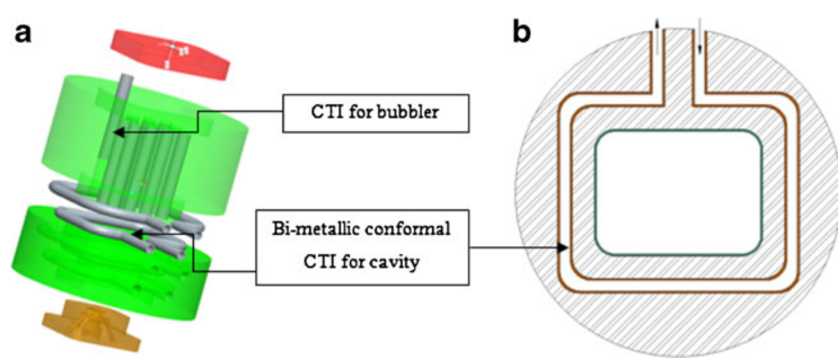

Fig. 5 **a** Bi-metallic conformal cooling channel (BCCC) with copper tube insert (CTI) in core and cavity; **b** sectional top view of cavity mould, showing the orientation of BCCC in the mould

Table 1 Different cooling channels and their abbreviations

Type of cooling channel	Description
CSCC	Conventional straight cooling channel
BSCC 2-mm CTI	Bi-metallic straight cooling channels with 2-mm copper tube insert
BSCC 3-mm CTI	Bi-metallic straight cooling channels with 3-mm copper tube insert
BCCC 2-mm CTI	Bi-metallic conformal cooling channels with 2-mm copper tube insert
BCCC 3-mm CTI	Bi-metallic conformal cooling channels with 3-mm copper tube insert

analysis, seven for conduction heat flux (heat flux for SS, RS and BS surfaces for both core and cavity side, and SHS surface shown in Fig. 6), two for convection heat flux (heat flux for CoCs and CaCS surfaces shown in Fig. 6) and two for convection coefficient.

Figure 6 shows the cross section of the entire mould assembly, showing different interface surfaces. In order to calculate different heat fluxes using Eqs. 1 and 2, it is necessary to know the variable temperature, T_{w}, T_{i} and T_{C} at these different surfaces (the interface of plastic and mould cavity, at the interface of cooling channel inner surface and cooling medium), as shown in Fig. 6. To get these temperature values, a complete injection moulding flow simulation (cool+flow+pack+warp analysis) has been carried out separately with Autodesk Moldflow Insight (AMI) software. Flow simulation with AMI, also gives the values of the variable injection pressure at different surfaces (surfaces that plastic materials are in contact during injection moulding process as shown in Fig. 6) and clamping forces, which will be used as boundary conditions for thermal–structural analysis. For plastic flow analysis with AMI, dual domain mesh has been used with 9,228 elements, mould and melt temperature were 50°C and 250°C respectively, total cycle time was 20 s (9, 8 and 3 s for injection/hold on, cooling and ejection, respectively), plastic and mould materials were PP and SS stainless tool steel correspondingly. Pure water with a temperature of 10°C has been used as coolant. Table 3 shows the temperature values at six different times (from 0 to 17 s) of the moulding cycle at different interface surfaces of the assembly mould (as shown in Fig. 6) for the case of CSCC, from AMI flow simulation. Similar values of temperature have been obtained for other four cases of bi-metallic cooling channel case. Values indicate that all four main interfaces cool down gradually during the moulding cycle. Average values of the temperature for each surface were taken for heat flux calculation using Eqs. 1 and 2. For a particular surface, same temperature values have been taken for core and cavity side because there is not much difference between them. Table 4 shows the heat flux values calculated at different times (0 to 17 s) and used as boundary conditions for various interface surfaces for CSCC case. Similar values of heat flux have been calculated for other four cases of bi-metallic cooling channel.

Result of transient thermal analysis, which includes the temperature response over the mould assembly for entire cycle, has been imported in the interface of transient structural analysis to perform thermal–structural FEA analysis. For structural analysis, four types of boundary conditions have been used, which are fixed support (bottom of the mould), injection pressure, clamping force (top of the mould) and the temperature from the thermal analysis. Table 5 gives the values of variable clamping forces and injection pressure for different surfaces for entire cycle, recorded from AMI flow simulation.

4 Results and Discussion

From transient thermal analysis, temperature distribution has been found for entire mould. Figures 7a, 8 and 9 show the comparative temperature distribution for all cooling channel moulds. In case of CSCC, after 1 cycle (20 s), temperature of the mould ranges from a minimum 13°C to maximum 74°C (Fig.7a), whereas, for BSCC and BCCC CTI, average minimum to maximum temperature ranges

Table 2 Properties of Stavax Supreme (SS), and copper alloy (BC)

Material	Composition (%)	Rockwell hardness (HRC)	Thermal conductivity (W/m×°C)	Density (kg/m^3)	Thermal expansion coefficient (×10^{-6}/°C)	Tensile strength S_{ut} (MPa)
Stavax Supreme (HRC 50, AISI 420 modified)	Cr–Ni–Mo–V (4.5–0.7–0.65–0.2)	50	20	7,740	11 Bubbler cooling	1,780
Copper alloy (beryllium–copper)	Cu–Br–Ni (balance–1.6–0.2)	40	400	8,350	18	400

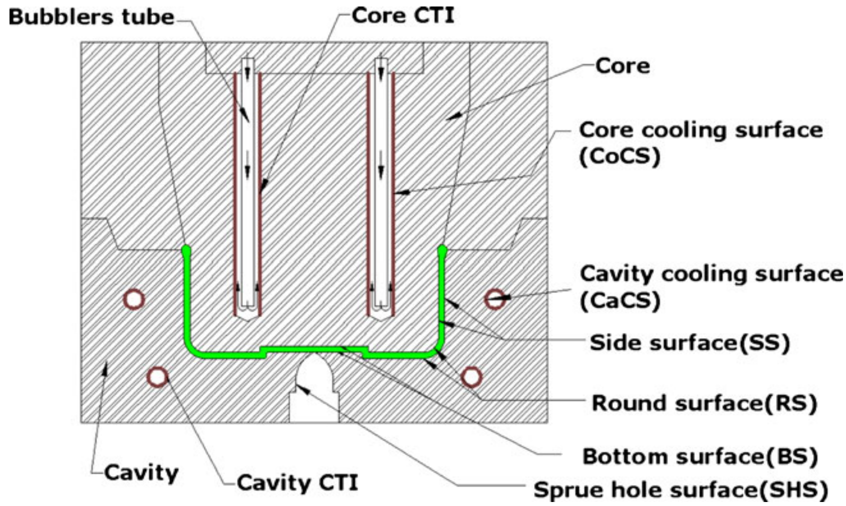

Fig. 6 Cross sectional assembly mould, showing different interface surfaces

from 16°C to 64°C (Figs. 8 and 9), respectively. So by using bi-metallic cooling channel, temperature reductions by 10°C could be possible, which ultimately reduces cycle time. Now, among the bi-metallic types, both the BSCC and BCCC, with CTI of 2 and 3 mm thickness, show almost similar results. But as copper is weaker than tool steel in strength, it is necessary to check the robustness of the moulds with bi-metallic cooling channels. Therefore, transient thermal–structural analysis has been carried out to verify whether weaker metal insertion (copper tube) may cause fatigue failure of the mould, before the required number cycles it can operate.

In order to determine the fatigue life, it is necessary to determine the maximum equivalent stress distribution for each case. Figures 7b, 10 and 11 give the equivalent stress or von Mises stress (S_{es}) distribution in the mould at 4.45th second of the cycle time, from transient thermal–structural FEA analysis, for different cooling configuration moulds. Table 6 also gives the peak values of maximum von Mises stress during injection cycle for different moulds. Results of Table 6 indicates that, in case of CSCC, the peak values of maximum equivalent stress or von Mises stress (S_{es}) is 675.7 MPa, which the mould experiences at about 4th second of the cycle time. On the other hand, for 2-mm CTI, this value is around 650 MPa, for both BSCC and BCCC. For 3-mm CTI, this value is a bit higher, which is around 685 MPa for both BSCC and BCCC.

It is noted that all these peak values of maximum equivalent stress in the mould are much less than the ultimate tensile strength (1,780 MPa) of the Stavax Supreme mould, therefore, indicating structurally safe design of moulds with bi-metallic cooling channels. We will use these peak values of stress, to calculate the fatigue life of the moulds in each case, to find out which type of bi-metallic cooling channel will be the best from fatigue failure point of view.

Using the equivalent stress and high cycle fatigue formula, which is given by Eq. 4 [17], the fatigue life of the mould or the number of cycle (N) mould can operate before failure can be calculated as follows

$$\text{Number of cycle before failure}, N = (S_{es}/a)^{1/b} \qquad (4)$$

where, $a=(f\times S_{ut})^2/S_e$ and $b=-(1/3)\times\log(f\times S_{ut}/S_e)$; $10^3<N<10^7$

S_{es} Equivalent stress or von Mises stress
S_{ut} Ultimate tensile strength
S_e Elastic strength
f Constant

Table 3 Temperature values at different surfaces for CSCC moulds from the AMI analysis

Interface surfaces	Temperature notation	Temperature (°C) at different times (s)					
		0	1	5	10	15	17
Side surface (SS)	T_i	50	245	175	100	71	65
Round surface (RS)		50	243	177	123	80	74
Bottom surface (BS)		50	250	212	195	111	99
Sprue hole surface (SHS)		50	250	247	242	168	159
Core cooling surface (CoCS)	T_W and T_C	T_W=14 T_C=10.15 (coolant temperature)					
Cavity cooling surface (CaCS)		T_W=12 T_C=10.15 (coolant temperature)					

Table 4 Heat flux values for different surfaces used as boundary condition for CSCC mould

Interface surfaces	Mode of heat transfer	Heat flux values (W/mm^2) for different time (s)					
		0	1	5	10	15	17
Side surface (SS)	Conduction	0	0.062	0.043	0.023	0.016	0.014
Round surface (RS)		0	0.061	0.044	0.029	0.018	0.016
Bottom surface (BS)		0	0.063	0.053	0.048	0.026	0.023
Sprue hole surface (SHS)		0	0.079	0.078	0.076	0.052	0.049
Core cooling surface (CoCS)	Convection	0.0054					
Cavity cooling surface (CaCS)		0.010					

Table 5 Values of clamping forces and injection pressure used as boundary conditions

Injection pressure								Clamping force	
Bottom surface (BS)		Round surface(RS)		Side surface (SS)		Sprue hole surface (SHS)		Top surface	
Time (s)	Pressure (MPa)	Time (s)	Pressure (MPa)	Time (s)	Pressure (MPa)	Time (s)	Pressure (MPa)	Time (s)	Forces (N)
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.35	2.0	0.9	1.2	0.96	0.18	0.5	8.65	0.2	94,032
1.0	5.0	1.0	2.0	1.01	0.4	1.078	13.22	0.5	3.9e+5
1.07	7.13	1.76	8.45	1.76	8.33	1.088	10.56	1.0	1.2e+6
1.088	6.28	2.5	8.47	4.0	8.12	10.5	10.56	4.0	2.9e+6
5.0	8.95	9.76	5.15	9.75	1.35	11.1	0.0	9.76	2.3e+6
9.75	8.5	10.5	6.4	10.5	0.0	20.0	0.0	10.5	2.5e+6
10.5	8.96	11.18	0.987	20.0	0.0	–	–	11.18	2.3e+5
11.0	5.5	11.98	0.0	–	–	–	–	11.98	0.0
11.18	0	20.0	0.0	–	–	–	–	20.0	0.0
20.0	0	–	–	–	–	–	–	–	–

For Stavax Supreme, S_{ut}=1,780 MPa, S_e=750 MPa. The values of f is normally taken as 0.9 [9] but it varies with S_{ut}, and for S_{ut}=1,780 MPa, f=0.7. Applying Eq. 4 and these values, the fatigue life of the mould with different cooling channels have been calculated and these values are also shown in Table 6.

Comparison of fatigue life (N) values in Table 6 shows that the BCCC with 2-mm CTI, gives the highest fatigue life of 9.925 million cycles, compared to all other cases. So, we will investigate further the cooling efficiency of the BCCC with 2-mm CTI by analytical and experimental investigation as described later.

Theoretical cooling time of a plastic part can be calculated by using general 3-D conduction heat transfer Eq. 5 as given, which is,

$$\frac{\partial^2 T}{\partial^2 X}+\frac{\partial^2 T}{\partial^2 Y}+\frac{\partial^2 T}{\partial^2 Z}+\frac{Qv}{K}=\frac{1}{\alpha}\frac{\partial T}{\partial t} \quad (5)$$

Because of cooling channel placement in the mould, heat can be considered to be removed or transferred only in one

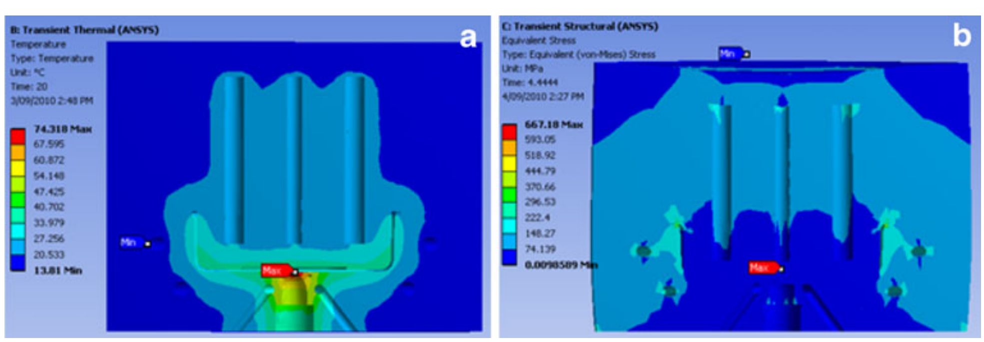

Fig. 7 **a** Temperature distribution after 1 cycle (20 s) in the mould, and **b** equivalent stress distribution at 4.45th second of cycle time for CSCC mould

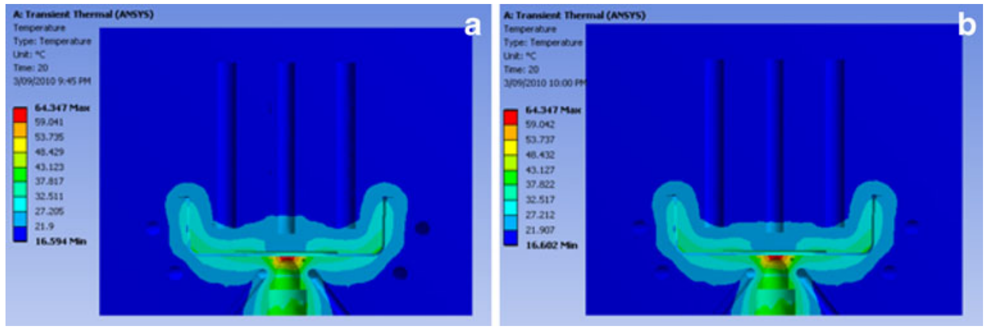

Fig. 8 Temperature distribution on mould assembly after 1 cycle" **a** BCCC 3-mm CTI and **b** BSCC 3-mm CTI moulds

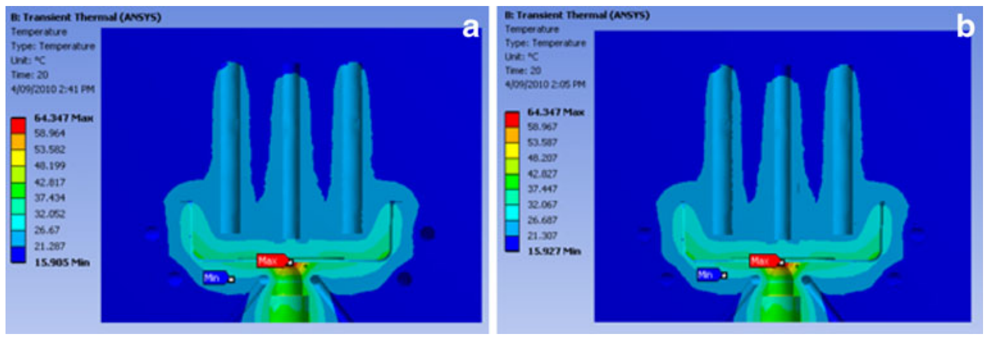

Fig. 9 Temperature distribution on mould after 1 cycle: **a** BCCC 2-mm CTI and **b** BSCC 2-mm CTI moulds

direction, the direction of the part thickness. Therefore, a one-dimensional heat transfer can be assumed for cooling time calculation. For one-dimensional heat flow and with no internal heat generation, $Q_v=0$, and therefore, Eq. 5 can be written in form:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial^2 Y} \tag{6}$$

Assuming that immediately after injection, the melt temperature of the plastic in the cavity has a uniform constant value of T_m, the temperature of the cavity and core wall that is in contact with molten plastic jumps rapidly to the constant value of T_w and remains constant, then the analytical solution of the Eq. 6 will give the expression for the cooling time (t_C) as given by Eq. 7 [2]:

$$t_C = \frac{S^2}{\pi^2 \times \alpha} \ln\left(\frac{8}{\pi^2} \frac{T_m - T_w}{T_d - T_w}\right) \tag{7}$$

where,

- S Thickness of plastic part=2 mm
- α Thermal diffusivity of plastic material $=\frac{k}{\rho Cp} = 8.87\times 10^{-8} \mathrm{m}^2/\mathrm{s}$
- k Thermal conductivity of plastic material=0.14 w/m °C
- ρ Density of plastic material=830 kg/m^3
- C_p Specific heat of plastic material=1,900 J/kg °C
- T_m Moulding temperature of plastic=250°C
- T_d Demoulding temperature of ejected plastic material =78°C

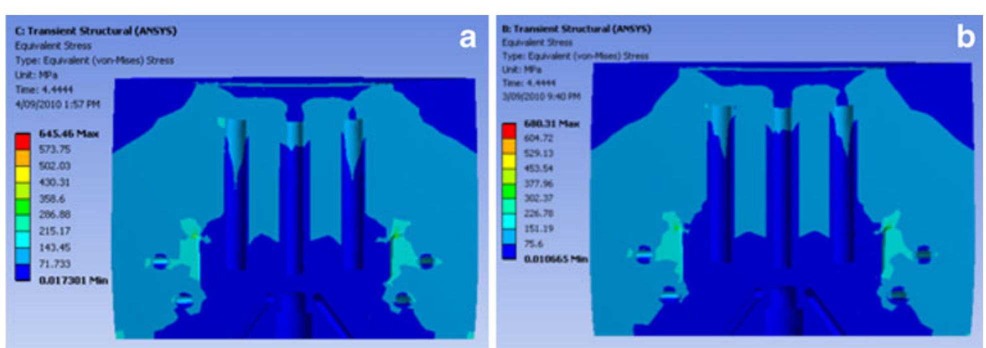

Fig. 10 Equivalent stress distribution at 4.45th second of cycle for **a** BSCC 3-mm CTI and **b** BCCC 3-mm CTI moulds

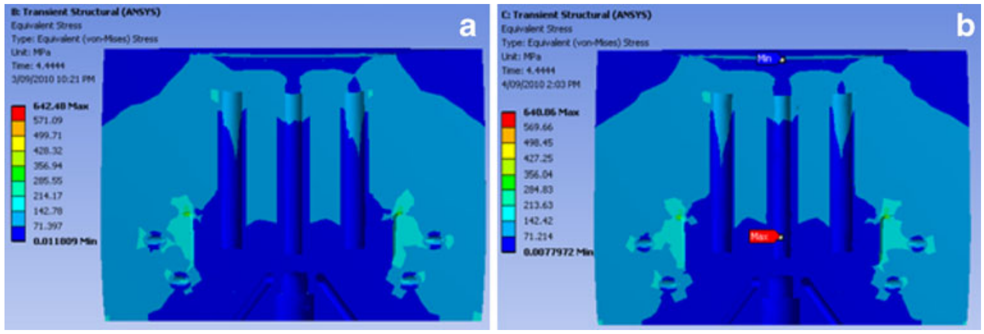

Fig. 11 Equivalent stress distribution at 4.45th second of cycle for **a** BSCC 2-mm CTI and **b** BCCC 2-mm CTI moulds

Table 6 Data for S_{es} and fatigue life for different cooling channels

Type of cooling channel	von Mises stress S_{es} (MPa)	Fatigue life (million cycle)
CSCC	675.7	5.683
BCCC 2-mm CTI	649	9.925
BSCC 2-mm CTI	653.6	8.998
BCCC 3-mm CTI	689	4.325
BSCC 3-mm CTI	682	4.984

T_w Maximum temperature of interface wall between molten plastic and cavity wall after 1 cycle=74.32°C (for CSCC from Fig. 11a)

Using the plastic part material as polypropylene (PP), theoretical cooling time for CSCC and BCCC 2-mm CTI, have been calculated and compared with the cooling time obtained from simulation results, and are shown in Table 7. From the results shown in Table 7, we can see that there is good agreement between theoretical cooling time calculations and the cooling time form simulation result for both types of cooling channels. Table 7 also shows that using 2-mm CTI, cooling time has been reduced by almost 3 s, thus providing faster cooling. Moreover, this bi-metallic cooling channel also gives the highest fatigue life (as shown in Table 6) .

Figure 12 shows the cooling curve for the plastic part for CSCC and BCCC 2-mm CTI, for the entire cycle of the moulding process using the numerical analysis. The part reaches a maximum temperature in the mould and then cools down to the ejection temperature. For the same ejection temperature, the cooling curve for the BCCC shows much lower time (5 s) for ejection than the CSCC (8 s). Thus simulation and analytical results both confirm that BCCC provide a better robust design option for injection moulds.

Table 7 Comparative cooling time data

Type of cooling channel	Cooling time (s) (theoretical)	Cooling time (s) (simulation)
CSCC	7.25	8
BCCC 2-mm CTI	4.76	5

5 Experimental work

Experimental verification of the numerical analysis result has been carried out by injection moulding of a plastic part using two different plastics, PP and acrylonitrile butadiene styrene (ABS), using conventional CSCC as well as BCCC moulds. The part was a disk shape with of a diameter of 40 mm and thickness of 7 mm. The mould was a square shape with overall dimensions of 100×100×25 mm. The mould material was mild steel. Experiments were carried out on a mini injection moulding machine, TECHSOFT mini moulder. Figure 13a shows the core and cavity moulds with cooling channels. Figure 13b shows the CTI being fitted. Figure 13c shows the injection moulded parts in PP and ABS produced during the experiment.

Two thermocouples, TC08 K-type of PICO Technology, have been used to measure temperature of top and bottom interface of the test part and cavity for every second of the cycle. Melting temperature used was 250°C for both ABS and PP. Normal water has been used as a cooling medium, and water temperature has been measured as 20°C. Cooling

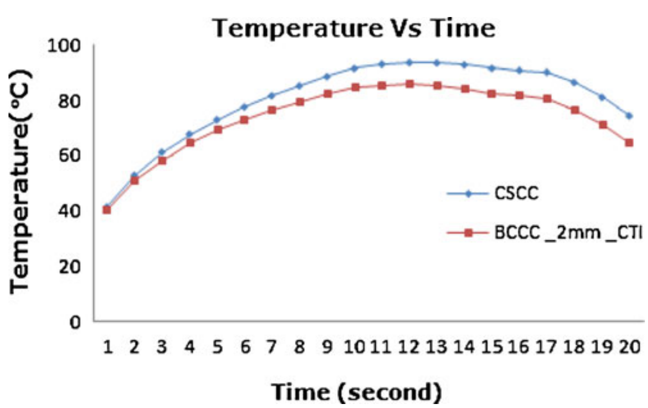

Fig. 12 Cooling curves for CSCC and BCCC 2-mm CTI

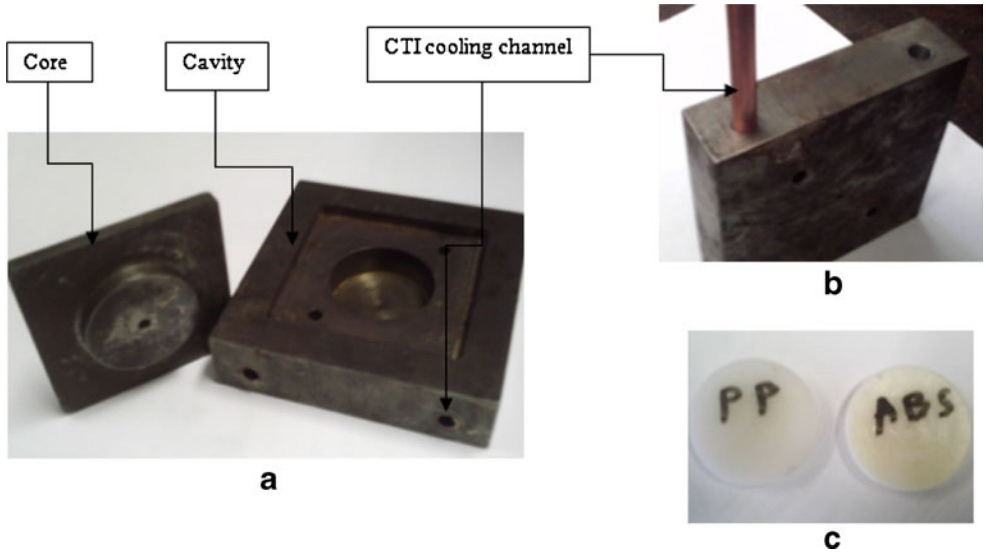

Fig. 13 **a** Core and cavity mould, **b** copper tube is being inserted into the cavity mould, and **c** test plastic parts

channel diameter used was 6 mm for CSCC mould and CTI inner diameter was 6 mm and CTI thickness was 1 mm used in bi-metallic mould. Copper tube has been inserted inside the cooling channel by heating the mould and cooling down after press fit. In this process, the air gap between two materials has been minimized.

Figures 14 and 15 show the comparative cooling time curves obtained from experimental results for CSCC and BCCC moulds. Cooling curves were obtained from the maximum temperature of the top and bottom thermocouple readings up to next 20 s. Both figures clearly show that for both types of plastic parts, using bi-metallic cooling channel, the plastic part can be cooled down much faster than using the CSCC. In average, 8–10°C temperature and 3–5 s of cooling time can be reduced using the bi-metallic cooling channel moulds.

6 Conclusions

From experimental and thermal–structural FEA, it can be concluded that high thermal conductive copper alloy tube can be used as a potential alternative to replace conventional straight and conformal cooling channels in injection moulding, as it reduces a significant amount of cooling time (35%), as well as it increases fatigue life time of the mould. But it is also notable that increasing too much thickness of the copper tube will also reduce the structural strength and fatigue life of the mould. So, the use of bi-metallic cooling channel with copper tube should be incorporated in such a way that it does not reduce the overall strength of the mould or decrease the total life cycle of the mould before its failure.

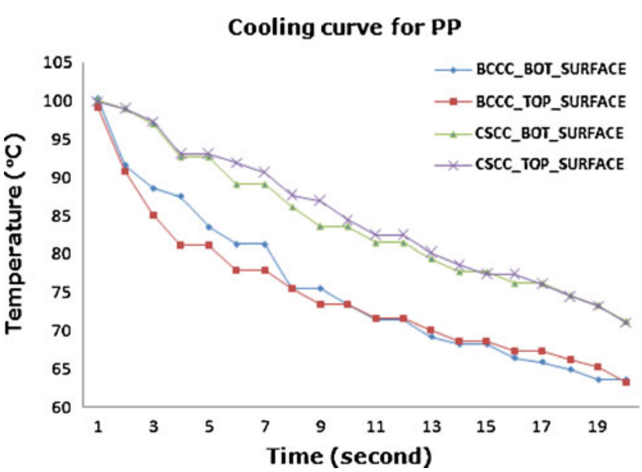

Fig. 14 Comparative cooling curve for CSCC and BCCC CTI moulds, showing temperature at the bottom and top surface of the polypropylene (PP) plastic part

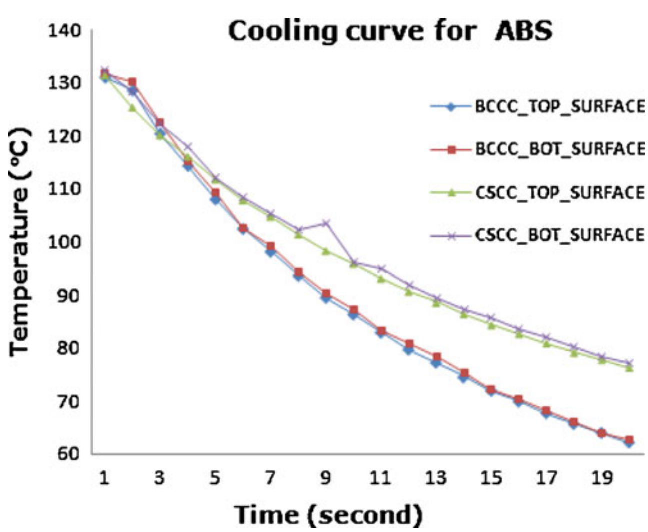

Fig. 15 Comparative cooling curve for CSCC and BCCC CTI moulds, showing temperature at the bottom and top surface of the acrylonitrile butadiene styrene (ABS) plastic part

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