Development of High Performance Copper Alloy Chill Vent for High Pressure Die Casting

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***Abstract*— In High Pressure Die Casting (HDPC) process, chill vents are used to allow residual air and gases to exhaust out from the mould cavity. The objective of this paper is to design and develop a high-performance chill vent for high pressure die casting using a new type of copper alloy material, which has high strength and high thermal conductivity, compared to conventional tool steel. Finite element analysis is applied to develop a numerical heat transfer model for chill vent and validated by experimental results. The model is used to compare the performance of copper alloy chill vent with conventional steel chill vent. It was found that the change in the chill vent material had a significant improvement on the cooling time, cooling rate as well as on the internal die temperature distribution. Results show that the copper chill vent increases the cooling efficiency of the solidifying aluminium alloy by about 158% compared to the conventional steel chill vents. It is concluded that the use of high strength copper alloy chill vents will enhance the efficiency and effectiveness of HPDC process with rapid heat transfer and faster release of gases, thus reducing porosity and flashing defects in the parts.**

***Index Terms*—High pressure die casting; Chill vents; Thermal analysis; Copper alloy; Thermal conductivity; Cooling rates**

I. Introduction

High Pressures Die Casting (HPDC) is widely used in the automotive industry to manufacture light weight metal parts. Several manufacturers are gradually moving toward increased use of lightweight aluminium alloy castings such as ADC12 for making components previously made from steel and cast iron. In high pressure die casting process, molten metal is injected under high pressure into a tool steel mould or die cavity to form products of desirable shape [1,2]. The schematic diagram of the HPDC process is shown in Fig. 1. Chill vent is a common method in high pressure die casting to remove the air from die cavity. Chill vent consists of a pair of steel metal blocks with a zigzag venting path typically 0.5 mm of gap provided for air flow as shown in Fig 1. The system formed on the surfaces of the two blocks is mounted on the die to permit easy escape of entrapped air from the cavity [3]. Chill vent helps to reduce defects like porosity in the castings that can affect product quality. In the conventional steel chill vents, sometimes molten metal is also flushed through the air venting surfaces which often becomes difficult to prevent because of low thermal conductivity of steel.

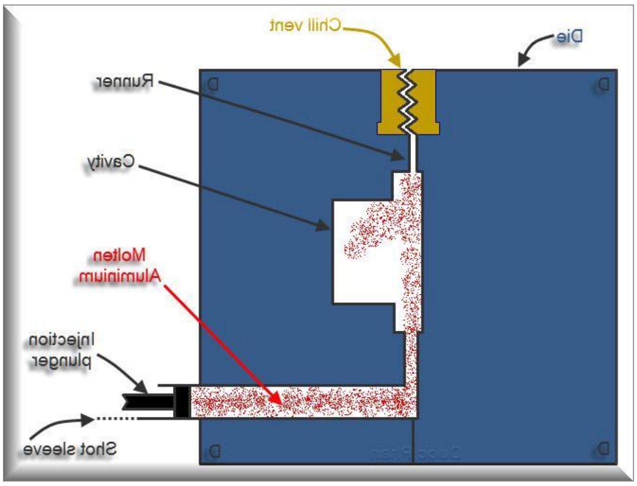

Figure 1. Schematic diagram of a typical HPDC process.

Since the function of a chill vent is to remove the air and gases from the mould cavity in least amount of time and to increase the solidification rate of castings, a material of high strength and high thermal conductivity would be more appropriate for its manufacture. One such material is beryllium copper alloy, also known as MoldMAX, which has not only higher strength than steel, but also exhibits six times higher thermal conductivity as compared to steel [4]. Therefore, these properties make MoldMAX alloy a suitable candidate to replace the conventional tool steel for manufacturing the chill vents. This study intends to investigate the performance of beryllium copper alloys for manufacturing chill vents in HPDC in comparison to steel vents.

In high pressure die casting, the numerical and finite element based modelling of solidification process and undergoing thermal processes can be highly beneficial in improving the efficiency of the die casting process and evaluating the possibilities to reduce the cooling time. There have been several investigations on simulation studies involving analysis of numerous process parameters, which are critical for accurate thermal analysis and reducing defects in the HPDC process.

Rosindale and Davey [5] developed a three-dimensional numerical model that was used to predict the

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steady state thermal behaviour of the metal injection system of a hot chamber pressure die casting machine. The model yields time averaged die and injection system temperatures and the heat input from localised heating arrangements, which can be used to identify potential problem areas and cold spots on the surfaces of the injection system, die cavity and casting.

Rasgado et al [6] have investigated the establishment of thermal models for bimetallic copper-alloyed dies protected with a thermally sprayed steel layer. Both steady state and transient thermal models were developed that can predict the time averaged and transient cyclic thermal behaviour of the new die designs.

Ahmed et al [7] have carried out a mold flow analysis using Castal simulation software to predict the defects in the die for the high pressure die casting of an aluminium alloy heat sink. They have shown that design changes in gate and runner system and increasing the over flow area helped in achieving zero porosity in small dies, where chill vents could not be included.

Kwon and Kwon [8] have used the simulation software (AnyCasting) to optimize the gate and runner design of an automobile part. Through modification of the gate and runner system and the configuration of overflows, internal porosities caused by air entrapments were predicted and reduced by a significant ratio.

Wenbo Yu et al [9] have studied the interfacial heat transfer behaviour at the metal/shot sleeve interface in the high pressure die casting (HPDC) process of AZ91D aluminium alloy. The effect of different slow shot speed on the interfacial heat transfer behaviour were investigated to optimise the conditions to reduce the externally solidified crystals or cold flake defects in the casting.

Jeong et al [10] have applied the MAGMAsoft casting simulation program to predict and prevent the possibility of casting defects that may occur in the filling process and solidification process for the high pressure die casting for an aluminium clutch housing product.

Although several factors have been studied using simulation methods, little attention is paid to the design and development of chill vents and air venting problem in a HDPC process. This investigation aims to fill this research gap and investigate the performance of a new chill vent configuration using MoldMAX instead of conventional tool steel. MoldMAX is a beryllium copper alloy, a material of high strength and higher thermal conductivity than steel. This alloy also provides the advantage of forming a preventive oxide film on the surface of chill vent, while in contrast the tool steel chill vents chemically react with molten aluminium and produce sticking depositions. Therefore, MoldMAX material can maintain several times larger vent gap than steel during the mould operating life. This study describes the process of developing a numerical heat transfer model for the tool steel chill vent and then compares it with the simulation results of beryllium-copper alloy chill vent. The simulation model has been validated with the real-time experimental test of aluminium alloy casting performed on a commercial 800 tonne die casting machine.

II. Heat Transfer Model

Fig. 2 shows the 3D computer aided design (CAD) model of the chill vent used in this study. The chill vent with zigzag surfaces was modelled in a commercial CAD system. Then, it was imported and meshed using the general-purpose finite element ANSYS® Workbench package for the heat transfer modelling and thermal analysis. The chill vent contains a fountain type single cooling waterline in each half. The flashing aluminium part was also created and meshed in order to use for applying the thermal loads, heat generation rate and heat flux.

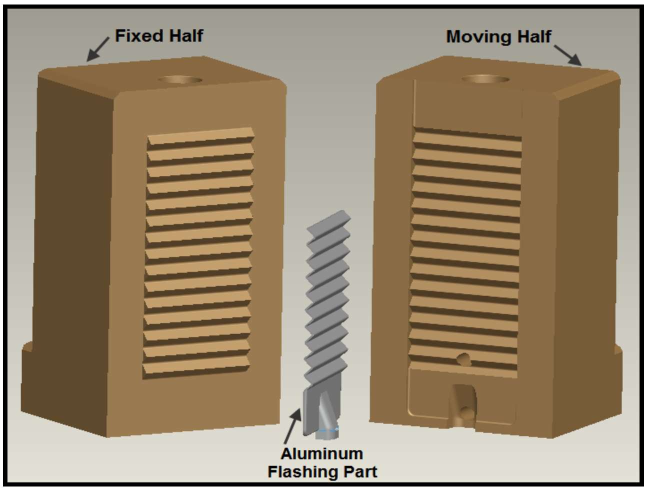

Figure 2. A CAD model of the chill vent used in HPDC

A. Boundary Conditions

After metal injection in the mold, heat energy is transferred from the melt to the chill vent. Heat is lost by convection to water in the cooling channels in the chill vent blocks and to air from the top surfaces. Heat is also extracted by conduction from the surfaces between the chill vent and die blocks. In brief, the heat transfer between a flashing casting and chill vent is governed by conduction, whereas heat is removed from the system principally by convection from the cooling system and the top surfaces of the chill vent blocks. The original material used for making the chill vent and the mold was hot work tool steel (H13) with the initial temperature considered for analysis was 73.8^{o}C. The casting material was aluminium alloy type – ADC12, which was prepared in an electric resistance furnace with the pouring temperature at about 615 ℃. At the time of the ejection, after 15.9s, the average temperature at the casting and chill vent surfaces are the same, 94^{o}C. It is noted that all of the values used as initial conditions were obtained from experimental test of aluminium alloy casting on a commercial 800 tonne die casting machine.

A convection load that occurs between the chill vent and the cooling system in the chill vent blocks was applied on the surfaces of the cooling channel to account for heat extraction. Water at 20^{o}C was used as the cooling medium in the chill vent cooling channels. For a circular tube of uniform wall temperature, the heat transfer coefficient can be calculated using the following equation based on Dittus-Boetler correlation for forced convective heat transfer [11].

$$\boxed{h_{water} = 0.023 Re^{0.8} Pr^{0.4} \frac{k_{water}}{D_{water}}}$$

where:

h_{water} = Heat transfer coefficient in the cooling system (W/m^{2}C)

Re and Pr = Reynolds and Prandtl number

k_{water} = Thermal conductivity of water at 20^{o}C (W/m^{o}C)

D_{water} = Cooling channel diameter (mm)

Using the appropriate values of Prandtl Number and Reynolds Number, the thermal properties of water, and the diameter of the cooling channel in the vent, the heat transfer coefficient h_{water} at the bulk fluid (water) temperature of 20^{o}C was calculated to be 1253 W/m^{2o}C.

Besides that, the ambient air temperature and heat transfer coefficient with air at the top chill vent surface were assumed to be 30^{o}C and 10 W/m^{2o}C respectively. The material properties for the ADC12 aluminium alloy were obtained from MatWeb material property data [12].

There are several parameters that influence the magnitude and variation of casting temperature. After analyzing many published experimental results, it is noted that when the casting temperature is plotted against the casting time, the variation follows an exponential profile. Consequently, the temperature at the aluminium casting surface $T_{casting}$ was assumed to be a function of time with an exponential behaviour. Considering the boundary conditions, the final expression, which was derived for estimating the cooling time curve for flashing aluminium casting part is given by the following equation:

$$T_{casting} = T_o e^{\frac{t}{t_{ejection}} \ln \frac{T_{ejection}}{T_o}}$$

where:

$T_{casting}$ Temperature at the casting surface (^{o}C)

T_o Injection temperature (^{o}C)

$T_{ejection}$ Ejection temperature (94^{o}C)

t Elapsed time (s)

$t_{ejection}$ Ejection time (15.9s)

By using this function and the boundary conditions, the cooling curve of flashing aluminium part was calculated. These values were then used to calculate the heat generation rate as well as heat flux for the FEA heat transfer model of the chill vent. It is noted that all ~~of~~ the values used as boundary conditions were obtained from experimental test on a high pressure die casting machine for ADC12 aluminium alloy. The pouring temperature was T_o = 615^{o}C and the temperature at the ejection time $t_{ejection}$ = 15.9 second was $T_{ejection}$ = 94^{o}C.

As the gap thickness between two steel chill vent blocks is much smaller than the other two dimensions, the heat of fusion of aluminium can be assumed to flow uniformly in the x and y directions, while the z-direction can be taken as perpendicular to the flow field. Therefore, the following one-dimensional heat conduction equation can be used to calculate the amount of heat released Q (W/m^3), and the total heat flux q (W/m^2) [13]:

$$\boxed{Q = mC_p \frac{\partial T}{\partial t} = V\rho C_p \frac{\partial T}{\partial t} \quad \text{and} \quad q = \frac{Q}{A}}$$

where:

m Flashing aluminium mass (Kg)

V Flashing volume (m^3)

A Flashing surface area (m^2)

ρ Flashing aluminium density (Kg/m^3)

C_p Flashing aluminium specific heat (J/Kg^{o}C)

From all the available and calculated parameters, the heat generation rate (Q) and the heat flux (q) released during cooling and melting of ADC12 alloy to the ejection temperature (94^{o}C) are calculated and are shown in Fig. 3. These thermal loads variations were then used in the ANSYS® simulation program to calculate the temperature distribution and cooling time.

B. Running and Validating the Model

The model took approximately two hours to simulate for one casting cycle using the current version of ANSYS® Workbench. A more refined mesh was also run to assess model sensitivity to mesh density. However, based on experience, reducing the mesh size beyond a certain threshold value causes negligible improvement in accuracy of results. In addition, increasing the number of sub-steps to higher values may cause the solution to converge, but this will add greatly to the computational time and computer hardware requirements.

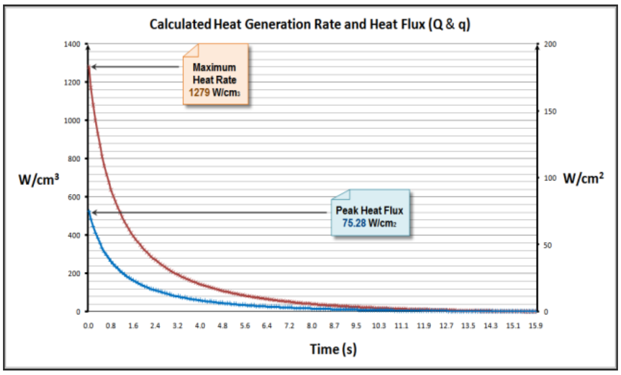

Figure 3. Heat generation rate and Heat flux values used for thermal analysis.

The simulated results indicate that the current mesh and the number of sub-steps (201 nodes) are adequate to compare with the experimental results. Fig. 4 shows the maximum and minimum surface temperatures for the moving tool steel chill vent block to be 98.67^{o}C and 67.15^{o}C respectively, as obtained from simulation. These temperature values were then compared with the real-time experimental results in order to validate the FEA heat transfer model.

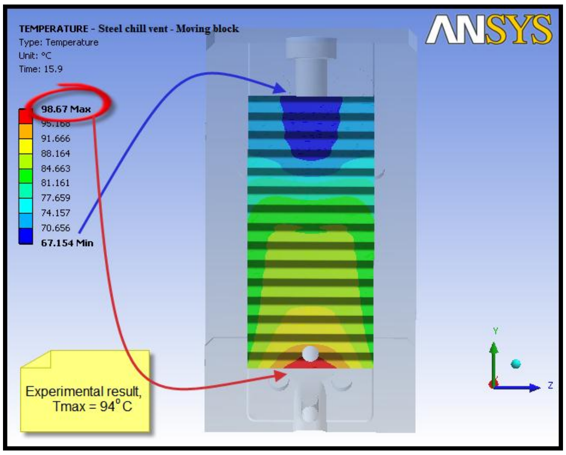

Figure 4. Temperature distribution at the surface of moving block - Steel chill vent.

An experimental die casting process was performed on a commercial 800 tonnes cold chamber HPDC machine. In this experiment, the temperature distribution on the chill vent surface at the ejection time of 15.9 seconds was captured using a high-speed infrared camera, FLIR PM850 at the HPDC machine, which was then compared with the simulation results.

Fig. 5 shows the experimental image depicting the relative temperature variation within the chill vent at the instant of die opening ($t_{ejection}$=15.9 seconds). The image is presented in many colours with black, magenta, blue, cyan, green, yellow, orange and red-listed in order of increasing temperature. The colour scheme represents an order to clearly identify the different temperatures on the chill vent surface. The average temperature at the moving chill vent block surface at the ejection time of 15.9 seconds was found to be 94°C. This value compares well with the maximum temperature of 98.67°C obtained by simulation, thus validating the heat transfer model.

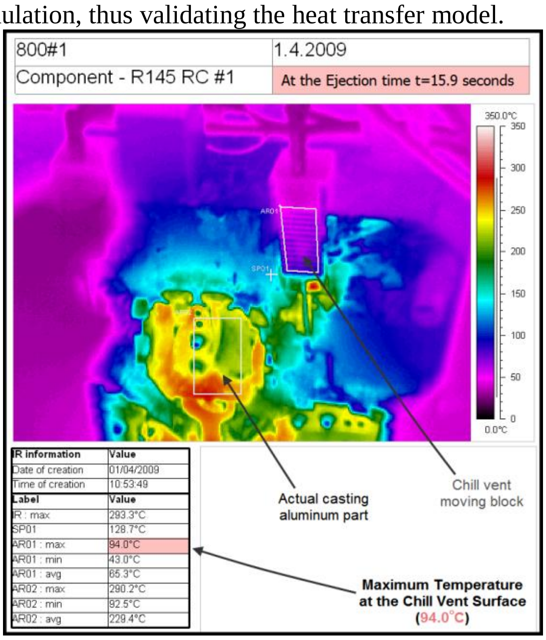

Figure 5. Experimental temperature distribution on the chill vent surface measured by infrared camera

It is observed that the simulated maximum die temperatures were higher than the real-time experimental temperature by 4.67°C. This difference could be due to the assumptions made when creating and running the analysis of FEA heat transfer model. However, since the difference was less than 5% between predicted and measured temperatures, therefore, it can be accepted that a good agreement exists between the simulation temperatures and the experimentally obtained temperatures.

III. Results and Discussion

To investigate the performance of the chill vents, the solidification time, cooling rate and temperature profile were obtained from the simulation model for the MoldMAX chill vent and were compared with those values obtained for the tool steel chill vent.

Since both high hardness and greater thermal conductivity are critical in achieving accelerated cooling of molten aluminium in HPDC, it is considered that a beryllium copper alloy would provide both higher thermal conductivity and hardness in combination. For that reason, the material of chill vent was changed from tool steel H13 to MoldMAX beryllium copper alloy.

In Fig. 6, the contour plots show the distribution of temperature at the moving copper alloy chill vent block surface just prior to the die open. It is shown that the copper alloy chill vent surface was cooled down to approximately 98.7°C in just about 6.70 seconds, whereas the time for H13 tool steel chill vent to get the same temperature was 15.9 seconds (see Fig. 4). It can also be observed from Fig. 6 that the chill vent surface temperature increased with increasing thickness of the flashing aluminium part. That is because the surface temperature of the thicker section at the bottom decreased more slowly than that of the other thinner near the top of the chill vent.

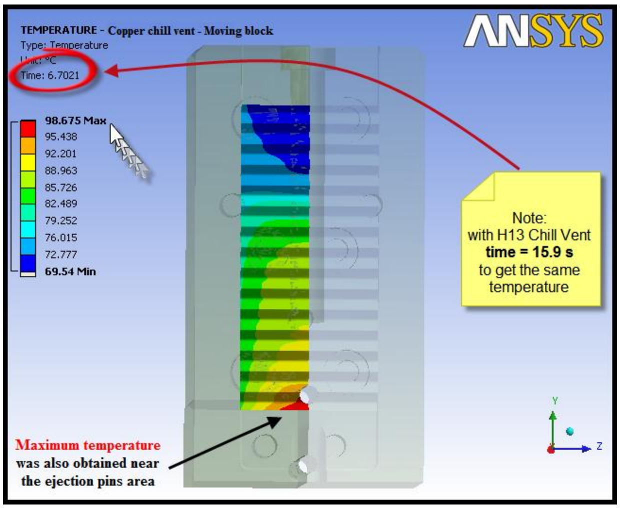

Figure 6. Temperature distribution at the surface of moving block - MoldMAX copper alloy chill vent

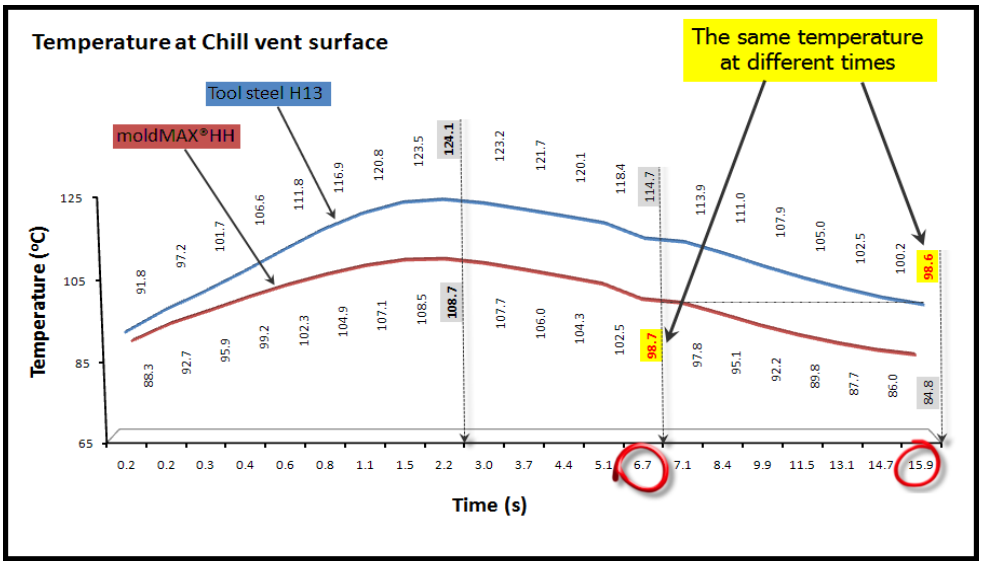

Figure 7. Comparison of cooling time curves during casting process using the steel and copper chill vents.

Fig. 7 shows the typical thermal histories at the MoldMAX and H13 chill vent surface during solidification of the ADC12 alloy.

It is noted that the chill vent temperature rose quickly after each shot until reaching its peak value of about 108.7°C and 124.1°C respectively, after which the temperature dropped until the next shot. In general, it can be seen that an increase in thermal conductivity from 27 W/m°C for tool steel to 155 W/m°C for copper material significantly reduces the peak temperatures of the chill vent surface. Once again, the time taken for the steel chill vent surface to cool from pouring temperature of melting aluminium, 615°C, to the ejection temperature, 98.7°C, was 15.90 seconds, whereas in the beryllium copper alloy MoldMAX chill vent, it took only about 6.70 seconds to cool to a similar temperature

The comparison of cooling rate and cooling efficiency of both tool steel and copper chill vents shows that the cooling rates to cool the flashing aluminium part from pouring temperature to ejection temperature are 32.5°C/s and 77°C/s for steel and copper alloy chill vents respectively. Thus, it is noted that the chill vent of MoldMAX material type increases the cooling efficiency by about 158%. Future work should consider the influence of other parameters such as pouring temperature, superheat, air gap formation, injection velocity, and pressure intensification.

IV. Conclusions

In this investigation, the Finite Element Analysis was used to develop a heat transfer simulation model for the tool steel chill vent used in HPDC and was validated by experimental measurements of the actual HDPC of aluminium alloy. The vaidated heat trasnfer model was then used to study the performance of beryllium copper alloy chill vent in comparison to steel chill vent. The results indicated that the use of high strength, high thermally conductive copper alloy as chill vent material had a significant improvement on the cooling time, cooling rate as well as the internal die temperature distribution. It was found that the time taken for the steel chill vent surface to cool from pouring temperature of melting aluminium to the ejection temperature was 15.9 seconds, whereas in the beryllium copper alloy MoldMAX material condition, it took only about 6.70 seconds to cool to a similar temperature. The calculated cooling rates to cool the flashing aluminium part from pouring temperature to ejection temperature for the steel chill vent and copper alloy chill vent were found to be 32.5°C/s and 77°C/s respectively, thus giving an increase of 158% in cooling efficiency for the copper alloy chill vent. The study has established that using a high strength copper alloy for chill vent improves the performance and the chilling ability of the permanent mold casting dies in High Pressure Die Casting of aluminium.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

DT Phan conducted the research and wrote the first draft of paper. SH Masood supervised the project and checked the data. SH Riza and H Modi revised and improved the paper with more literature review. All authors had approved the final version.

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