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CHARACTERIZATION OF CONTACT HEAT TRANSFER COEFFICIENTS AND MATHEMATICAL MODELING OF A SEMI-SOLID ALUMINIUM DIE CASTING

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Abstract

Contact heat transfer coefficients were characterized for a die cast semi-solid A356 aluminum alloy. Temperatures were measured in the mold as castings were produced and an inverse heat conduction technique was used to obtain coefficients that were consistent with these measurements. Transient and steady state regimes were observed in the evolution of the contact coefficients. The transient regime showed a peak of approximately 3.5 kW/m^2 K that appeared early in the heat transfer process and this was followed by an exponential decay. During the steady state regime, the contact coefficient was approximately 0.25 kW/m^2 K. The measured coefficients were inserted in a mathematical model to simulate the cooling of the part during casting. The results showed it could be ejected from the press within 30 s, in agreement with what was observed during the actual casting experiments. The feedstock used for this work was produced with a new slurry-on-demand process called SEED.

Introduction

The predominant resistance to heat flow in the die casting process is at the interface between the die and the casting [1]. This resistance is the inverse of the conductance, the latter being more generally known as the contact heat transfer coefficient. Values of these coefficients are necessary inputs for mathematical heat transfer models used to optimize mold design, adjust

process parameters and reduce the number of casting trials prior to the mass production of castings. Several factors may affect how they evolve; among them are the mold material and its surface condition, lubricant, temperature and geometry of the mold, initial solid fraction and composition of the feedstock metal, intensification pressure and time. These coefficients are thus the result of a set of operating conditions and may become inaccurate when used out of their context. Although mathematical modeling has become commonplace, there are few reports on contact heat transfer coefficients particularly for semi-solid processing [2,3].

The study described in this paper is part of a larger research to characterize heat transfer in pressure die casting of aluminum alloys and to obtain a predictive model for the contact heat transfer coefficients. The experimental work consisted in measuring temperatures in the mold as castings were produced under a given set of operating conditions. Parameters such as pressure, initial temperatures of the mold and the aluminum, lubricant, etc, were kept constant, the influence of their variation to be investigated in a later experimental campaign. An inverse heat conduction technique was used to determine the contact coefficients that were consistent with the measured temperatures. These were carried out at two different locations in the mold in order to determine the effect of geometry on the coefficients. The resulting values were then inserted in a mathematical model and a simulation of the heat flow between the mold and the casting was carried out.

Experimental Procedure

The castings were produced with a semi-solid mixture of A356 alloy prepared with a new slurry-on-demand process developed by Alcan International Limited and called Swirled Enthalpy Equilibration Device (SEED). Details on the preparation of the feedstock have been given by Doutre et al. [4]. After exiting the SEED reactor, the feedstock, having a mass of approximately 2 kg and a solid fraction of 50%, was transferred to the shot sleeve of a Bühler SC N/53 die casting machine and then injected in the mold. The cast part represented an automobile suspension component as depicted in Figure 1. Also shown in this Figure are the thermocouple locations with respect to the mold wall.

The mold consisted of H13 tool steel onto which was sprayed a lubricant (Dasco Cast 1130) using an automatic spraying system (Rimrock 195 extractor). The temperature rise in the mold during casting was monitored at two different locations. One of them was near the feeding system where the geometry was cylindrical while the other was near a section of the casting that was rectangular (Figure 1). For each location, two type-K thermocouples with exposed hot

junctions were inserted into drilled holes at different depths near the mold wall. Springs were used to insure a good mechanical contact between the hot junctions and the bottom of the holes. Several parts were cast before the measurements to allow the press to attain its steady state. Five castings were then produced under identical conditions to evaluate the reproducibility in the temperature measurements. The operating parameters for the press are listed in Table I.

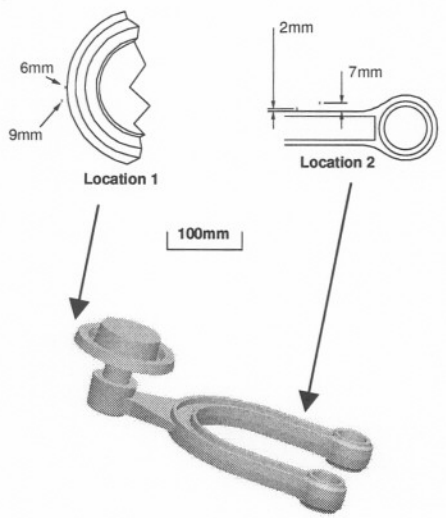

Table I. Casting Parameters

Metal Temp. (°C)	585
Sleeve Temp. (°C)	315
Mold Temp. (°C)	170
Ram speed – prefilling (m/s)	0.75
Ram speed – filling (m/s)	0.45
Pressure (MPa)	700-850

Figure 1. Casting with thermocouple positions in the mold.

Characterization of the Contact Heat Transfer Coefficients

The heat transfer at the interface between the mold and the casting is governed by Newton's law of cooling :

$$q(t) = h(t)\left(T_c^s(t) - T_m^s(t)\right) \tag{1}$$

It is seen from this equation that the contact heat transfer coefficient, $h(t)$, can be determined from knowledge of the heat flux, $q(t)$, as well as the casting and mold surface temperatures, $T_c^s(t)$ and $T_m^s(t)$. Distinct steps were used to determine these parameters. One of them consisted in solving a classical inverse heat conduction problem to obtain the heat flux per unit surface area entering the mold, $q(t)$. This consisted in measuring temperatures in the mold and determining interfacial heat fluxes that best reproduced these measurements. For this purpose, the sequential function specification method [5,6] was used and it called upon the following iteration formula:

$$q_m^{n+1} = q_m^n + \frac{\sum_{i=1}^{r}\sum_{j=1}^{J}\left[Y_{m+i-1,j} - T_{m+i-1,j}\left(q_m^n\right)\right] Z_{m+i-1,j}^n}{\sum_{i=1}^{r}\sum_{j=1}^{J}\left(Z_{m+i-1,j}^n\right)^2} \tag{2}$$

In this equation, J is the number of thermocouples and r is the number of future time steps – a feature that reduces the sensitivity of the solution to measurement errors. $Z_{m+i-1,j}^n$ is a sensitivity coefficient for sensor j given by :

$$Z_{m+i-1,j}^n = \frac{T_{m+i-1,j}\left(q_m^n(1+\delta)\right) - T_{m+i-1,j}\left(q_m^n\right)}{\delta q_m^n} \tag{3}$$

$Y_{m+i-1,j}$ refers to a measured temperature at the time interval $m+i-1$ with sensor j, while $T_{m+i-1,j}\left(q_m^n\right)$ and $T_{m+i-1,j}\left(q_m^n(1+\delta)\right)$ are calculated temperatures for that sensor location when fluxes q_m^n and $q_m^n(1+\delta)$ are imposed at the interface. Finite difference approximations of the Fourier equation were used to calculate the entire temperature profiles in the mold from which $T_{m+i-1,j}\left(q_m^n\right)$ and $T_{m+i-1,j}\left(q_m^n(1+\delta)\right)$ could be obtained. δ is a small quantity that incremented q_m^n, and the superscript 'n' refers to the nth iteration. Equation (2) was iterated until negligible changes occurred, i.e.,

$$\frac{q_m^{n+1} - q_m^n}{q_m^n} \langle 0.005 \tag{4}$$

When the above condition was met, the interfacial heat flux that reproduced a measured internal mold temperature was found. It should be noted that this procedure not only yielded $T_{m+i-1,j}\left(q_m^n\right)$ and $T_{m+i-1,j}\left(q_m^n(1+\delta)\right)$ in equations (2) and (3) but also the surface temperature of the mold, $T_m^s(t)$. Thus, the solution to the inverse heat conduction problem provided two inputs for equation (1), the interfacial flux per unit area, $q(t)$, as well as the surface temperature of the mold, $T_m^s(t)$. From equation (1), it is also seen that the contact heat transfer coefficient, $h(t)$, could be calculated if the surface temperature of the casting, $T_c^s(t)$, were known. This temperature was obtained assuming that the heat flux entering the mold, $+q(t)$, was the same as the heat flux exiting the casting, $-q(t)$. Thus by solving the Fourier equation with $-q(t)$ as an interface condition for the casting and the initial temperature for the aluminum given in Table I, the surface temperature of the casting, $T_c^s(t)$, was calculated. The calculation of this surface temperature amounted to solving a direct heat transfer problem rather than an inverse one. The thermophysical properties of the mold material are listed in Table II and the properties of the A356 alloy were taken from the ProCAST databank [7]. The latter were very close to those published elsewhere [8].

Table II: Thermophysical Properties of the Mold.

H13 steel	Ref
$C_p = 3.22 \cdot 10^2 + 4.23 \cdot 10^{-1}\ T$ (J kg^{-1} K^{-1})	9
$k = 25.15 - 1.158 \cdot 10^{-3}\ T$ (W m^{-1} K^{-1})	10
$\rho = 7800$ (kg m^{-3})	10

Results and Discussion

Figure 2 illustrates the internal mold temperatures measured during casting as well as those calculated at the surface of the mold. The reproducibility in the temperature measurements was good and the curves that are shown are averages for the five tests that were performed. In this graph, t=0 s was arbitrarily chosen as the onset of the temperature rise detected by the thermocouples.

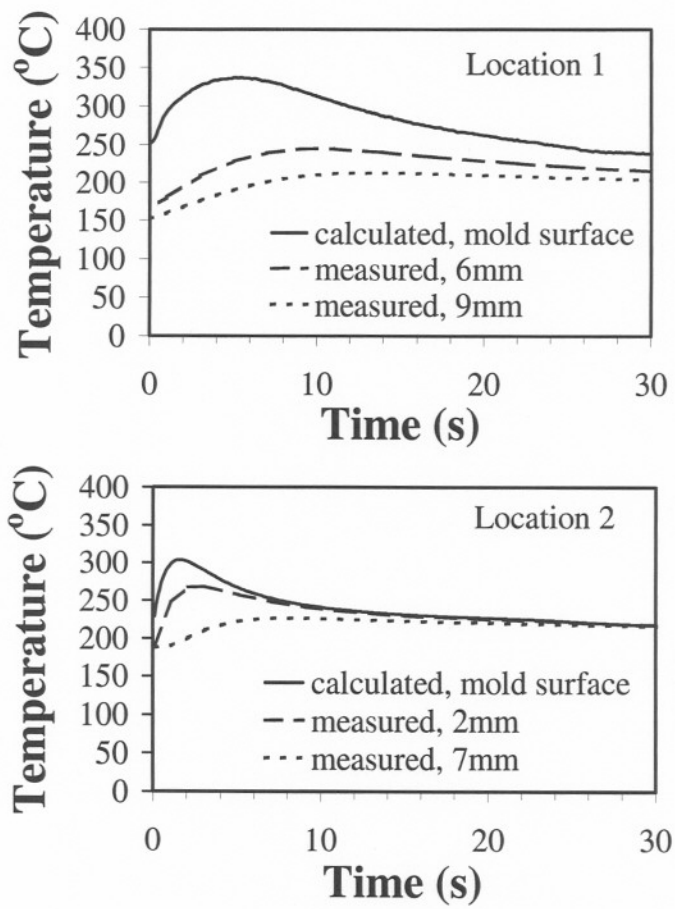

Figure 2. Temperature evolution in the mold at locations 1 (Figure 2a) and 2 (Figure 2b).

In Figure 3, the heat fluxes at the two investigated locations are shown. These fluxes are those that reproduced the measured temperatures in Figure 2. It is noted that one curve is smoother than the other. This could be a consequence of the meshing in the mold and the number of future time steps in equation (2) used to obtain the heat fluxes. In addition, location 1 had thermocouples further from the mold wall and this can also have an incidence on the calculations. Peaks are observed in both cases at approximately 1000 kW/m^2. At location 1, the peak was reached in approximately 2 s while at location 2 it was reached at initiation. The geometry of the casting near location 1 was cylindrical while that of location 2 was rectangular. Although the flux at location 1 dropped more slowly than at location 2, this was probably caused by the thicker solidified section rather than the radial component of the heat flux for the cylindrical configuration. For both locations, two heat transfer regimes were observed; transient followed by steady state. The heat flux at location 2 became very small during the steady state regime, especially after 15 s. This is consistent with the measured temperatures at this location. It is seen in Figure 2b that the temperature gradient in the mold became very small after this time and this generated a small heat flux.

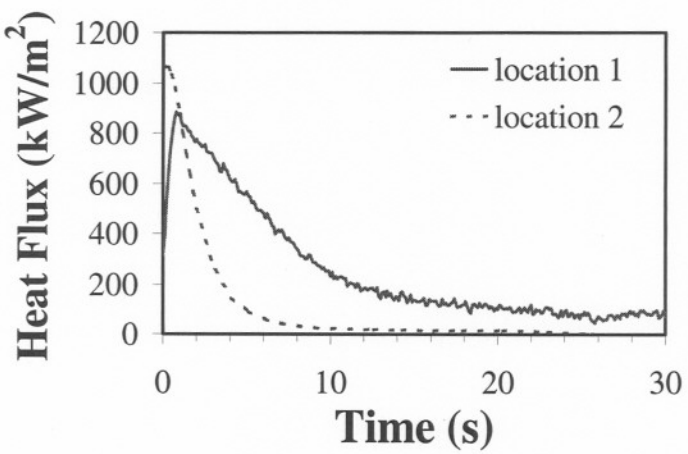

Figure 3. Heat flux evolution with respect to time.

The contact heat transfer coefficients are illustrated in Figure 4. It is seen that as with the heat fluxes, these coefficients varied considerably with time and the two regimes (transient and steady state) are also present. Maximum values for the coefficients are at approximately 3.5 kW/m^2 K and appeared early. This was followed by an exponential decay and stabilization. The main difference between the two curves in this Figure is the necessary time for stabilization. This was achieved after approximately 15 s for location 1 and 10 s for location 2. As with the heat flux curves, this can be explained by the fact that a thicker section had to solidify at location 1 than at location 2. The two geometries, cylindrical and rectangular, do not appear to have as strong an influence on the coefficients as the thickness of the solidified

section but this will require further tests to validate. These sections were 10 mm at location 1 and 4 mm at location 2. The rapid decrease in the values of the heat transfer coefficients is explained by the loss of thermal contact between the mold and the casting due to contraction of the latter during cooling. A steady state value between 0.1 and 0.5 kW/m^2 K can be observed for the two locations.

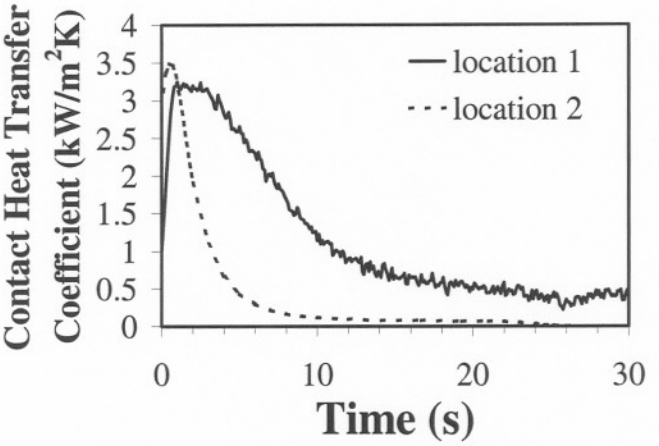

Figure 4. Evolution of the contact heat transfer coefficients with respect to time.

The peak values for the heat transfer coefficients in this study are smaller than those of Schnorf et al. where values between 20 to 60 kW/m^2 were obtained [3]. In their experiments, the thermocouples were reported to be directly at the mold surface and no interior temperatures were measured. Their maximum surface mold temperatures reached 450 ^{o}C and this is higher than those in this study, shown in Figures 2a and 2b to be the range of 300 to 325 ^{o}C. In both studies the mold temperature was initially close to 200 ^{o}C and thus the difference in the measured temperatures is probably the main factor accounting for the difference in the peak values for the coefficients. In our work, the surface mold temperatures were not measured but rather calculated with the inverse method using the interior mold temperatures as input data.

An idealized curve for the contact coefficient is shown in Figure 5. The two regimes mentioned earlier are identified, the transient followed by the steady state. The transient regime is characterized by a rapid rise to a peak value that may remain constant for a short period and an exponential decay. During steady state, the coefficient is characterized by a low value. Similar heat transfer models have been proposed [11,12]. Further work will be necessary to have a predictive model for the length of the transient and steady state regimes as well as the peak and steady-state values. As stated in an earlier section, several factors may affect how the

coefficients evolve. Determining the influence of mold lubricants and thermocouple position in the mold is of interest.

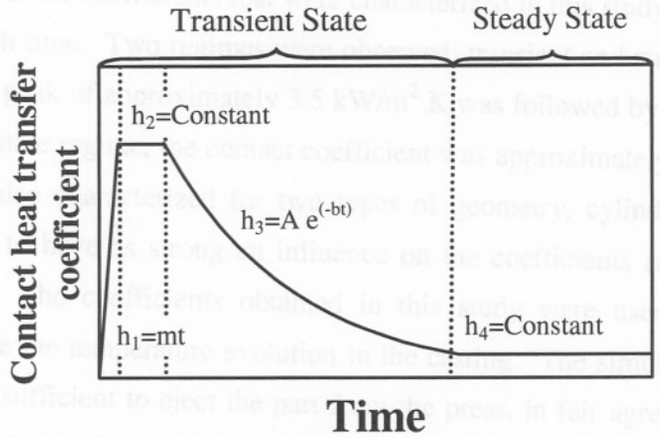

Figure 5. Idealized curve for the evolution of the contact heat transfer coefficient.

When actual suspension parts are cast, experience in the laboratory has shown that after 30 s, they have sufficiently cooled and can be ejected from the mold. The coefficients illustrated in Figure 4 were thus used as interfacial conditions to simulate the heat flow and to determine the temperature evolution in the casting. The simulation was carried out with ProCAST [7] and Figure 6 illustrates the results at four difference times. After 30 s, the average temperature in the casting is approximately 250 °C while in the feeding system is around 375 °C. The calculation thus shows that the casting could be ejected from the mold after 30 s, in fair agreement with the time observed when parts were cast.

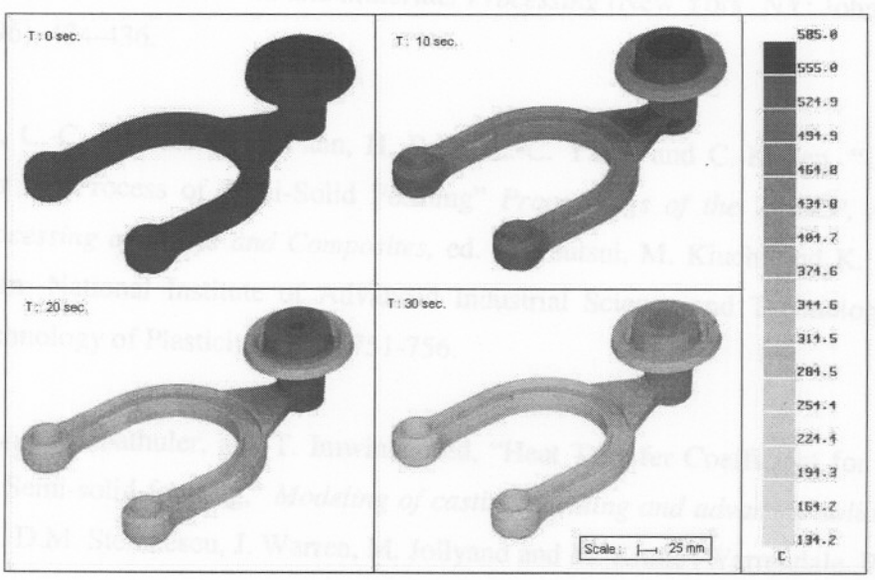

Figure 6. Mapping of temperature evolution during casting of a suspension part.

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Conclusions

The contact heat transfer coefficients that were characterized in this study showed that that they strongly varied with time. Two regimes were observed; transient and steady state. During the transient regime, a peak of approximately 3.5 kW/m^2 K was followed by an exponential decay. During the steady state regime, the contact coefficient was approximately 0.25 kW/m^2 K. The coefficients were also characterized for two types of geometry, cylindrical and rectangular. This did not seem to have as strong an influence on the coefficients as the thickness of the solidified section. The coefficients obtained in this study were used with the ProCAST software to simulate the temperature evolution in the casting. The simulation predicted that a period of 30 s was sufficient to eject the part from the press, in fair agreement with what was observed during casting trials.

Acknowledgments

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