Measuring the Effective Heat Transfer Coefficients at the Mold-Metal Interface in Permanent Mold for the Purpose of Solidification Modeling

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ABSTRACT

The problem of using a reliable value for the heat transfer coefficient (HTC) at the mold-metal interface for the purpose of modeling the filling and solidification inside the mold is a recurrent problem; it has been particularly crucial in permanent mold where it is the overriding factor governing the flow of heat from the casting to the mold. Numerous measurements have been made for simple geometries showing that HTC varies during the course of solidification, dropping sharply when an air gap forms at the mold metal interface. A case rarely studied is the one when the casting is pressed against the mold by the contraction of the aluminum alloy, when HTC increases sharply. The complexity in the phenomenon cannot be practically considered when solving the heat transfer problem so that simplified "effective'' values of HTC are used. Since the HTC's depend greatly on the mold coating practice, our conviction is that these "effective values" should be determined in-house on a wide variety of casting sizes and shape, which implies that the empirical determination of HTC's should be simple. In this paper, a method is proposed where the recordings of two thermocouples is sufficient to determine the HTC's during the filling and cooling phases of the solidification process. The method is demonstrated on the cluster of the standard ASTM B108 test bars, where HTC's values of 550 and 1150 $Wm^{-2}C^{-1}$ were determined for the filling and subsequent cooling part of the process.

Keywords: Solidification modeling, heat transfer coefficients, HTC, permanent mold casting, metal-mold interface

INTRODUCTION

Since the inception of solidification modeling of metalcasting, the measurement of the metal-mold interfacial heat transfer coefficient (HTC) has been a preoccupation. Scores of works on the subject have been published from many universities exemplified by the work of Pehlke,[1] these were mostly carried out on simple geometries, where an air gap is invariably generated at the interface. Rare cases involved a situation where the casting was pressed on the mold,[2,3] with an increase of HTC as solidification proceeds. In one case,[3] it was shown that an initial HTC of 2000 $Wm^{-2}°C^{-1}$ increased to 2750 $Wm^{-2}°C^{-1}$ on the inner core while it dropped to 300 $Wm^{-2}°C^{-1}$ at the mold interface.

Despite the simplicity of the experimental set ups, HTC varied considerably during the cooling and solidification process, as exemplified by the graph in Figure 1, where HTC was determined by the inverse method.[3]

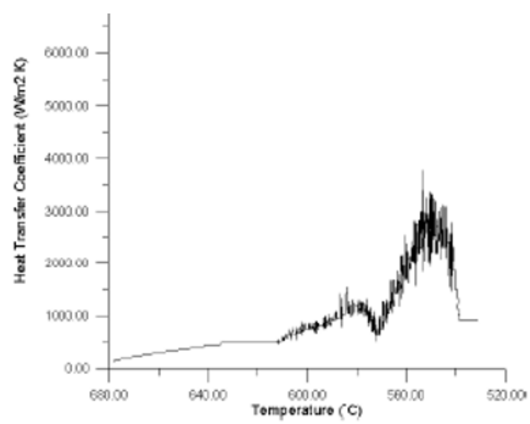

Figure 1. A case of variation of HTC at the interface.[3]

These curves cannot be used for the purpose of modeling the solidification of castings, so that simplifications must be made. A practicable "effective" value for the metal-mold heat transfer coefficient must first be defined. Modeling filling and solidification in a permanent mold requires one to describe the heat transfer between the metal and the mold. This is done by defining a surface heat transfer coefficient (HTC) which, when multiplied by the contact area and the difference in temperature between the metal and the mold, gives the heat power transferred from the metal to the mold.

Hence, HTC is expressed in $Wm^{-2}°C^{-1}$. Innumerable academic studies have been carried out to measure HTC's and what can be concluded from the many results is:

a) HTC's depend a lot on the experimental set-up, however simple it may be.
b) HTC's are dependent on time, or on the metal interface temperature, depending on how one chooses to plot it.
c) When measured continuously, for instance using the Inverse Method, the variation is erratic and cannot be described by a mathematical equation.
d) There is a drop in HTC at some point in the cooling process when a gap forms due to the thermal contraction of the casting.

However, the gap formation is common in simple academic set-ups where the casting surface is free to move away from the mold. In real life, the complex shape of castings makes it that, if the casting may move away from the mold at some locations, it is inevitably pressed against the mold at other locations, resulting in a sharp increase in HTC; this happens in all cases, or the solidified casting would drop from the mold with no ejecting force necessary. Considering the case of the casting shown in Figure 2, one would expect that HTC1 > HTC2 > HTC3.

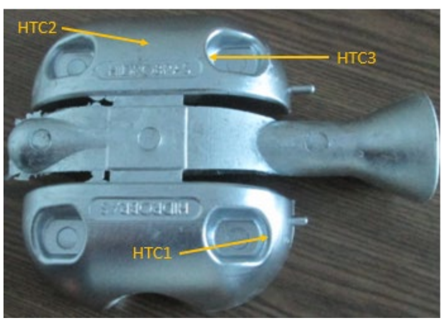

Figure 2. Zones of different HTC values in a casting.

In reality, most of the surface of the casting is pulled away from the mold rather than pressed against it, so that the variation of HTC with temperature is generally represented by the simplified curves shown in Figure 3, even in the more sophisticated commercial codes. The formation of the air gap may be considered by applying a continuous drop in HTC from the liquidus to the solidus temperature (Figure 3a). The model used in the present work applies a step function (Figure 3b) with a drop in the value of HTC of 1/3 at the solidus temperature,[5] it is thought to better represent the gap opening process, which is believed to be discontinuous, i.e., taking place when the internal stresses pulling the casting away from the interface overcome the adherence of the casting to the mold coating. Also, this gap opening can only take place when the casting can sustain a substantial tensile stress, i.e., when it is close to full solidification.

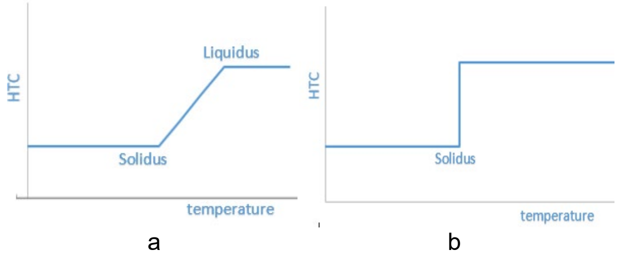

Figure 3. Simplified variation of HTC used in modeling.

If measuring the HTC's will be done on the ASTM B108 standard mold, the method applies to any mold as long as the last metal to fill the mold is accessible for temperature measurement (generally in an open riser). HTC's during filling have been found[6] to be substantially less than during the cooling and solidification process, with values substantially less than 1000 $Wm^{-2}°C^{-1}$. This has been corroborated by the fact that when the mold/metal HTC was not reduced during filling, misruns were systematically predicted which did not actually occur.[7] This can be explained by the fact, during the early phase of the metal/mold coating contact, air is entrapped in the valleys of the peaks and valleys configuration of the coating surface, this air being expelled by the pressure of the metal after filling.[8]

SCOPE OF PRESENT WORK

The objective of the present work is to devise an experimental method to determine the values of "effective" HTCs in molds in operation on the shop floor. This method must be very simple to be implemented in a production environment. The method will be demonstrated by determining HTC's during filling, and during cooling and solidification inside the ASTM B108 standard mold used to produce a pair of 0.5''diameter as-cast tensile test bars. However rough this approach using an "effective HTC" concept might be from a scientific standpoint; it is the most likely to provide the closest results to what takes place in the mold.

HOW EFFECTIVE HTC'S ARE MEASURED

The principle of the method is to record the temperature-time curve in the metal at two locations, at the beginning and at the end of filling, and until complete solidification takes place. The two recordings between the beginning and the end of solidification will allow to determine, by trial and error, the values of HTC's which provide the best fit between the measured and modeled temperatures, first at the end of filling (HTC_{fill}), and then on cooling until complete solidification (HTC_{static}). The casting poured in the present example is shown in Figure 4.

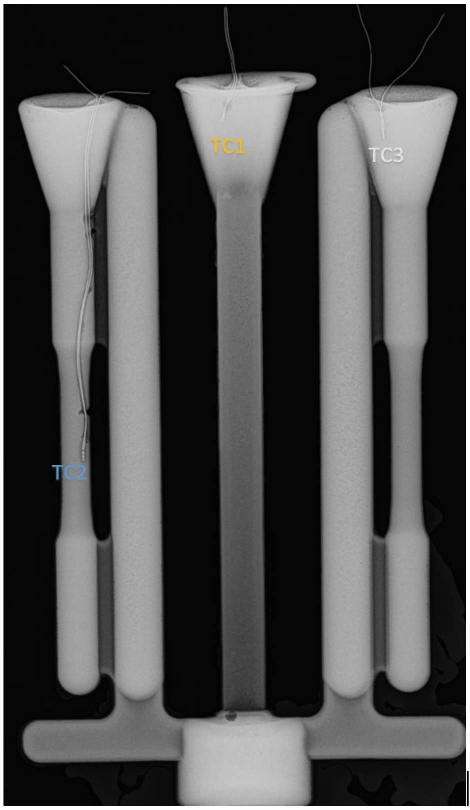

Figure 4. Locations of thermocouples TC1 and TC3.

Thermocouple TC1 is located in the pouring basin, to accurately measure the pouring temperature, while TC3 is located in one of the risers. Thermocouple TC2, located in the reduced section, was used for another project. Points on the TC3 recording will be compared to what is predicted in the modeled solution; values of HTC's will be changed by increment of 50 $Wm^{-2}C^{-1}$ until the "best match" is obtained at these points on the experimental recordings.

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EXPERIMENTAL PROCEDURE

The mold was soaked in an oven to achieve a constant temperature of 400°C ± 5°C (752°F ± 9°F). The pour was done within one minute, after the 2 thermocouples had been placed in the cavity; their exact locations (x, y, z) have been determined by X-ray images at 2 angles of view. The mold coating was one of the most widely used commercial "white" coating; its thickness was measured before heating up, on the flat surfaces of the mold cavity (sprue and bottom channel) at a thickness of 52 ± 15µm.

The experimental recordings are shown in Figure 5. The type K thermocouple wire used, gage 24, resulted in a twisted junction 1.2mm in diameter providing a 0.8s response time in a flow of liquid metal.

FITTING MODELED AND EXPERIMENTAL RESULTS

The temperatures recorded by thermocouples TC1and TC3 are shown in Figure 5. The pouring temperature, given by TC1 was 732C/1350F and the fill time was 6.1s.

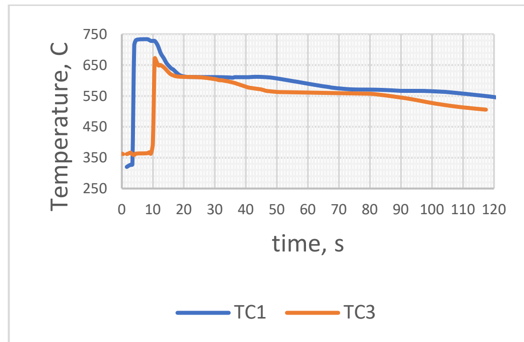

Figure 5. Responses of thermocouples TC1 and TC3.

HTC during filling (called HTC_{fill}) was obtained by finding the best fit between the maximum temperature recorded by TC3 (671C/1,240F) while HTC between filling and solidification (called HTC_{static}) was determined by finding the best fit between the solidification time recorded by TC3 (81s); the solidification temperature used for A356 was 556C/1,033F. The modeled results for the temperature history at points TC2 and TC3 are shown in Figure 6.

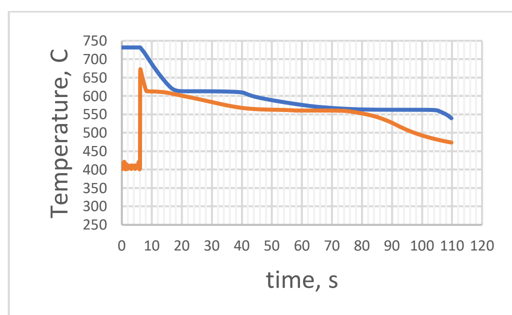

Figure 6. Predicted thermal history at TC1 and TC2.

Using HTC_{fill} = 550 $W.m^{-2}C^{-1}$ results in a predicted maximum temperature of 675C/1247F for TC3, which corresponds to the end of filling, compared to 672C/1242F experimentally. The predicted temperature distribution in the liquid metal at the end of filling is shown in Figure 7.

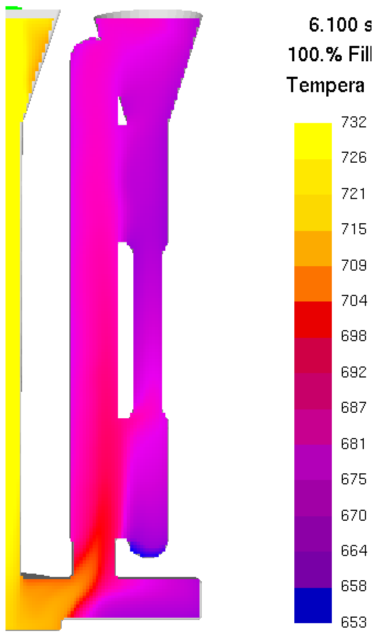

Figure 7. Predicted temperature at the end of filling.

The solidification time is shown in Figure 9. One may argue that, because of the time lag in the temperature recording, the actual maximum temperature at the end of filling would be higher than 671C/1240F, in which case our value of HTC_{fill} would be overestimated. Let us note that in a real bigger casting, this problem would not take place because of the much slower change in temperature after the maximum temperature is reached.

Figure 8. Modeled distribution of the solidification time.

Likewise, using HTC_{static} = 1150 $Wm^{-2}C^{-1}$ after the end of filling results in a predicted solidification time of 78 seconds at TC3, compared to 82 seconds experimentally. One may verify that the predicted end of solidification at the tip of TC1 (104 s) is reasonably close to the experimental value (108 s).

It is noteworthy that HTC_{fill} is less than HTC_{static}, probably due to the fact that, as explained in the introduction, air is not expelled from the valleys of the rough surface of the coating before the liquid comes to rest when pressure and surface tension effects kick in.

Comparing Figure 5 and Figure 6 shows that the difference between the experimental and predicted curves is important in between the anchor points (i.e., temperature at end of filling and solidification time). This highlights the fact that the "effective" HTC does not describe the reality "second after second." As has been demonstrated in numerous academic studies, HTC varies considerably with the setup and during the process in a manner which cannot be put into equation; the straight lines in Figure 3 are oversimplifications which cannot be avoided from a practical standpoint.

This simple way of determining "effective" HTCs should be done in foundries using filling and solidification modeling when designing permanent mold gating/risering systems. These custom "effective" HTCs are bound to produce predictions closer to reality than values determined away from the shop floor, under conditions which by no means resembles what takes place in an actual casting. The exercise should be repeated several times on the same casting to assess its repeatability (or lack of); this will gage the degree of confidence one may attribute to the result of modeling. This uncertainty highlights the elusive nature of modeling in permanent mold, mainly because of the mold coating variability on initial application and during the casting campaign; but also because of additional simplifying assumptions concerning, for instance, the heat losses to the attachments of the mold to the casting machine. The modeler should be particularly aware of these limitations, keeping in mind that the result of modeling is a representation "probably close to the reality" and never the reality itself; this should bring about the necessary caution when interpreting the predicted results of a simulation.

The knowledge of HTC_{fill}, value of HTC during filling, is particularly important in predicting misruns or cold shuts. It must be borne in mind that the numerical CFD solution of the filling problem implies hypothesis and simplifications which are particular to each commercial software; therefore, the predicted filling will never be exactly the same for two different codes (this is not the case when no fluid flow exists). The consequence is that

HTC_{fill} will depend on the software used, which is not a problem if the software used to design the rigging in the foundry is the same that the one on which HTC_{fill} has been determined.

CONCLUSIONS

This paper has described a simple method to determine the "effective" values of the interfacial HTCs between the mold and the alloy during production. When used in filling and solidification modeling, these values are expected to produce predicted results closer to the reality than when determined on laboratory setups which in many ways differ from the production conditions. The method has been demonstrated on the small standard ASTMB108 mold but could be applied as easily on any production mold.

Assuming that the HTCs are constant in value was a necessary oversimplification because it is not possible to mathematically describe the variations of HTCs as a function of the interface temperature; this is why the simplified workable HTCs were qualified as "effective." The mold-casting heat transfer coefficient during filling HTC_{fill}, was found equal to 550 $Wm^{-2}C^{-1}$ while it was equal to HTC_{static} = 1150 $W.m^{-2}C^{-1}$ between the end of filling and full solidification. The reproducibility of these results is not expected to be particularly good; this is why, after carrying several runs, it was found appropriate to have results rounded to multiples of 50 $Wm^{-2}C.^{-1}$

Looking at Figure 9, our HTC_{static} values fall reasonably in line with previous results measured on coatings applied according to the procedures of 6 foundries.[9]

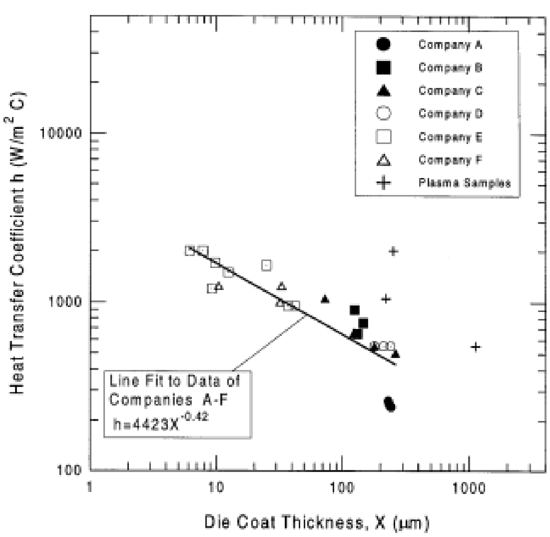

Figure 9. HTC values for different coating procedure.[9]

It is striking that the coating application procedures are very different from company to company, in terms of thickness: around 10-20 µm for company B, up to more than 200 µm for company A; company A used a proprietary coating rather than commercial ones, like most the other companies did. It is important to bear in mind that HTC_{fill} will depend on the CFD code used to solve the filling problem.

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