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EXECUTIVE SUMMARY

Accurate modeling of the metal casting process prior to creating a mold design demands reliable knowledge of the interfacial heat transfer coefficient at the mold metal interface as a function of both time and location. The phenomena concerned with the gap forming between the mold and the solidifying metal are complex but need to be understood before any modeling is attempted. The presence of mold coatings further complicates the situation.

A commercial casting was chosen and studied in a gravity permanent mold casting process. The metal/mold interfacial heat transfer coefficient (IHTC) was the focus of the research. A simple, direct method has been used to evaluate the IHTC. Both the simulation and experiments have shown that a reasonably good estimate of the heat transfer coefficient could be made in the case studied. It has been found that there is a good agreement between experiments and simulations in the temperature profiles during the solidification process, given that the primary mechanism of heat transfer across the gap in permanent mold casting of light alloys is by conduction across the gap. The procedure utilized to determine the interfacial heat transfer coefficient can be applied to other casting processes.

A recently completed project involving The University of Michigan and Mississippi State University, together with several industrial partners, which was supported by the USDOE through the Cast Metals Coalition, examined a number of cases of thermal contact. In an investigation which gave special consideration to the techniques of measurement, several mold coatings were employed and results presented as a function of time. Realistic conditions of coating thickness and type together with an appropriate combination of mold preheat and metal pouring temperature were strictly maintained throughout the investigation.

Temperature sensors, in particular thermocouples, play an important part in validating the predictions of solidification models. Cooling curve information, as well as temperature gradient history both in the solidifying metal and within the mold are invariably required to be validated.

This validation depends upon the response of the sensor concerned, but also on its own effect upon the thermal environment.

A joint university/industry team has completed an investigation of the invasive effects of thermocouples upon temperature history in permanent molds determining the degree of uncertainty associated with placement and indicating how the time-temperature history may be recovered.

In addition to its relevance to the all important study of thermal contact of the casting with metallic molds, the observations also impact the determination of heat flux and interfacial heat transfer coefficients. In these respects the study represents the first of its kind that has tackled the problem in depth for permanent mold castings.

An important ramification of this investigation has been the errors likely to be encountered in mold temperature measurement with thin section aluminum castings, especially with respect to the plans for thermocouple placement.

A comparison between the degree of uncertainty experienced in sand molds compared with that found in permanent molds reveals that the associated problems have a lesser impact.

These conclusions and the related recommendations have been disseminated to industry and the technical community through project reports and publications.

INTRODUCTION

For the simulation of permanent mold casting, the interfacial heat transfer coefficient (IHTC) is the most important factor in determining the cooling rate which must be controlled. In order to make castings solidify directionally, hence resulting in high quality, the role of the IHTC cannot be emphasized enough in the prediction of freezing patterns during solidification. The solidification analysis during filling is crucial for thin sections to avoid premature freezing.

There has been a lot of research on both the experimental procedures and modeling to understand the complexity of heat around a wide range, 500-16000 W/m²K [1]. A large number of them have been focused on rather simple castings, either a plate mold or a cylindrical shape [2-7]. Although they have shed some light on the behavior of the heat transfer at the metal-mold interface, they cannot represent the real world, which includes a lot of complicated castings. In this paper, we have selected a commercial casting, called a hubcap, as our test piece. A number of experimental trials have been conducted with temperature measurements in both the casting and the mold. A large number of simulations have been carried out and the virtual temperature measurements have been compared with those obtained experimentally. An evaluation of the value of the IHTC was then made based on the comparisons. The use of the procedure in determining the heat transfer coefficient has been discussed. It is concluded that the procedure can be applied to other casting processes.

Calculation of the heat flux requires accurate temperature measurement near the mold side of the interface. These temperatures are highly transient, particularly in permanent mold casting processes, and are difficult to measure accurately. The method generally used to determine the temperature near the mold-side of the interface is to embed a thermocouple near the mold wall (8-11).

Distortion of the thermal field is a problem with embedded thermocouples. In permanent molds, a hole is typically drilled in which the thermocouple is placed. This cavity contributes to the distortion of the thermal field (12). In contrast, for sand molds there is usually no cavity, depending on how the thermocouple is embedded, since the mold distortion by embedded thermocouples is the heat conduction in the thermocouple and its insulator. Also, the orientation of the thermocouple affects the distortion of the thermal field depending on whether the couple is parallel or perpendicular to the temperature gradient (13,14). Ruddle has recommended placement parallel to the temperature isotherms, minimizing conduction down the thermocouple (15).

Xue, et al. have made a one dimensional parametric study of errors in thermocouple measurements (16). In the present work, a comprehensive, three dimensional finite element model was used to evaluate embedded thermocouple configurations for molds of mild steel and sand.

Parallel analytical/computational studies were conducted of how the true time-temperature information, which is strongly affected by the intrusion of thermocouples into the mold medium, may be recovered. Subsequently recommendations have been made regarding appropriate temperature measurement practice. A fully documented report on the project is to be made available through AFS.

This research which was highly focused on permanent mold casting promises to provide the basis for improved mold design and the resulting control of heat transfer which will raise the quality and reduce scrap. In this way, significant energy savings would be realized in this segment of the casting industry. Also, the use of the results developed in this research can be applied to other casting processes. There should be economic benefit to the domestic casting industry.

As quoted in Modern Casting (17), "the financial incentive to reduce scrap can be easily seen when it is demonstrated that a 5% reduction in scrap rate would net a 25% increase in bottom line profit." Conversely, "an excess scrap rate of 15% also can compound the financial loss if the customer asks the foundry for a re-run to make up for the short shipment. Including the cost of re-running the castings, the foundry suffers a 56% reduction in profit due to the excessive foundry scrap."

The potential energy savings can be addressed directly. The designs of castings which would benefit the most from optimized mold cooling/heating involve large and/or complex geometries, which are widely used in automotive applications. Apart from the lead time reduction benefits, there are substantial energy savings which can be attributed to optimization. The productivity improvements identified result in reduced energy consumption for a given level of production and reduce total energy requirements.

If the shipments of aluminum permanent mold and die castings are 1,652,000 tons/yr (18), allowing for 4% growth in the market for the next ten years, this comes to 24,545,000 tons over the next ten years. As there are riser, etc. associated with the castings, the actual mass of cast metal would be roughly double the shipped casting mass, such that the mass of metal cast comes to 48,900,000 tons. If the energy required to manufacture these castings is 23.4×10^6 BTU/ton (19), then the energy required to produce these castings over the course of the next ten years comes to 1.14×10^{15} BTU. If the amount of scrap, reworked material and lost production which is reduced by implementation of this program averages out to 8% of the total, and the penetration of these techniques into the industry affects 40% of the castings produced, then the total energy saved is 3.66×10^{13} BTU.

There are also substantial potential environmental benefits which can be estimated. The environmental benefits can be addressed in terms of the reduction of scrap, which if it is only 8% of the total and affects 40% of the castings produced would be 782,400 tons. In addition, perhaps 80% of this scrap could be recycled, such that 20% or 156,480 tons of primary aluminum would be required to supply this casting market over the next 10 years. The additional required 156,480 tons of primary aluminum

would result in emissions of: 657 tons of particulate, 2817 tons of SO_x, 227 tons of NO_x, 19,560 tons of CO, 219,072 tons of CO₂, 20.3 tons of organics and 203 tons of fluorides (20). This additional primary aluminum would generate solid waste: 17.2 tons of liquid waste (oils, grease), 31.3 tons of packaging, 13.5 tons of environmental abatement, and 587 tons of other waste (21). The melting and casting processes would add various environmental emissions and solid wastes depending on the processing. These effluents could include fluorides, chlorides, copper, lead, zinc, phenols, oils and grease, suspended solids, lubricants, dross and other solid wastes (22).

BACKGROUND

The objectives of the research have been to provide the basis for modeling permanent mold casting which would be broadly applicable to other processes, including low and high pressure die casting, squeeze casting, and semi-solid casting processes, as well as other casting processes. The project has involved solidification modeling, including mold filling, interfacial heat transfer measurements with consideration of the effects of mold coatings, and construction of a thermal modeling reference source. This portion of the project has been supported by the thermal measurements. Experimental verification was used to evaluate the modeling efforts, and was supported by in-process measurements. An inverse heat transfer procedure, utilizing thermal measurements of the casting process has provided descriptions of thermal contact between casting and a test mold.

The research offers the casting and process designer the capability of optimizing the design of the casting and related mold, and to accomplish this in a much shorter time with far less trial and error and a shorter concept to part time. This organized understanding of heat transfer at the mold/metal interface provides the basis for the production of castings with thinner walls, of lighter weight, with high integrity, less distortion, and increased yield with the concomitant savings in energy.

Domestic and international technologies are viewed as moving concurrently in a global economy and an era of every increasing communication, particularly in the area of permanent mold casting processes, mold design and the supporting computer implemented modeling for related and supporting technologies.

Heat transfer between a solidifying casting and the mold is critical for achievement of high quality in the cast product. This is especially important in permanent mold casting where the rate limiting steps for heat transfer between the casting and the mold are primarily controlled by conditions at the mold-metal interface. The mold-metal interface is emphasized, since as the casting solidifies, it tends to shrink which creates areas where gaps form between the casting and the mold surface. Quantification of these conditions is key to understanding the permanent mold casting process and optimizing the casting process.

At the 1995 Conference on Modeling of Casting, Welding and Advanced Solidification Processes, Pehlke (23) reviewed the status of technology with regard to the modeling of heat transfer at the mold/metal interface in permanent mold casting. Examples of permanent mold casting modeling were presented where estimates of interfacial heat transfer were used. The serious limitations imposed by resorting to these estimates were described.

The most common industry practice is to assume interfacial heat transfer coefficient (IHTC) values that are constant during the casting cycle, although some modelers have used time or temperature dependent values. These coefficients are only estimates, based on engineering judgement. Variations in IHTC over the surface of the casting are generally not accounted for, except by rough estimates. In the case of permanent mold casting, metal-mold heat transfer, as for example, indicated by solidification time as discussed below, is very sensitive to the interfacial heat transfer coefficient. A quantitative basis for establishing IHTC's is needed by the industry.

Several methods can be used to determine the metal/mold heat transfer coefficient from a knowledge of internal temperatures in the mold. One being used currently at the University of Michigan is a forward feed approach in which heat transfer coefficients and their variation with time in the casting cycle or local temperature are assumed and heat transfer simulation results are compared with thermal monitoring. This method is slow, perhaps cumbersome, but has been greatly enhanced with advances in computer hardware.

The numerical method that enables determination of the interfacial heat transfer coefficient from a knowledge of temperature histories at interior points on both sides of the interface is an example of the inverse heat conduction problem. The use of this technique has been applied in shaped casting solidification by Ho and Pehlke (24,25). More recently, Das and Paul have used the Boundary Element Method to implement the inverse heat conduction method and to examine interfacial heat transfer in casting and quenching (26).

In the ordinary direct heat conduction problem, either temperature or heat transfer conditions are prescribed on the surface of the body, and a solution at the interior points of the body is desired. In contrast, the inverse heat conduction problem seeks to determine the surface temperature or heat flux from a knowledge of other conditions, such as temperature histories at interior points. Difficulties arise in the solution of the inverse heat conduction problem as a consequence of the diminished and delayed thermal response in the interior of a body. Errors associated with the use of truncated temperature data at an exterior point are numerically amplified during the determination of the time varying thermal conditions at the surface. Moreover, since solidification of a casting involves 1) a change of phase and 2) temperature variable thermal properties, the inverse heat conduction problem becomes nonlinear.

A new method for solving linear, inverse heat conduction problems using temperature data containing significant noise has been applied in this research. The main

advantage of the method is the robust treatment of noisy temperature data and lack of ad hoc parameters. The method avoids amplification errors in temperature data by properly conditioning the inversion procedure through singular-value decomposition. The technique has been applied to derive interfacial heat flux and time varying thermal contact resistance from experimentally obtained A356 sand cast temperature data (27).

Ho and Pehlke (24) developed a comparison of the solidification time as influenced by a variation in thermal resistance at the metal-mold interface. The extent of the influence is dependent upon the thermal properties of the mold as well as that of the cast metal. However, thermal properties of mold materials generally vary within much broader extremes than those of the cast metals. In order to compare the influence of interfacial heat transfer with some typical mold materials, a purely computation example was chosen considering the solidification time required to freeze unidirectionally 3 cm of pure aluminium initially at the freezing temperature, against a planar mold. Three mold materials were considered: copper, low alloy steel, and dry sand. A simple finite difference computer program was used to solve this one dimensional heat flow problem with solidification.

The results of this numerical example reveal some important implications on the computer aided modeling of solidification in casting, particularly for permanent mold and die casting. This work illustrates that for metallic molds, the sensitivity of solidification time to interfacial thermal resistance is much more prominent than in the corresponding case for sand molds. For permanent mold or die castings, special research efforts should therefore be directed toward the study of interfacial heat transfer.

The understanding of interfacial heat transfer between a casting and its mold is critical for the achievement of high product quality. To improve casting quality, solidification software is being used with greater frequency. In order to accomplish the modeling, thermal contact has been oversimplified in current studies of solidification. Development of a better understanding will permit production of castings with thinner walls, of lighter weight, of higher integrity, at lower cost and with improved mechanical properties. This is of particular importance with aluminum castings produced by the permanent mold process.

Specifically, the process of permanent molding provides the greatest challenges which relate to the need to reduce prototyping times, mold costs, attaining higher casting yields and facilitating more efficient production which will contribute significantly to broad energy savings. The market for such castings is the automotive industry where substitution for iron and steel components present continuing opportunities.

The project team has drawn upon the resources of two universities, the University of Michigan (UM) and Mississippi State University (MSU). The two co-principals have a long and successful history of working together and are recognized as leaders in the

area of solidification heat transfer. Each has received numerous national awards and each has managed successfully several million dollars of research. They were supported by innovative and productive research groups. A consortium of several industry units has provided appropriate facilities and technical know-how. Three software houses have also supplied licenses to the universities, and have undertaken simulation work on an in-kind basis. The project was guided by a steering committee made up of representatives from the industrial partners.

Professor Robert D. Pehlke at UM and Professor John T. Berry at MSU both have been conducting casting research programs for over 30 years. In addition to Professors Pehlke and Berry, Dr.'s Rogelio Luck and Jeff Shenefelt will participate on the MSU team. Their specialty is inverse methods in heat transfer applications. They were wholly responsible for the development of a recently published technique, for determining interfacial heat transfer coefficient data with a low degree of uncertainty (27).

RESULTS

A. Solidification Modeling of a Commercial Casting

A commercial 4 cavity hubcap casting to be thermally monitored at the Hayes-Lemmerz Technical Center in Ferndale, Michigan was chosen. Experiments were conducted on the 30 lb A356 casting shown in Figure 1. Temperatures were monitored at 7 locations, with two in the casting. The casting temperatures were recorded using Nanmac thermocouples while those in the mold were monitored using K-type thermocouples, as shown in Figure 1. The mold was coated prior to use with an insulating mold coating provided by Foseco International Inc. Metal temperature was monitored in the casting ladle immediately prior to pouring. Pouring temperatures were controlled to within ± 20 C and the mold temperatures were controlled to within $\pm 2^{\circ}\text{C}$. A constant cycle time was maintained, One of the thermocouples in the mold was used to determine the start of the next cycle in a continuous mode. A minimum of 15 cycles were cast for each trial. The experimental conditions were the following:

- Mold initial temperature: 260°C
- Pouring temperature: 728°C
- Dwell time 120 seconds
- Average pouring time: 9 seconds
- Thermal data acquisition: every 0.5 second

A summary of these experimental results are presented in Appendix 1. The temperature vs time curves shown in Figure 2, represent an experimental trial where 25 cycles were conducted. The temperatures, representing the average of two sets of experimental data in the mold cavity, were recorded by means of Nanmac thermocouples, namely TC #1 shown in Figure 1. This thermocouple is at the surface

of the mold cavity. A corresponding simulated temperature profile will given later, in order to make a comparison.

Figure 1 A schematic diagram of the hubcap casting of A356 with the locations of thermocouples.

Figure 2 The cooling curves for all 25 cycles in the hubcap casting represented by TC #1.

It can be seen that except for cycle 17 which has a longer cycle time due to metal leaking out the back of the mold, the cycle time throughout the trial was very consistent. It was found that the casting quality was good in the trial.

The Effect of Mold Temperature

Because of the complexity of the casting, initial experiments were conducted to determine the optimum mold temperature so that all parts could be filled. In the later trials, a constant dwell time of 120 seconds was maintained regardless of mold temperature. It was found that it took the mold 16 cycles to reach a steady state, at which point the casting condition was considered ideal and the starting

Figure 3 The starting mold temperature for each cycle in a trial.

mold temperature was close to 700°F. The starting mold temperature for each cycle in this trial is shown in Figure 3.

The Effect of Mold Coatings

The issue of heat transfer from casting to mold is a complex one, and no single theory or set of empirical data describes the process accurately. This is mainly due to the fact that mold coatings are always used in permanent mold casting of aluminum alloys, and that the formation of an air gap is an inevitable consequence of the solidification process. In this work, the effect of mold coatings and the air gap at the metal-mold interface is not directly investigated. Instead, their influences on the rate of heat transfer at the interface are reflected in the value of the IHTC to be determined by comparing the modeling with experimental trials.

The Effect of Metal Temperature

The metal temperature was set at 1350 F for all cycles throughout the trial. Figure 4 shows the metal (pouring) temperature and the maximum temperature observed in each cycle in the hubcap casting. It can be seen that the maximum casting temperature measured reached a steady state after about 15 cycles. This is consistent with the observation of the temperature changes in the mold in the same trial.

Figure 4 The metal temperature for each cycle in a trial.

The Effect of Cycle Time

In order to evaluate the rate of heat transfer without affecting the quality of castings, a reasonable value of cycle time should be determined. The hubcap castings were cast using different cycle times. The intention was to reduce the cycle time, but not place the casting quality in jeopardy. Table 1 shows the average cycle time for each trial.

Table 1 The Average Cycle Time for Each Trial

Trial No.	Dwell Time (seconds)	AVG Cycle Time (seconds)	Casting quality
1	140	317	Poor
2	125	295	poor
3	120	227	good
4	120	218	good
5	120	236	good

An average cycle time of 227 seconds, including a dwell time of 120 seconds, provided the highest casting quality.

Modeling Procedure

Interfacial Heat Transfer Coefficient

In order to determine the heat transfer coefficient at the metal-mold interface, it is necessary to know the heat flux and the surface temperature of the media at both interfaces. The rate, at which heat is transferred by conduction, q , is proportional to the temperature difference, shown as:

$$q = h(T_{cast} - T_{mold})$$

where h is the interfacial heat transfer coefficient (IHTC) and T_{cast} and T_{mold} refer to casting and mold surface temperatures, respectively.

However, it is not feasible to experimentally measure directly the surface temperatures. It is a common practice, though, that thermocouples be placed as close to the surface as possible so that the surface temperature could be later determined, using the so-called Inverse Heat Conduction Problem (IHCP). This is not the procedure used to determine the IHTC in this work. Rather, a direct method is used, meaning that the IHTC is evaluated by finding the best match between the experimental and simulated temperature profiles in the casting. This is becoming a more commonly used approach with the rapid advance of both hardware and software in computer technology.

Modeling Parameters

MAGMAsoft, a commonly used commercial software, was used in the analysis of filling and solidification. In order to increase speed without sacrificing accuracy, different approaches to meshment were used for the mold, the casting, and the thin sections such as the inlet. The resulting model contained a total of more than 6 million control volumes, of which 537,240 are in the casting.

Comparison of Modeling and Experiment

In the cyclic experimental trial, it was found out that it usually takes about 10 – 15 cycles to reach equilibrium temperature conditions, namely the so-called steady state in the mold. Therefore, thermal simulations were conducted at least 15 times (cycles) in each run so that temperature profiles obtained could be compared with experimentally measured profiles.

At the beginning of simulation stages using MAGMAsoft, the initial temperature used was 728 °C, with the mold temperature at 260 °C. The heat transfer coefficient used was from the MAGMA database, the profile of which is shown in Figure 5. A total of 25 cycles were modeled in the first version without filling analyses. In the second run, 5 cycles were carried out and the filling analysis was conducted at the 5th cycle. Figure 6 shows the cooling curve for the 5th cycle in the second run using the IHTC function (IHTC-2) in Figure 5. The cooling curve obtained experimentally is also included in Figure 2 for comparison purposes.

Figure 5 Metal surface temperature dependent IHTC from MAGMA database.

Figure 6 Comparison between the modeling and experimental cooling curves of the hubcap casting

It can be seen from Figure 6 that there is a discrepancy between simulation and experiment. The casting temperatures obtained in the experimental trials are always lower than those in the modeling. The difference is about 50 °F (27.8 °C). One of the reasons for this discrepancy was believed to be the improper selection of initial metal temperature and mold temperature in the simulation settings. According to MAGMA, T_{initial} should be the temperature when the molten metal first comes into the inlet, which is, of course lower than the pouring temperature measured. The issue of mold temperature is more complex because it depends on whether a filling analysis is conducted in the “warm-up” cycles before the mold reaches a steady state. When “do filling” is switched off, the subsequent solidification simulation will start with a uniform temperature. Otherwise, it will start with the temperature profile obtained from the filling analysis, which of course provides a non-uniform temperature distribution throughout the mold. The results show that the solidification simulation can better describe the heat transfer behavior at the metal-mold interface when the filling analysis is included. Such an approach was always applied in later runs.

Another possibility was that the IHTC profile was not a good description of what really happens at the interface. After some trials, a reasonably good IHTC was chosen for the computer simulations. The initial metal and mold temperatures were adjusted as well. Figures 7 and 8 show the IHTC function (IHTC-35) and the simulated cooling curves when such an IHTC function is used.

Figure 7 Metal surface temperature dependent IHTC (self-defined)

Figure 8 The cooling curves of A356 obtained from both simulations and experimental trials.

There is a reasonably good agreement in the temperature distributions between simulation and experiment in V35. The simulated cooling curve can be shifted downward 30 °F (16.7 °C) to have an almost perfect match with the experimental one. The IHTC used in this run is a good estimate of the overall heat transfer behavior at the metal-mold interface. Therefore, such an IHTC is considered to be accurate to represent the value for the hubcap casting in the present permanent mold casting process of aluminum alloy A356.

Although a rather complicated permanent mold casting was chosen, it seems possible that the IHTC could be estimated in a fairly easy manner. The evaluations of some of the complex issues like the mold coating thickness, the air gap forming between the casting and the mold, and casting geometry could be avoided in such a process. Investigation can be focused only on the comparisons between the experimental and modeling cooling curves in the casting. More modeling efforts can be focused on finding appropriate simulation set-ups so that the virtual temperature distributions can be as close to the experimental ones as possible. The selection of the IHTC is critical. A good starting IHTC function can save a lot of simulation time and its selection depends on a modeler's experience or available data in published work. At least, an approach of trial and error, although sometimes time-consuming, can almost always lead to a reasonably good estimate of an IHTC or set of IHTC's. Table 1 gives the simulation set-ups under which Figures 7 and 8 have been obtained. It can be seen that the IHTC function plays a significant role in reaching a good agreement between experiment and simulation.

Table 2 Simulation Set-ups for Each Modeling Version

Version No.	IHTC Function	T_{initial} (C)	T_{mold} (C)	Filling Analysis	Cycle Definitions		
					Cycle #	Dwell Time (s)	Cycle Time (s)
1	IHTC-1	728	260	No	5	120	230
2	IHTC-2	728	260	Yes	5	120	230
35	IHTC-35	680	267	Yes	15	120	230

B. The Determination of Accurate Heat Transfer Coefficient Data for Permanent Mold Aluminum Alloy Casting

Background

There is now an immense body of knowledge concerning the measurement of heat transfer coefficient data in casting applications. A previous paper by Weathers et al, (2005) cited several recent publications (28). Other works describing practical aspects of determinations, which will be of value to practitioners calling on casting simulation to solve pouring and freezing related problems, are cited here (29-35). Several of these contain comprehensive discussion of the literature.

As has been pointed out by Weathers, et al, locating temperature sensors within a metallic mold in order to determine interfacial heat transfer coefficient data involves drilling of holes and the placement of the sensors (for example, thermocouples) themselves (28).

The very act of removing material and, further, replacing that material with what is obviously a second and third, and possibly a fourth material (the two thermocouple wires and the layers of insulation) all disturbs the thermal field set up by the heat flux. The earlier work of Weathers et al, pointed out that the orientation of the holes drilled will also have an effect on the degree of disturbance of the thermal field (28).

All of these effects are initially strongly time dependant and thus are of special importance where thin sectioned castings are involved, for example in die-cast parts.

Experimental Approach

Metal casting facilities located at Mississippi State University were used to conduct all of the experiments involved. Aluminum A356 was chosen as the casting alloy because of its wide commercial use. The permanent mold employed for the study was a three-piece low carbon steel assembly with a simple, rectangular top-poured

slab plate geometry. The mold was designed to accept one of four interchangeable center inserts having thickness of 1/8", 1/4", 1/2", and 1", respectively. The 1/2" insert was selected to be used for the entirety of the present project. Photographs of the three-piece steel mold in its disassembled and partially assembled form are shown in Figure 9 and Figure 10. A dimensioned drawing of the mold is presented in Figure 11.

Figure 9- Three-piece Steel Mold (disassembled)

Figure 10- Three-piece Steel Mold (partially assembled)

Figure 11- Permanent Mold Dimensions

Although not all castings are exceedingly complicated geometrically, a recognized benefit of metal casting is that it can be used to create complex geometries that would normally prove difficult or even unattainable to produce by other processes, such as machining. Nonetheless, this program's goals focused on the methodology and procedure of obtaining "good" temperature data for the prediction of heat transfer coefficient data through inverse methods. Therefore, it was considered best to begin the study with a very basic, understandable geometry, and leave more complex casting geometries to be considered in the future.

Permanent mold practice involves spray on mold coatings used to protect the mold and also attempt the management of solidification at specified locations within a casting, such as gates, runners, or feed paths. These coatings add a heat resistive layer on the mold cavity surface to slow solidification, and in some instances, improve the casting surface finish. Because the same thin or narrow section areas in castings which receive coatings are often the critical areas of interest in casting simulations, mold coatings can bear an important role. Therefore, multiple experiments were performed at Mississippi State to collect sets of experimental temperature data

representative of typical industry standards, with the intention of calculating interface heat transfer coefficient data for each configuration.

An industry standard base coating media and insulating media, Foseco Dycote 39ESS (base coat) and Foseco Dycote 34 (insulating coat), were donated for use in the experiments.

Determining Interface Heat Transfer Coefficient (IHTC) Data

Following the collection of experimental temperature data, the heat flux at the mold-metal interface was estimated using the matrix transform method reported by Shenefelt (36), combined with a three-dimensional finite element model as comprehensively reported by Weathers (37). The solution to the inverse portion of this problem is the most arduous step in determining the IHTC. Once inverse estimates of time dependent heat flux values are determined, they are used as the input to the three-dimensional finite element model to establish an estimate for the mold-metal interface temperature, T_i . A discrete, time dependent interface heat transfer coefficient (IHTC) can then be evaluated for a given coating experimental configuration using:

$$IHTC_t = \frac{q_t}{T_{c_t} - T_{i_t}} \quad \text{Equation 1}$$

where q = estimated heat flux
 T_c = casting temperature
 T_i = interface temperature
 t = discrete time index

The IHTC data obtained using the method described in this section is a time-dependent lumped heat transfer coefficient. The resistance to the flow of heat through the interface can be attributed to several factors including mold coating type and air gap formation. These factors are accounted for in the experimental temperature data and, consequently, the heat flux and interface temperature calculations.

Three thermocouples concerned in the experiments were installed in the mold at two unique distances from the interface of 0.04 inches and 0.185 inches . (See Figure 11) The purpose of the installation of more than one thermocouple within the mold was for assurance that at least one channel of data would be useable ideally. A further thermocouple was located at the centerline of the casting.

Experimental results

The data obtained in the above experiments are described in full in the report to be published by AFS (It is also described in the MSU master theses of Mr. James Weathers and Mr. August Johnson which are summarized in Appendices 2 and 3, respectively).

Figures 12 through 15 show the IHTC data obtained together with a record of the metal temperature. Each IHTC curve presented represents the mean of data contributed by three thermocouples.

Four coating conditions are included representing extremes in practice. They apply only to vertical surfaces for metal-coating-mold conditions described previously. Prior to each coating application, the application contact surfaces of the mold were sand blasted at 80 psi with 25 -70 mesh size aluminum oxide. These coatings were then applied per the recommended coating procedure in configurations and thicknesses shown in Table 3. An experimental run was performed and temperature data were collected for each configuration.

Table 3. Mold Coating Configurations

ID	Number of Replications	Coating Configuration	Pours/ Replication
1	1	No Coating	1
2,3	2	Base Coating @ 2 mils	1 – 3
4,5	2	Base Coating @ 2 mils + Release Coat BN	1 – 3
6,7	2	Base Coating @ 2 mils + Insulating Coating @ 2 mils (light)	1 – 3
8,9	2	Base Coating @ 2 mils + Insulating Coating @ 4 mils (heavy)	1 – 3

Multiple replications of each configuration were run, and several castings were produced per coating application. The temperature data collected from each run were used to determine, through inverse methods, the heat flux at the mold-metal interface, and subsequently a time dependent interface heat transfer coefficient for each configuration. The mold preheat was obtained by heating the mold set in a muffle furnace and was maintained at $400^{\circ}\text{F} \pm 5^{\circ}\text{F}$. The metal superheat was

maintained between 1290-1300°F. The metal concerned was carefully selected high quality scrap from previous investigations reported by Zhang et al, (38). No further metal treatment was undertaken.

Figure 12 – Avg. Heat Transfer Coeff.: Base Coat @ 2 mils

Figure 13 – Avg. Heat Transfer Coeff.: Base Coat @ 2 mils+Boron Nitride Lubr.

Figure 14 – Avg. Heat Transfer Coeff.: Base Coat @2 mils+Insulating Coat @2 mils

Figure 15 – Avg. Heat Transfer Coeff.: Base Coat @2 mils+Insulating Coat @4 mils

Discussion of interface heat transfer coefficient (IHTC) results

It will be seen that not only is the IHTC data highly time dependent; but as the coating material increases in thickness, its resistance to the flow of heat also increases. Consequently, the thickest coating would be expected to produce the lowest peak IHTC. In contrast, the thinnest coating should produce the largest peak IHTC. The 2 mil base coat and the 6 mil base coat/insulating coat combination are the thinnest and thickest, respectively, of the coating combinations. Therefore, one would expect these coatings to produce the two extreme IHTCs. Indeed, the 2 mil base coat produces the largest peak IHTC (2.7 BTU/in²-hr-F @ t = 34s) and the 6 mil base coat/insulating coat combination produces the smallest peak IHTC (1.2 BTU/in²-hr-F @ t = 21s).

As an alloy solidifies, the casting begins to separate from the interface, and a gap forms. It is often assumed that this does not occur until the coherency point is reached, that is a rigid dendritic network is then in place. The air or gases filling the gap will then contribute to the resistance to the heat flux. As a result, the IHTC should begin to decrease as coherency occurs. This probably takes place just prior or at the start of the eutectic precipitation as noted by Gunasegaram et al (39). In each case presented previously, the IHTC certainly begins to decrease just prior to or at the beginning of the eutectic plateau.

In connection with the features of this time dependence of the IHTC data, it should be pointed out that many previous investigations were concerned with cast sections considerably heavier than those associated with common permanent mold practice. Consequently, the time scales involved will differ greatly from those observed in the present series of experiments. Noteworthy is the fact that under those conditions (overly thick sections) the effects of thermocouple embedding etc. eventually minimize.

Discussion of Potential Errors and their sources

When attempting to estimate the IHTC inversely, it is important that the experimental temperature measurements be as accurate as possible. The thermocouples should be installed such that the installation error is kept to a minimum. That is, the positioning of the thermocouple relative to the isotherms is crucial in dealing with transient temperature measurements. Properly positioning the thermocouple will greatly reduce the installation error. Ideally for permanent molds, the length of the thermocouple should be situated perpendicular to the isotherms. This configuration produces less overall error in temperature measurements and allows for more control of the distance between the interface and the thermocouple bead. In sand molds, the thermocouple should be positioned parallel to the isotherms, which leads to less conduction through the lead wires and, thus, more accurate temperature measurements.

Regardless of the thermocouple configuration relative to the isotherms, the installation error can never be totally alleviated. The installation error however can be partly undone through the matrix transform method. A realistic model should thus account for the installation error.

The noise in the thermocouple signal poses a problem due to the unfortunate amplification that occurs in the inverse analysis. The matrix transform method allows the noise to be filtered using singular value decomposition (36).

A full discussion of the problems associated with embedded thermocouples (those within the mold) is to be found in Appendix 4 in the report to be published by AFS.

The following bulleted summary on embedded thermocouple practices for permanent molds is documented in the summary presented as Appendix 4, mentioned immediately above/

C. Embedded Thermocouple Practices for Permanent Molds

- Check continuity of thermocouple using a multi-meter to ensure that thermocouple bead is in proper contact with the metal mold.
- External high frequency noise/interference can be reduced by turning electrical devices such as fluorescent lights, ovens, fans, etc. off during the time period when temperature data is actually being recorded by DAQ equipment.
- Use of a shielded data acquisition cable and connector block can help shield the electrical connectors and circuitry from external high frequency noise.
- Use of twin bore ceramic insulating sleeves for portions of thermocouples to be inserted within the mold to:
 - Control bead location at base of hole
 - Prevent “short circuit” of thermocouple wires above the thermocouple bead
 - Allows for a means to affix the thermocouple wires to the mold using high temperature cement
- A common cold junction reference temperature is used for all thermocouple channels. The common cold junction reference temperature is set using an ice bath and the thermocouples are wired in way such that each thermocouple can use the same common cold junction.
- Thermocouple insertion holes are drilled as small as possible in the mold in order to reduce the total amount of subsequent distortion to the temperature field.
- Thermocouple beads should be as small as possible in order to provide more of a “point of contact” temperature reading rather than an average over a larger volume (for larger beads).

- The drilled holes should be clean and as free from rust as possible to ensure good contact between the mold material at the base of the hole and the thermocouple bead.
- Refer to “The Effects of Thermocouple Placement on Highly Transient Temperature Measurements” submitted for acceptance to AFS by MSU in October 2004 for further details on the suggested orientation for thermocouples.

D. The Importance of Sensor Placement In Support of Solidification Modeling

In this phase of the project, the placement of embedded thermocouples was modeled in both a mild steel mold and a sand mold. This research effort is described in an AFS Casting Congress paper which is presented as Appendix 5.

Finite Element Modeling

The finite element modeling considered a block of material with an embedded thermocouple. Model 1 simulated the measurement of temperature near the mold-side of the mold/metal interface in a permanent mold. The model described a block of mild steel with an embedded type-k thermocouple protected by a twin-bore, alumina insulator with the thermocouple bead in contact with the base of the cavity. The block had an initial uniform temperature of 600 F and a step temperature of 1200 F was imposed on one face of the block. Three cases were considered for Model 1: (1) a thermocouple mounted with its length parallel to the thermal gradient; (2) a thermocouple mounted perpendicular to the thermal gradient; and (3) no thermocouple as a reference for comparison of cases 1 and 2. Model 2 simulated a sand mold in a similar manner with the same block dimensions and thermocouple placements. No preheat was applied to the sand mold. The material properties were constant with respect to temperature. The time dependent solution for each model was obtained using 100 3.6 second time steps.

Discussion

The finite element analysis illustrates the importance of thermocouple placement for measurement of transient temperatures. The drilled hole becomes a source of thermal field distortion. As a result, the temperature at the base of the hole will be offset relative to the "ideal" temperature. Model 1 presents the distortion due to the combination of the thermocouple and the hole in permanent mold casting. The air between the thermocouple bead and the wall of the hole acts as a thermal barrier which causes the vertically positioned thermocouple to produce lower temperature measurements. When the thermocouple is positioned perpendicular to the isotherms, it is subjected directly to the heat flux. Thus, the horizontally placed thermocouple produced a maximum error of about 10.8 F which is substantially less than the error produced by the vertically mounted thermocouple (-45.4 F), although this error requires more time to dissipate.

Also, the horizontally positioned thermocouple has an advantage in control of the position of the bead relative to the interface regardless of where the bead is located relative to the base of the hole. The location of the bead in vertically mounted couples is often in slight doubt, a variable which can be quite important. Therefore, there are considerable advantages in mounting the thermocouple horizontally in permanent molds, both for smaller measurement error and control over the distance of the bead from the mold/metal interface.

Thermal field distortion due to embedded thermocouples is also a problem in sand molds, where the thermocouple is more conductive than the surrounding mold material. Thus, the thermocouple produces readings which are below the "ideal" values. When the thermocouple is mounted vertically, the length is parallel to the isotherms. Thus the temperature difference between the bead and lead wires remains very small, and heat is not conducted away from the thermocouple bead through the lead wires. However, when the thermocouple is positioned horizontally, the temperature of the lead wires can be much less than the temperature of the bead, and heat is conducted away from the bead through the lead wires. Consequently, the horizontally positioned thermocouple will generate larger errors than produced by a vertically mounted thermocouple.

E. Evaluation of Time Response of Nanmac Thermocouple

Given the importance of thermocouple measurements in the validation of solidification modeling in permanent mold casting processes, an experimental program was undertaken at Mississippi State University to evaluate the time response of the Nanmac eroding type thermocouple which promised a more rapid response, particularly in liquid metal because of the direct contact of the bath with the thermocouple lead wires.

Background

Four separate thermocouples were utilized consisting of the Nanmac eroding type and three conventional beaded thermocouples in 28, 30, and 40 gauge sizes (Figure 16). Both the Nanmac eroding and beaded 28 gauge thermocouples are K-type thermocouples. The 30 and 40 gauge beaded thermocouples are T-type which has a similar voltage curve as K-type and were readily available for testing.

Figure 16. Thermocouple types tested

Introduction

In the initial draft of “Nanmac Thermocouple Evaluation for use in Permanent Mold and Die-Casting” the response time of the Nanmac thermocouple was reported under three test conditions. These values are now believed to be partially suitable due to the method of evaluation. After further investigation and thought, it is currently believed that the flow of solder across the thermocouple tip and solder drop tests are not fully applicable to providing “response time” as commonly related to thermocouples. Since the upper boundary temperature is unknown in the solder drop test and channel flow across the tip of the thermocouple test, the 63.2% span from initial to final temperature cannot be reliably calculated.

To make a proper comparison between the four thermocouples in how fast they respond to a temperature change (input), it makes more sense to compare their response to this input by calculating the maximum rate of change in temperature with respect to time (dt/ds) for each respective thermocouple. This method is only applied here to the tests where the upper boundary temperature is unknown as in the solder drop test and the channel flow test.

For the tests where the thermocouple is dipped or plunged into a molten bath of known temperature, the lumped capacitance model for heat transfer can be assumed and thus the commonly measured thermocouple response time calculated at 63.2% of input indeed applies.

Experimental procedure

For the solder drop test, the thermocouple in the test was rigidly held while a drop of solder was dropped onto the tip from a height of three inches. To facilitate this action, the solder bar stock was heated using a propane torch until a droplet formed and released itself from the bar stock and then dropped the three inch distance onto the thermocouple tip or bead positioned below it as shown in Figure 17.

Figure 17. Test rig for solder droplet test.

In the channel flow test, a test rig was utilized in which a 0.25" diameter hole is drilled in one of the channels as shown in Figure 18. The Nanmac eroding thermocouple was inserted and aligned flush with the base of this channel. Molten solder was then poured into the channel at a point above the thermocouple location and allowed to flow across the tip. Temperature data were recorded using Labview.

Figure 18 Test rig for solder flow in channel across Nanmac tip.

To facilitate dropping the Nanmac thermocouple into the solder or aluminum bath, a test rig was assembled as shown in Figure 19. Labview was used to record the temperature data.

Figure 19. Test rig used to control dropping the Nanmac thermocouple into a solder bath.

Technique of analysis

Temperature versus time data were captured using Labview and written to a file. A real-time capture of a test in progress can be seen in Figure 20. These data were then plotted using Excel as shown in Figure 21. Indicated on this figure is an example calculation from run number 11 of data set Test A. This was a channel flow test wherein solder was poured into the channel and allowed to flow across the tip of the Nanmac eroding thermocouple. As indicated earlier, this test lends itself to be indicative of how fast the thermocouple can react to a step change in temperature

Figure 20. Labview virtual instrument data collection real-time screen

Figure 21. Temperature plot and example calculation of dt/ds .

The more commonly used response time for thermocouples is represented in Figure 22. This 'response time' is commonly referred to as the 'time constant' of a thermocouple and is defined as the delta time from initial temperature to the temperature value at 63.2% of maximum. When a thermocouple is exposed to an environment temperature as represented by a 'lumped capacitance' model, its behavior can be described mathematically.

Figure 22. Temperature plot of and example extraction of time constant at 63.2%

Table 4. Results from tests tabulated for average and standard deviation.

Test statistics for thermocouple testing								
	Test Type							Test H
	Test A dt/ds C/sec	Test B dt/ds C/sec	Test C dt/ds C /sec	Test D dt/ds C/sec	Test E dt/ds C/sec	Test F dt/ds C/sec	Test G dt/ds C/sec	time constant sec
Run 1	209.6	724.8	157.2	200.1	3916	433.7	12016	
Run 2	281.2	587.6	52.0	221.5	2474	1594.9	14382	
Run 3	630.4	834.0	196.0	226	2631	1204.6	12498	2.091
Run 4	348.2	436.0	86.1	990	12557	501.2	13446	1.932
Run 5	366.4	849.9	81.7	273.1	1833	497.7	10506	
Run 6	222.4		177.4	192.4	1908	2187.8	5471	
Run 7	505.6		83.3	543.3	5742	1047.9	4550	
Run 8	319.4		65.9	290.4	3236	3261	12256	
Run 9	192.5		99.0	484.2	1403	1851.9	14521	
Run 10	380.4		124.6	347.9	4919	2597.4	10150	
Run 11	322.8			692.6	4732			
Run 12				557.1				
Run 13				407.6				
Avg	343.5	686.5	112.3	417.4	4122.8	1517.8	10979.6	
std dev	130.7	175.0	49.3	234.2	3131.8	962.6	3461.0	
Tests A - G are in units of degree C/sec which is the maximum rate of change in temp per unit time								
Test H is in units of seconds and describes the thermocouple's time constant at 63.2%								

Description of Tests

Test A – Solder poured into channel and flows across tip of Nanmac eroding thermocouple mounted in the channel test rig, flush with surface.

Test B – Droplet of solder dropped from a height of 3” onto tip of Nanmac eroding thermocouple mounted in the channel test rig, flush with surface.

Test C – Droplet of solder dropped from a height of 3” onto tip of coated Nanmac thermocouple mounted in channel of test rig, raised 1” from surface.

Test D – Same as Test C, with coating removed.

Test E – Drop of solder onto T-type beaded thermocouple of 30 gauge (0.010” dia. wire).

Test F – Drop of solder onto K-type beaded thermocouple of 28 gauge (0.013” dia. wire).

Test G – Drop of solder onto T-type beaded thermocouple of 40 gauge (0.00315” dia. wire).

Test H – Nanmac eroding thermocouple dipped into Al bath initially at 719 C.

Table 5 Thermocouple test reference table.

	Nanmac (coated)	Nanmac (uncoated)	K-type 28 gauge	T-type 30 gauge	T-type 40 gauge
3" solder droplet test	Test C	Test D	Test F	Test E	Test G
Solder flow in channel	O	Test A	-----	-----	-----
Solder bath	O	O			
Alum. Bath	E (partial data)	Test H (partial data)			
Boiling water bath	O	O	E	E	E
Open ended thermocouple in channel w/ solder flow	-----	-----	O	-----	-----

O – Test to be run (some of these tests have been run yet do not contain a valid amount of runs to be considered representative).

E – Test has been run yet data have not been completely evaluated.

Note: Testing concerning the Nanmac eroding thermocouple is incomplete due to a partial failure of the thermocouple. A replacement is recommended.

Discussion of results

The objective of these tests is to give some general guidance and insight into thermocouple selection for use in other ongoing testing related to the determination of the heat transfer coefficient at the metal/mold interface during the casting process. In order to measure the process temperatures accurately the response time of the thermocouple needs to be significantly smaller than the response time of the system when reacting to an input change. The transient response of the [solid-embedded] thermocouple is solely governed by F_{OD} [Fourier number] in this case; for example, by the radius of the thermocouple and the thermal diffusivity of the measured domain. This observation is at odds with the commonly accepted assumption that the transient response of a thermocouple is governed by its thermal diffusivity and its radius, regardless of the thermal diffusivity of the measured domain. Since the embedded thermocouple relies on the conduction heat transfer process rather than convection, the response time will be much faster. In observation of these statements it may be conservative to assume that a solid embedded thermocouple will have a somewhat faster response time, although this refers to the solid embedded thermocouple as being a model and may or may not be realistic in actual die configurations where thermal contact resistance may be present.

Further investigation into the proper thermocouple selection and its implementation in measuring die temperatures is still needed.

Compilation of raw data

Some compiled data have been presented above. The complete data set is too large to present unless someone is specifically interested. To accommodate anyone interested in the raw data, MSU can provide them with a CD containing all test data.

ACCOMPLISHMENTS

Publications

1. "Heat Transfer at the Mold/Metal Interface in the Permanent Mold Casting of Light Alloys" by Robert D. Pehlke and John T. Berry, presented at the 2nd International Aluminum Casting Technology Symposium at the 2002 ASM Materials Solutions conference on October 9, 2002 in Columbus, Ohio.
2. "Specifying Interfacial Heat Transfer Conditions in Permanent Mold Castings: A Comparison of Two Promising Techniques" by X. Xue*, R. Luck*, J.T. Berry*, and R.D. Pehlke, published in the Proceedings of the Conference on Modeling of Casting, Welding and Advanced Solidification Processes X at Sandestin, Florida, May 25-30, 2003. **Department of Mechanical Engineering, Mississippi State University, Department of Materials Science and Engineering, The University of Michigan.*
3. "Modeling Of Temperature Measurement Process With a Thermocouple: a Comprehensive Parametric Study and Some Experimental Results" by X. Xue, J. Berry, R. Luck, B. Dawsey, Mississippi State University, presented at the 2004 Casting Congress at the Hyatt Regency - O'Hare, June 12-15, 2004 and published in the 2004 AFS Transactions.
4. A panel discussion on "Heat Transfer Coefficients in Permanent Mold Casting" by Chung-Whee Kim, Robert D. Pehlke and John T. Berry was presented at the 2004 Casting Congress at the Hyatt Regency - O'Hare, June 12-15, 2004.
5. A paper, "Computer Simulation of the Effect of Helium in Permanent Mold Casting Processes" by Xianhua Wan and Robert D. Pehlke was presented at the TMS and AIST MS&T Conference 2004 in New Orleans, September 26-29, 2004 and published in the Conference Proceedings.
6. A paper, "Modeling Solidification of a Hubcap Casting in a Gravity Permanent Mold Casting Process" by Xianhua Wan¹, Robert D. Pehlke¹, David Moore², and Kip Mohler², was presented at the 2005 AFS Metalcasting Congress - CastExpo '05, St. Louis' America's Center, April 16-19, 2005 and published in the 2005 AFS Transactions. ¹ The University of Michigan, Ann Arbor, Michigan ² Hayes-Lemmerz Technical Center, Ferndale, Michigan
7. A paper, "The Effects of Thermocouple Placement on Highly Transient Temperature Measurements in Mold Media for Aluminum Castings" by J. Weathers, A. Johnson, R. Luck, K. Walters, J. T. Berry, Mississippi State University, was presented at the 2005 AFS Metalcasting Congress - CastExpo '05, St. Louis' America's Center, April 16-19, 2005 and published in the 2005 AFS Transactions.

8. "Thermal Contact in Permanent Molding of Aluminum Alloys", John Berry, Rogelio Luck, Robert Pehlke, August Johnson and Jeffrey Weathers, Accepted for presentation at the 2006 TMS Annual Meeting and Exhibition and publication in the Proceedings of the "Simulation of Aluminum Shape Casting Processing: From Alloy Design to Mechanical Properties Symposium".
9. "Sensor Placement and the Problems of Solidification Model Validations", R.D. Pehlke, J.T. Berry, R. Luck, A. Johnson and J.T. Weathers, Accepted for presentation at the 2006 Modeling of Casting, Welding and Advanced Solidification. Process XI and publication in the Conference Proceedings.
10. "The Determination of Accurate Interfacial Heat Transfer Coefficient Data for Permanent Mold Aluminum Alloy Casting – The Results of an AFS Research Project", by Rogelio Luck, John Berry, and Robert Pehlke has been submitted for presentation at the 2006 American Foundry Society Casting Congress and publication in the 2006 AFS Transactions.

Inventions/Patents – None

CONCLUSIONS

Heat transfer analyses were conducted on the solidification of a commercial casting of A356 alloy in a permanent mold casting. The interfacial heat transfer coefficients were estimated using a direct method, i.e. by finding the best match between the experimental and simulated temperature profiles in the casting. A reasonably good agreement has been observed between experiment and modeling, thus resulting in the generation of the value of the IHTC. The benefits of such an approach have been discussed. The procedure utilized to determine the interfacial heat transfer coefficient can be applied to other casting processes.

A series of controlled laboratory experiments were conducted at Mississippi State University on a three-piece low carbon steel mold which was designed to provide a substantial area of one-dimensional heat flow. The heat flow was measured using thermocouples embedded in the mold. The purpose of this segment of the program was to execute controlled experiments in which accurate temperature measurements would be collected within a permanent mold near the mold-metal interface during a casting process, and utilized through inverse methods, to estimate the heat transfer coefficients at the interface. The two key objectives were to develop and maintain good practices for obtaining accurate temperature data from the thermocouples embedded in the mold and to use the temperature data obtained to estimate, through inverse analysis, the mold-metal interface heat transfer coefficients.

The literature contains many discussions concerning the way in which small errors in measured temperature data can be amplified through the inversion process, resulting in large errors in estimated boundary conditions. To produce sound estimations, eliminating much of the noise and installation error from the signal was imperative. These errors made the inverse problem a difficult one. However, with the proper methodology as discussed in this document meaningful estimations of the IHTC were obtained for various mold coatings. The experimental data and subsequent calculations showed that the IHTC begins to decrease just prior to or as the eutectic begins to solidify, initiating an air gap. This was true for each of the coating combinations. The largest peak IHTC corresponded to the thickest insulating coating and the smallest peak IHTC corresponded to the thinnest mold coating as anticipated.

In all of the experiments reported for this project, embedded thermocouples were used to collect temperature measurements. In the one-dimensional heat flow experiments, these temperature measurements were applied in inverse conduction solutions to estimate the heat flux and heat transfer coefficient at the mold-metal interface. Appendix 4 on Embedded Thermocouple Practice discusses in detail a variety of factors that can contribute error to solid-embedded thermocouple temperature measurements. Systematic and random errors are considered, with a particular focus on the inherent systematic error that is induced when a thermocouple is embedded within a solid, designated as installation error. References are cited that provide detailed studies regarding the significant errors in signal magnitude and phase due to the installation of the sensor, particularly during transient measurement periods, and these installation errors are established as problems that may be too often overlooked in industry.

Appendix 5 presents methods to minimize errors in embedded thermocouple measurements. Modeling techniques are presented to simulate transient heat conduction within the measured domain, with and without the thermocouple installation in place.

The important contribution of this research program is that it is a definitive effort in permanent mold casting processes to define the requirements for determining heat fluxes and interfacial heat transfer coefficients.

RECOMMENDATIONS

Although this research program has greatly advanced the knowledge and understanding of temperature measurement and determination of heat fluxes and interfacial heat transfer coefficients, thus advancing the design of molds and other aspects of permanent mold casting, there are additional critical research issues to be addressed.

The designers of permanent mold casting processes, in particular the designers of the tool steel molds, can use a greatly expanded data base in heat transfer coefficients. The time-dependent interfacial heat transfer coefficient is the result of many factors which greatly complicates the resolution of the problem. Using the temperature measurement techniques described in the present program, and awaiting advances in computer techniques for defining three-dimensional inverse analysis techniques, the determination of the thermal and mechanical behavior of a casting in a permanent mold can be resolved. A further study of the time response of direct contact thermocouples is suggested. Continued support of research in this area is encouraged..

Additional experimental programs for determining interfacial heat transfer coefficients in permanent mold casting processes for a variety of geometries and alloys should be pursued.

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APPENDICES

APPENDIX 1 – Experimental Results for Casting Trials at Hayes-Lemmerz Technical Center
Summary of the Experimental Results in October 2003

Data analysis of the experimental trials from 10/01/03 to 10/09/03

Date	Trial No.	No. of Parts	Rows of data	Dwell Time	AVG Cycle Time	AVG Metal Temp (°F)		AVG Mold Temp (°F) TC 10
						T _{pour}	T _{max} (TC 1)	
10/01	13	13	8475	160	407	1392.7	957.8 (514)	536.3 (280)
10/02	14	15	8538	140	317	1387.0	1007.3 (542)	664.6 (351)
10/06	15	15	7586	125	295	1334.8	990.1 (532)	650.8 (344)
10/07	16	15	6094	120	227	1348.2	1009.9 (543)	713.2 (378)
10/08	17	20	8013	120	218	1298.7	1002.6 (539)	688.4 (365)
10/09	18	25	8436	120	236	1346.9	1009.4 (543)	700.0 (371)

Figure 1 The dwell and cycle time becomes shorter as the trial continues.

Figure 2 The pouring temperature is relatively consistent. So is the metal temperature.

Figure 3 The mold temperature is close to 700 F.

Top Mold

Figure 4 The location of thermocouples in both the casting (TC 1) and the top mold with the exception of TC 10, which is in the bottom mold but at the same position from the top view.

Figure 5 Tool misaligned, causing longer cycle times and early termination of the trial.

Figure 6 Mold temperatures are not consistent throughout the trial.

Figure 7 Metal temperatures are consistent except in cycle 8.

Figure 8 Cycles 2 and 4 have problems with short shot or loss vent.

Figure 9 Mold temperatures are not consistent until cycle 12.

Figure 10 Metal temperatures are still close to 1000 °F, but are lower than expected.

Figure 11 The dwell time is further reduced to 120 seconds, but TC 10 was monitored for cycle start.

Figure 12 Mold temperatures are consistent from cycle 10 on.

Figure 13 Metal temperatures are consistent from cycle 10 on.

Figure 14 These results are obtained with a constant cycle time of 120 sec disregarding tool temperature.

Figure 15 A thermal steady state of the mold has not been reached after 15 cycles.

Figure 16 Metal temperatures are consistent from cycle 8 on.

Figure 17 These results are obtained with a constant cycle time of 120 sec disregarding tool temperature.

Figure 18 A thermal steady state of the mold has not been reached after 20 cycles.

Figure 19 Metal temperatures are consistent from cycle 15 on.

Figure 20 These results are obtained with a constant cycle time of 120 sec, disregarding tool temperature.

Figure 21 A thermal steady state has been reached after about 15 cycles.

Figure 22 Metal temperatures are consistent from cycle 12 on.

APPENDIX 2 – Summary of M.S. thesis of J.W. Weathers

Author:

[weathers, jeffrey wayne](#)

Degree:

Master of Science in Mechanical Engineering, 2005-05-06

Title:

COMBINING THE MATRIX TRANSFORM METHOD WITH THREE-DIMENSIONAL FINITE ELEMENT MODELING TO ESTIMATE THE INTERFACIAL HEAT TRANSFER COEFFICIENT CORRESPONDING TO VARIOUS MOLD COATINGS

Abstract:

The interfacial heat transfer coefficient is an important variable regarding the subject of metal castings. The error associated with the experimental temperature data must be dealt with appropriately so that they do not significantly affect the resulting interfacial heat transfer coefficient. The systematic and random errors are addressed using a combination of three-dimensional finite element modeling and the matrix transform method, respectively. Experimentally obtained A356 permanent mold casting data was used to estimate the interfacial heat transfer coefficient corresponding to common industrial mold coatings.

Keywords:

- thermal distortion
- singular value decomposition
- inverse conduction

Conclusions:

When attempting to estimate the IHTC inversely, it is important that the experimental temperature measurements be as accurate as possible. The thermocouples should be installed such that the installation error is kept to a minimum. That is, the positioning of the thermocouple relative to the isotherms is crucial in dealing with transient temperature measurements. Properly positioning the thermocouple will greatly reduce the installation error. For permanent molds, the length of the thermocouple should be situated perpendicular to the isotherms. This configuration produces less overall error in temperature measurements and allows for more control of the distance between the interface and the thermocouple bead. In sand molds, the thermocouple should be positioned parallel to the isotherms, which leads to less conduction through the lead wires and, thus, more accurate temperature measurements.

Regardless of the thermocouple configuration relative to the isotherms, the installation error can never be totally alleviated. The remaining installation error is addressed in the modeling of the experimental apparatus. The installation error can be undone through the matrix transform method. A more realistic model will account for and correct more of the installation error than a simplified model.

The noise in the thermocouple signal poses another problem due to the amplification that occurs in the inverse analysis. The matrix transform method allows the noise to be filtered using singular value decomposition. The relatively small singular values correspond to the high frequencies in the signal. The noise in the signal also corresponds to these high frequencies. Therefore, eliminating the small singular values filters the noise from the signal.

The final goal is to produce IHTC estimations for various mold coatings. To produce sound estimations, eliminating much of the noise and installation error from the signal is imperative. These errors make the inverse problem a difficult one. However, with the proper methodology as discussed in this document meaningful estimations of the IHTC are obtainable. The experimental data and subsequent calculations showed that the IHTC begins to decrease as the eutectic begins to solidify, initiating an air gap. This was true for each of the coating combinations. The largest peak IHTC corresponded to the thickest insulating coating (2 mil Base Coat plus 4 mil Insulating Coat) and the smallest peak IHTC corresponded to the thinnest mold coating (2 mil Base Coat). These findings were consistent with our expectation.

APPENDIX 3 – Summary of M.S. thesis of A.N.F. Johnson

Author:

[Johnson, August Nathan Fletcher](#)

Degree:

Master of Science in Mechanical Engineering, 2005-05-07

Title:

CORRECTION OF TRANSIENT SOLID-EMBEDDED THERMOCOUPLE DATA WITH APPLICATION TO INVERSE HEAT CONDUCTION

Abstract:

The current research investigates the use of solid-embedded thermocouples for determining accurate transient temperature measurements within a solid medium, with emphasis on measurements intended for use in inverse heat conduction problems. Metal casting experiments have been conducted to collect internal mold temperatures to be used, through inverse conduction methods, to estimate the heat exchange between a casting and mold. Inverse conduction methods require accurate temperature measurements for valid boundary estimates. Therefore, various sources of thermocouple measurement uncertainty are examined and some suggestions for uncertainty reduction are presented. Thermocouple installation induced bias uncertainties in experimental temperature data are dynamically corrected through the development and implementation of an embedded thermocouple correction (ETC) transfer function. Comparisons of experimental data to dynamically adjusted data, as well as the inverse conduction estimates for heat flux from each data set, are presented and discussed.

Keywords:

- thermal field distortion
- conduction heat transfer
- singular value decomposition
- finite difference
- dynamic calibration

Conclusions:

Solid-embedded thermocouples are utilized for a variety of industrial applications where the internal temperature of a solid is desired. Depending upon the application, the accuracy requirements for the temperature data collected may be very stringent. Inverse conduction problems, where internal temperature measurements are used to estimate boundary condition, are one such application in which very accurate temperature measurements are essential. The literature contains many discussions concerning the way in which small errors in measured temperature data can be amplified through the inversion process, resulting in large errors in estimated boundary conditions. Therefore, when considering the design of an experiment to collect temperature data for use in inverse conduction calculations, it is imperative to recognize the wide variety of sources from which error can be introduced into a temperature signal, as well as to be able to minimize their contributions. Chapter II discussed in detail a variety of factors that can contribute error to solid-embedded thermocouple temperature measurements. Systematic and random errors were visited, with a particular focus on the inherent systematic error that is induced

when a thermocouple is embedded within a solid, designated as installation error. References were cited that provide detailed studies regarding the significant errors in signal magnitude and phase due to the installation of the sensor, particularly during transient measurement periods, and these installation errors were established as problems that may be too often overlooked in industry.

The practices employed during metal casting experiments, in which internal mold temperatures were collected during casting processes, were summarized in Chapter III. In these experiments, embedded thermocouples were used to collect temperature measurements for application in inverse conduction solutions to estimate the heat flux and heat transfer coefficient at the mold-metal interface. Equipment and practices utilized to minimize the random error introduced into the temperature signals through electrical noise in the testing environment were presented.

With the minimization of random errors typically managed during the experimental set up, the goals of additional error reduction led to the techniques discussed in Chapter IV for the elimination of the bias error in an embedded thermocouple temperature signal due to the presence of the sensor within the measured domain. Modeling techniques were presented to simulate transient heat conduction within the measured domain, with and without the thermocouple installation in place. Methods for determining an embedded thermocouple correction (ETC) transfer function from these models, used to correct for installation error in temperature data, were presented and a MATLAB program was constructed to automate the assembly of this transfer function based on user defined system descriptive parameters.

Chapter V provided examples demonstrating the effectiveness of the ETC transfer function in removing installation bias errors from simulated noisy embedded thermocouple data to recover estimated undistorted temperature data. A simulation was also presented showing the inaccuracy of simulated noisy embedded thermocouple data estimated boundary heat flux, when used for an inverse conduction solution. However, the ETC transfer function recovered response, when alternatively used in same inverse conduction solution, was shown to accurately estimate the actual boundary heat flux. The ETC transfer function method was also demonstrated with a sample set of experimental temperature data collected during the casting experimentation described in Chapter III to recover an undisturbed temperature response. The differing estimates of boundary heat flux produced for the recovered and “raw” temperature data, when employed in an inverse conduction scheme, were also compared to published values and discussed. For the assumed situation of an air filled thermocouple cavity, it was observed that the amount of distortion in temperature signal and IHC estimated boundary heat flux were fairly minimal.

The ETC transfer function can effectively be considered as a filter, or a dynamic calibration tool, that can adjust a temperature response in both phase and magnitude to remove the bias error due to the sensor installation. This type of data adjustment can be very beneficial for applications in which accurate transient temperature measurement is vital, such as that of inverse conduction problems.

This thesis has investigated the use of solid-embedded thermocouples as a specific means for determining accurate transient temperature measurements within a solid. However, no cause is without its effect, and the apparent simplicity of being able to

measure accurate transient temperatures within a solid by simply embedding a thermocouple does not come without cost. By installing a sensor in the solid domain, the dynamics of the heat conduction system are changed. This can result in temperature measurements that can potentially turn into hindrances, if the presence of installation induced bias errors in the temperature signal are not recognized and managed in an effective and appropriate fashion.

APPENDIX 4 – Report to the American Foundry Society on Embedded Thermocouple Measurement Practices

(PRELEMINARY ROUGH DRAFT)

A GUIDE FOR EMBEDDED THERMOCOUPLE MEASUREMENTS

Introduction to Solid-embedded Thermocouples

Industrial Applications

A thermocouple is a thermoelectric sensor used to measure temperatures. A typical thermocouple consists of two dissimilar metal wires joined together to form a junction. The thermocouple operates through the heating and cooling of the junction, which produces a voltage that can be measured across the free ends of the thermocouple and can be correlated back to the temperature of the junction. This is known as the Seebeck effect [1]. The four most common calibrations of thermocouples and their compositions are shown in Table 1.1 [2].

Table 1.1 - Common Thermocouple Calibrations

Thermocouple Type	Composition Positive Lead (+)	Negative Lead (-)
K	Nickel-Chromium	Nickel-Aluminum
J	Iron	Copper-Nickel
T	Copper	Copper-Nickel
E	Nickel-Chromium	Copper-Nickel

Solid-embedded thermocouples are thermocouples that are inserted into a solid medium to track the temperature history within the medium at the thermocouple location.

Embedded thermocouples are used in a wide variety of industrial and research oriented applications, for example gathering thermal history data of a workpiece during a welding or machining operation [3, 4] or collection of thermal effects associated with stress waves in a solid [5]. This type of thermocouple installation is of particular interest for the work of this report.

Internal temperature measurements obtained by embedded thermocouples are frequently used in industry applications in which the temperature measurement is collected for use in an inverse conduction problem solution. These inverse conduction problem solutions can aid engineers in understanding a variety of interfacial situations, including applications such as determining boundary conditions of gas turbine blades and gun barrels [6], thermal deformation of machine tools [7], and the heat transfer at the mold-metal interface during a casting solidification process [8-14].

As previously mentioned, inverse conduction solutions are very sensitive to thermocouple measurement error. A relatively small uncertainty in measured temperature can result in a much larger uncertainty in the inverse conduction

estimates for boundary conditions. Therefore, obtaining quality thermocouple data is a high priority when the data is intended for use in IHC problem solutions.

Design of Experiments Employing Solid-embedded Thermocouples

Any experimentally measured signal will inevitably include some amount of uncertainty. The uncertainty can never be completely eliminated, but there are a variety of measures that can be taken to reduce the total amount of uncertainty in a signal [15]. Before uncertainty can be reduced, however, it must first be recognized. Therefore, the initial step in uncertainty reduction is to gain a thorough understanding of the various sources that make up the total uncertainty in a signal.

In the design of an experiment, an imperative initial action is to perform a preliminary uncertainty analysis in order to better understand the system under investigation. This step is important in order to identify specific sources of uncertainty, estimate the contribution of each source component, and implement methods for the reduction of these uncertainty components.

For this research, the various categories of the uncertainty will be discussed in a manner relative to experimentation involving solid embedded thermocouples in order to provide some basic guidelines to consider when collecting temperature data. These guidelines will focus primarily on the embedding of thermocouples within permanent molds in the casting industry to obtain time histories of temperature at specific locations within the molds for use in inverse methods to estimate mold-metal interface heat flux.

Types of Temperature Measurement Uncertainty

The uncertainty in a measuring device can be divided into two major categories: systematic uncertainty and random uncertainty. Systematic, or bias, uncertainties are the fixed or constant components of the total error [15]. These types of uncertainties are usually contributed by limitations in the manufacturing, calibration, installation, or perhaps modeling of the sensors. Random, or precision, uncertainty is the portion of the total uncertainty that is typically associated with measurement noise and usually, but not always, follows some type of statistical distribution [1]. Random uncertainty, or the signal noise, is usually due to electrical interference, either external or within the data acquisition circuitry. The systematic and random components sum to yield the total uncertainty component for any measured signal.

Static and Dynamic Measurements

When using an embedded thermocouple to obtain temperature measurements, the type of measurement could either be static or dynamic, depending on the state of the system. It is important to understand the type of measurement required of an experiment in order to design the experiment with appropriate measures to meet its purpose. Static measurements are those types that are obtained after the entire system in consideration, both the measured material and the thermocouple sensor, has been allowed adequate time to “thermally settle” after any boundary condition changes. In other words, the temperature to be measured is not changing with time. However, many practical situations exist in which a temperature within a solid medium is to be obtained during a period when the boundary condition is changing with time [6-14].

Dynamic measurements are measurements that are intended to obtain temperature at a location as it changes with time. Dynamic, or transient, measurement capabilities would be considered necessary to measure temperature during a time prior to a system reaching its steady-state response, or perhaps if the system exhibited a time varying steady response. Uncertainties for dynamic measurements include all the components found in a static measurement, as well as some additional uncertainty components that are specific to dynamic measurements, such as phase errors. For a metal casting process, when considering temperature collection within a permanent mold after molten aluminum is poured into the mold cavity, the necessity for accurate transient temperature measurements is evident.

Systematic Uncertainty Components – Static and Dynamic Measurements

The purpose of this section of the current research is to discuss several systematic sources of uncertainty for dynamic measurements using embedded thermocouples. As previously stated, any static measurement uncertainty component would also contribute in the case of a dynamic measurement; therefore components common to both will be discussed first, followed by additional uncertainty sources unique to dynamic measurements.

Manufacturer's Uncertainty and Calibration

All measurement sensors come from the manufacturer with a specified systematic component of measurement uncertainty. This component is commonly referred to as manufacturer's uncertainty, and can either be specified as an absolute value or as a percentage of the measured scale. This portion of the systematic uncertainty is due to limitations prescribed by the manufacturing operations to produce and assemble the sensor. Thermocouples that are typically used in industry are purchased as prefabricated units from a supplier or as rolls of industry standard thermocouple wire. In either case, the manufacturer would specify a level of accuracy to which the sensor is certified. Typically, the manufacturer's uncertainty can be reduced through the process of calibrating the thermocouple to a well known standard [1, 15]. However, no standard itself is perfect; therefore calibration can never completely eliminate the manufacturer's uncertainty, only reduce it to the level of uncertainty of the calibration standard.

Data Acquisition and Data Reduction Uncertainties

Coleman and Steele [15] discuss another category of systematic error that concerns the biases in the actual data acquisition system that acquires, possibly conditions, and stores the output of the sensor. Any uncertainty contributed by the DAQ componentry falls into this category.

Coleman and Steele [15] refer to another category of systematic errors known as data reduction errors. Uncertainties of this type would include those relating to round-off or truncation when transferring thermocouple voltage outputs to the digital domain of data acquisition hardware and the personal computer used to control the DAQ devices. Once the voltage values from a thermocouple sensor are obtained, they must be correlated to

a corresponding thermocouple junction temperature for each voltage value. This process is accomplished using experimentally determined correlation curves for temperature values. These empirical curves also have a certain levels of uncertainty associated with them as well.

Uncertainty due to Conceptual Errors

Systematic uncertainties can also arrive from conceptual errors, such as when a measured value is taken to be a point value for a specific location in space when it is, in realistically, an average temperature over a larger region. For embedded thermocouples, this error might arise from the assumption that a thermocouple is measuring the temperature at a point location within the medium of interest. In actuality, the thermocouple is likely registering an average temperature over the entire junction bead [2, 13]. This type of error can be reduced most obviously by reducing the thermocouple junction size.

Installation Uncertainties

Another type of elemental systematic error source, and the one that is of key interest for this research, is that of the installation error. Installation errors for measurements include uncertainties that are due to the intrusive nature of an embedded thermocouple installation and the inhomogeneity subsequently caused. Geometric tolerances involved in pinpointing the location of a thermocouple bead embedded within the solid medium, as well as effects due to heat loss through the thermocouple leads are also considered as types of possible installation uncertainties [7, 13, 16-21].

The contributions from installation uncertainties have been shown in various sources throughout the literature to be of sufficient magnitude to merit efforts to recognize and, if possible, reduce them [5, 7, 13, 16-23]. These types of errors for a static measurement occur as typical bias offsets in magnitude from the “true” temperature value. However, when considering installation errors for a transient measurement, more consideration must be exercised because the presence of the embedded sensor within the medium completely alters the dynamic response of both the measured medium and the measurement sensor from what they would be independent of each other [3, 19, 22].

Additional Systematic Uncertainty for Dynamic Measurements

Dynamic, or transient, temperature measurements can be described as measurements collected while the temperature at the sensor location is still varying as a function of time. Transient measurements can incorporate additional sources of error due to the dynamic response characteristics of the embedded thermocouple and the measured medium, as well as the dynamic interaction between them. These sources can cause errors not only as biases in magnitude of the signal, but also as a phase shift of the signal in time [3, 5, 19, 22, 24]. These additional distortions in magnitude and phase can further increase the total uncertainty of the temperature measurements. During a transient period, a thermal system is dynamically responding to changes in the boundary conditions, such as a change in the heat flux or surface temperature, resulting in the temperature field varying with time. A previously discussed example that is the practical interest to this research is the pouring of molten aluminum into a preheated steel mold. The mold is

subjected to a rapid change in heat flux at the mold/metal interface as the molten aluminum enters the mold cavity. It is during this period that boundary heat flux identification is desired, and therefore it is when transient temperature data is collected to assist in determining these unknown, unsteady boundary conditions.

Distortion of the Localized Thermal Field

In order to determine a temperature within a solid body, such as a metal mold, a hole must be machined into the solid in order to provide access to the point of interest by the sensor. A major concern when collecting transient temperature data is the localized distortion experienced in portions of the thermal field surrounding the installed sensor. The presence of a cavity within a solid body, whose contents have differing material properties than the surrounding medium, has been shown in the literature to induce distortions in the local thermal field around the cavity [7, 16-18]. Isotherms in the measured solid near the sensor installation can actually “bend” and distort due to several factors relating to the presence of the sensor in an otherwise homogeneous medium. The distortion can be attributed to several factors, such as the thermocouple installation cavity dimensions and orientation, differences in thermal properties of the medium, thermocouple, and filler material in the cavity, and heat loss conducted through the thermocouple leads.

Chen et. al [6, 21] performed a number of laboratory experiments several years ago to investigate the transient temperature errors due to the embedded installation of type K thermocouples parallel to an applied heat flux. They ascertained that the degree of distortion depended largely on the differing properties of the parent material and the materials which filled the cavity (air and thermocouple) and the diameter and depth of the installation hole. As is consistent with expectations, they showed that the temperature measurement error decreased with a decrease in the size of the installation cavity and embedded thermocouple.

More recently, Attia et. al [7, 16-18] has published several comprehensive studies investigating the thermal distortions induced by the insertion of an embedded thermocouple into a solid material, as well as the effects of heat loss through the thermocouple leads. Multiple in-depth studies were conducted to determine the effects of varying the thermal conductivity of the parent material, the thermocouple, and the cavity filler material, as well as geometric placement of the thermocouple bead in the cavity base on thermocouple measurement error. It was concluded that distortion within the local thermal field around the embedded thermocouple was highly dependant upon the ratio of the thermal conductivities of the cavity filler material to the parent material. Also, a local “hot” and “cold” zone was discovered to form at the perimeter of the thermocouple installation cavity due to the disturbance to the local thermal field. The size and location of the zones varied depending upon the ratio of material properties considered. Studies investigating the effect of positioning of the thermocouple bead within the cavity on thermocouple measurement error showed significant amounts of deviation from the expected value, as both temperature overestimation and underestimation, depending upon which zone at the cavity base the bead was in contact with. It was also shown that reduction of the thermal gradient across the parent material

allowed for a significant increase of heat flow into the thermocouple leads and that this heat loss through the leads will generally result in an overall underestimation of the “true” temperature. Temperature measurement errors as much as 20 percent of the temperature drop over a distance equal to the cavity radius were shown to be possible.

Woodbury and Gupta [13] recently investigated the impact of deterministic thermocouple errors in sand molds on inverse heat conduction problems. They showed through finite element modeling how four typical thermocouple sizes, AWG 24, 30, 36, and 44, with glass braid and alumina sheathing can cause distortion to the thermal field around the thermocouple. They reported that for a typical 24 AWG size thermocouple embedded in a sand mold, transient errors of up to 35 C were possible, which led to errors of up to 40 percent for the estimated boundary heat flux.

In conduction systems with multiple types of materials involved, it is important to note that the temperature drop across the interface may be significant [25]. The temperature drop is caused by what is known as a thermal contact resistance. The thermal contact resistance usually arises when two solids are butted together and heat is conducted across their interface. The contact resistance usually occurs as an additional resistance to heat travel due primarily to surface roughness of each surface in contact.

For embedded thermocouple installations, a thermal contact resistance could exist between the thermocouple junction and the surrounding parent material due to the fact that they will most likely be in less than perfect contact. There may be air, filler cement, etc. between the two materials and which will cause additional resistance to heat flow to the point of interest over the same geometrical location in a solid block of parent material with no thermocouple installed. Incropera and DeWitt [25] suggest that increasing contact pressure or reducing the surface roughness can lead to greater contact area therefore reducing the contact resistance. They also mention that using filler materials to bond two surfaces of interest can decrease the contact resistance, assuming the filler material has a higher conductivity than that of air.

Heat Loss Through Thermocouple Leads

Another thermocouple error contributor that must be recognized is the possibility of conduction of heat away from the point of interest via the thermocouple leads. Through the insertion of the measurement device, a path has been created for heat to escape, leading to a bias error that could, depending upon other error sources, lead to the underestimation of the desired temperature value. This source of error has also been investigated and discussed in the literature [7, 16-18, 23, 26].

According to Weathers et. al. [23], the amount of heat dissipated through the thermocouple leads depends greatly on the orientation of the leads with respect to the predominant direction of the heat flux. They conducted a three dimensional finite element study of the effects of installation orientation of solid embedded thermocouple within permanent (steel) and sand molds. Horizontally (perpendicular) and vertically (parallel) positioned thermocouples, with respect to the isotherms across the temperature gradient, were examined. For permanent (steel) molds, it was shown that

horizontal installation, perpendicular to the isotherms, proved to produce more accurate transient temperature data and allow for more geometrical control of the thermocouple junction with regards to the distance from the metal-mold interface. For sand molds, the vertical installation, parallel to the isotherms, was shown to be preferable due to the reduction in the amount of heat conducted and lost through the thermocouple leads.

Positioning of the Embedded Thermocouple Near the Interface of Interest

In preparation for temperature history logging for use in inverse problems, thermocouples are usually embedded very near to the surface where the boundary conditions are applied so that the thermocouple will be more sensitive to the abrupt changes at the mold-metal interface. However, it is important to realize that if the sensor is installed too near to the interface, the previously discussed distortion due to the presence of the probe could extend into the interface surface, disturbing the surface condition and boundary heat flux as stated by Chen et. al. in [27]. Because the installation of a thermocouple in a solid medium produces a local region of thermal distortion around the installation cavity, it is crucial to understand the relative size of this distorted region in relation to the cavity size. If the “reach” of the distortion effects is known, the sensor can be placed at the optimal distance from the boundary of interest, without being so close as to disturb the thermal field at the boundary surface. This critical distance from the boundary surface is suggested to depend upon the cavity dimensions, as well as the material properties of the parent material and cavity contents.

Chen and Li [6] created an idealized finite element model of a type K thermocouple embedded in a flat circular steel disc in which a large steady heat flux was applied to one surface. They presented graphical plots demonstrating the dependence of thermocouple measurement errors on a variety of the thermocouple installation geometrical parameters, such as cavity diameter, thermocouple diameter, distance from the interface, etc. They suggest, for best sensitivity to boundary changes, the distance from the interface should be as small as possible. In Chen and Thomson’s work [27], however, a reminder is given suggesting that a sensor at the surface will disturb the surface conditions and heat flow at the interface. Therefore, an optimal sensor distance from the interface surface must exist to provide as accurate a representation of the dynamics of the surface conditions as possible without disturbing them.

In [21], Chen and Danh revisited presence of a cylindrical cavity in a flat slab through a well controlled laboratory experiment. The thermocouples in their experiments were mounted in steel blocks parallel to the direction of the boundary heat flux application. Included in their work is a summary of the typical maximum errors observed for the prescribed variations of the thermocouple cavity geometry and the boundary condition application time. They stated through their findings that the distortion in temperature response was much more sensitive to cavity diameter than depth of the thermocouple hole.

Elphick et. al [20] discuss how thermocouple assemblies installed in solids can create changes in the heat flux distributions therefore resulting in steady-state or transient temperature measurements that are quite different from the expected temperature.

They conducted numerical simulations to assess the error involved in using several sheathed thermocouple configurations to obtain a temperature history within a solid. They found that through the selection of a filler, or plug material, with an appropriate thermal conductivity to “balance” the dynamics between the parent and thermocouple material properties, the thermocouple error could be minimized. Thermocouple cavity diameter, distance from the cavity tip to boundary interface of interest, and the magnitude of the surface boundary conditions were presented as some of the most important factors contributing to the amount of error for a thermocouple signal.

Phase Errors Encountered

In addition to errors in magnitude, for transient temperature measurements, errors can also occur as shifts in the phase of a signal, commonly observed as delays in sensor response in time. Rittel [24] investigates the use of embedded thermocouples for transient temperature measurements in polymer discs undergoing dynamic deformation and straining. He shows that through using a theoretically derived impulse response of the system, the experimental data can be deconvolved to an estimated signal that occurs a bit earlier, faster, and with higher values of observed temperature. Rabin and Rittel [5] follow the investigation of transient temperature measurement using solid-embedded thermocouples with a model for the time response of the thermocouple. They discuss the idea of the existence of a “thermal inertia” effect that can cause undesired delay in the response of an embedded thermocouple. This “thermal inertia” effect is shown to be due to the rate of change of temperature of the measured material, the differing thermophysical properties of the thermocouple and the measured material, and the geometry of the thermocouple installation. They examined thermocouple response with respect to the ratios of the thermal diffusivity of the thermocouple material to the domain material. Thermal diffusivity ratios of one or less were reported to be inadequate for transient measurement situations. Also, for locations within the measured domain greater than three times the thermocouple radius, the presence of the thermocouple was shown to have no significant effects.

In his analyses of transient measurements, W. G. Alwang [22] suggests that a transient measurement consists of two pieces of information: the value measured and the time at which it was measured. He proceeds to state that transient measurements depend on all error sources which depend on the dynamic response of the measurement system, and therefore also the time behavior of the quantity being measured.

Modeling Errors

In [19], Alwang approaches the problem of uncertainty estimation and reduction in transient measurements through modeling of the systems under investigation and deconvolution of the experimental signals. Two extremes of the effects of time-dependant uncertainty are presented: the case where additional uncertainty due to transient measurement are negligible and the case where these additional uncertainties are large. He shows that through a process of time-dependant calibration of the system, a measured response can be corrected for many of the inherent transient measurement errors encountered. Analytical approaches [28] and a variety of modeling efforts [3, 22] have been made to characterize and aid in the reduction of experimental temperature

measurement installation errors. However, as no model will ever exactly duplicate a real life situation, differences between the model and the real process it simulates will result in modeling uncertainties being present in the signal. For embedded thermocouples, errors could exist due to inadequacies of the model to represent the dynamics of the real process or perhaps uncertainty as to the exact location of the thermocouple bead in the cavity once installed. Still, if the model sufficiently represents the real process, the total uncertainty can be reduced.

Random Uncertainty for Solid-embedded Thermocouples

Random uncertainty, or the signal noise, is usually due to electrical interference, either from external devices or within the data acquisition circuitry. As stated previously, the random uncertainty components for a set of collected data typically follow a statistical distribution. For a transient temperature measurement, at each instant in time that a temperature value is measured, a component of random, or precision, uncertainty will be included within the signal. These components should be comparable to the random uncertainty within a static measurement with the same physical sensor setup.

Summary of Solid-embedded Thermocouple Error

This chapter has presented a detailed overview of several categories of uncertainty that can be anticipated when using embedded thermocouples for transient temperature measurements. This information was offered as evidence of the presence of a variety of errors in measured temperature data, and to illustrate the necessity to improve embedded temperature measurements, especially when considering temperature data collected for highly sensitive inverse processes. The key point of this chapter is to emphasize that, in addition to common sensor uncertainties (manufacturer's, data acquisition, etc.), the installation of a temperature sensor within a solid domain changes the dynamic behavior of the domain in the region surrounding the sensor. This results in experimental data that does not accurately reflect what the theoretical temperature within the domain would have been were the sensor not installed. Therefore, with all the sources of error in temperature measurement presented in this chapter, opportunities for improvement of the measurement will always exist.

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The Effects of Thermocouple Placement on Highly Transient Temperature Measurements in Mold Media for Aluminum Castings

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Abstract

Transient temperature measurements are important in various experimental situations.

One important situation involves the determination of the temperature of a mold near the mold/metal interface. When a thermocouple is introduced into the mold medium, the temperature field associated with that medium becomes distorted. The distortion caused by the introduction of the thermocouple produces errors in the temperature readings. Finite element modeling is used to determine the effects that both horizontally and vertically mounted thermocouples have on the temperature field. Both permanent (steel) and sand molds are considered.

Introduction

When producing a casting, the heat flux at the mold/metal interface is an important variable affecting the quality of the casting. In order to calculate the heat flux, the temperature near the mold side of the interface often becomes important. These temperature measurements are highly transient and difficult to measure. Embedding a thermocouple near the mold wall is a widely used method in determining the temperature near the mold-side of the interface^[1-4].

The problem with embedded thermocouples is that, when introduced, the temperature field will be distorted. In permanent molds, a hole is typically drilled to make space for the thermocouple. The introduction of the cavity contributes to the distortion of the temperature field^[5]. In sand molds, the mold material surrounds the thermocouple so there is no cavity contributing to the distortion. However, the large difference in material properties between the sand and the thermocouple still leads to distortion in the temperature field that results in errors in the temperature measurement. Thermocouple placement also has an effect on the temperature field. The amount of distortion will differ depending on whether the length of the thermocouple is embedded parallel or perpendicular to the isotherms associated with the temperature gradient^[6,7]. Traditionally, following Ruddle^[8], the placement has been parallel to the isotherms, minimizing conduction down the thermocouple leads.

A simple, one dimensional, comprehensive parametric study of the errors in thermocouple readings have been reported by Xue et al^[9]. In this paper, the process of embedding thermocouples was investigated for two mold materials: mild steel and sand. A comprehensive, three dimensional, Finite element (FE) model was used to determine the most effective thermocouple configuration for each material.

Finite Element Modeling

In each FE model, a block of material with an embedded thermocouple was considered. Model 1 was designed to simulate the measurement of temperature near the mold-side of the metal/mold interface in a permanent mold. The model consisted of a block of mild steel with an embedded, type-K thermocouple, which was protected by a twin-bore, alumina insulator. A step temperature of 1200 F was imposed on the front face of the steel block, which had an initial temperature of 600 F, equivalent to conditions observed in permanent mold casting of aluminum. Three cases were considered for Model 1. Case 1 was used to determine how much distortion the temperature field experienced due to a thermocouple mounted with its length parallel to the isotherms associated with the temperature gradient (Figure 1). For Case 2, the thermocouple was mounted with its length perpendicular to the isotherms (Figure 2). Case 3 was designed to simulate a block of mild steel containing no thermocouple. Case 3 was used as a reference for the comparison between Case 1 and Case 2. For all cases, the thermocouple bead was in direct contact with the base of the cavity.

Model 2 simulates the distortion that occurs when a thermocouple is introduced into a sand mold. The three cases considered for Model 2 (Figures 3 and 4) are similar to the cases illustrated previously for Model 1, only differing in that there is no pre-heat applied to the sand mold.

The material properties associated with Model 1 and Model 2 are listed in Table 1. All properties were assumed to be constant with respect to temperature.

Figure 1. Dimensions for Model 1 - Case 1

Figure 2. Dimensions for Model 1 - Case 2

Figure 3. Dimensions for Model 2 - Case 1

Figure 4. Dimensions for Model 2 - Case 2

Table 1. Material Properties Used in the FE Models

Material	Density, ρ (lb/in ³)	Specific Heat, C (BTU/lb-R)	Conductivity, k (BTU/in-R- hr)
Mild Steel	0.285	0.115	2.889
Alumina	0.143	0.203	1.444
Type-K Thermocouple	0.303	0.107	0.578
Air	1.68E-5	0.191	0.013
Sand	0.055	0.260	2.64E-3

The time dependent solution to each FE model was obtained using a time step, Δt , of 3.6 seconds. Each solution includes 100 time steps, which translates into 360 seconds of data and 100 data points.

For Model 1 and Model 2 the temperature at the center of the thermocouple bead was assumed to be the temperature that the thermocouple would read in an experimental situation. Ideally, the measured temperature would be identical to the temperature obtained at the same location for Case 3. However, when a thermocouple is introduced, the measured temperature is not necessarily the “real” temperature. Subsequent temperature field distortion occurs, resulting in measurement error.

Results of the FE Modeling

Model 1

Figure 5 depicts the data collected from the simulations created to approximate the temperatures measured by vertically (Case 1) and horizontally (Case 2) mounted thermocouples. These data sets were compared to the data obtained from Case 3, which approximated the actual temperature at the location of the thermocouple bead for Cases 1 and 2.

Figure 5. “Measured” Temperature vs. No TC

Figure 6 shows how the temperatures measured by vertically (Case 1) and horizontally (Case 2) mounted thermocouples differ from the temperature resulting from Case 3.

Figure 6. Temperature Difference Obtained by Comparing Each Thermocouple Configuration to Case 3

Cutting a plane through the thermocouple bead allows the temperature field distortion to be seen (Figures 7 and 8). A contour plot is shown for several instances in time to show how the distortion progresses.

Figure 7. Temperature Field Distortion Caused by a Thermocouple Mounted Vertically in a Permanent Mold

Figure 8. Temperature Field Distortion Caused by a Thermocouple Mounted Horizontally in a Permanent Mold

The arrow in Figures 7 and 8 represents the step temperature applied to the front face of the mold material, and each frame is a close-up view of the temperature field around the thermocouple bead at an instant in time. The temperature scale is in units of Fahrenheit.

Model 2

The analysis performed on Model 1 was repeated for Model 2 (Figures 9, 10, 11, and 12).

Figure 9. "Measured" Temperature vs. No TC

Figure 10. Temperature Difference Obtained by Comparing Each Thermocouple Configuration to Case 3

Figure 11. Temperature Field Distortion Caused by a Thermocouple Mounted Vertically in a Sand Mold

Figure 12. Temperature Field Distortion Caused by a Thermocouple Mounted Horizontally in a Sand Mold

Discussion

The FE analysis previously described pinpoints the importance of thermocouple placement when measuring transient temperatures. In permanent molds, a hole must be drilled so that the thermocouple can be positioned properly, and the hole becomes a source of distortion, regardless of its contents. As a result, the temperature at the base of the hole will be offset relative to the actual temperature at the same location in an unaltered mold. Thus, even a perfect thermocouple would produce erroneous temperature measurements. When the thermocouple is positioned vertically, a hole must be drilled to accommodate the thermocouple and insulator. The temperature field is clearly distorted purely due to the introduction of the hole (Figure 13). Consequently, a thermocouple bead placed at the bottom of the hole will produce readings that are offset relative to the actual temperature.

Continuing discussion with respect to permanent molds, when the thermocouple is positioned horizontally (perpendicular to the isotherms), the hole itself has a significant effect on the temperature field (Figure 14 on the following page). As a result, the thermocouple readings obtained from the horizontally positioned thermocouple differ slightly from the actual temperature (Figure 6).

(The model used to obtain the following figures was identical to Model 1 apart from the hole being filled with air rather than a thermocouple.)

Figure 13. Temperature Field Distortion Due to a Vertically Positioned Cavity in a Permanent Mold

Figure 14. Temperature Field Distortion Due to a Horizontally Positioned Cavity in a Permanent Mold

Model 1 permits the observation of the distortion due to the combination of the thermocouple and the hole. The air between the thermocouple bead and the wall of

the hole acts as a thermal barrier, which causes the vertically positioned thermocouple to produce readings that are less than the actual temperature. When the thermocouple is positioned perpendicular to the isotherms, the thermocouple is subjected to the heat flux directly. Concisely, the horizontally placed thermocouple produces a maximum error of approximately 10.8 F, which is much less drastic than the error produced by the vertically mounted thermocouple (-45.4 F) (Figure 6). However, the error produced by the horizontally mounted thermocouple requires more time to dissipate.

Also, the horizontally positioned thermocouple has the advantage in the control over the position of the thermocouple bead relative to the interface. Often, the distance between the interface and the thermocouple bead becomes an important variable. Therefore, control over that distance is critical when the desired temperature readings must be a certain distance from the interface. When the thermocouple is positioned vertically, the bead may be positioned anywhere inside the perimeter of the base of the hole. Controlling where the bead comes into contact with the base of the hole can be difficult, especially when the depth of the hole is considerable. For that reason, the distance between the bead and the interface becomes questionable (Figure 15).

Figure 15. Distance Between a Vertically Positioned Thermocouple Bead and the Mold/Metal Interface

When the thermocouple is positioned horizontally, however, the distance between the thermocouple bead and the interface is the same regardless of where the bead is located at the base of the hole (Figure 16).

Figure 16. Distance between a Horizontally Mounted Thermocouple Bead and the Mold/Metal Interface

Therefore, there are advantages to mounting thermocouples horizontally in permanent molds. The horizontally embedded thermocouple produces a smaller error in

temperature measurements. Also, positioning the thermocouple horizontally allows for more control over the distance between the thermocouple bead and the mold/metal interface.

Temperature field distortion due to embedded thermocouples is also a problem in sand molds (Figures 11 and 12). In a sand mold, the thermocouple is much more conductive than the surrounding material. Therefore, the thermocouple will tend to produce readings that are less than the actual temperature. When the thermocouple is mounted vertically, the length of the thermocouple is parallel to the isotherms. Thus, the temperature difference between the thermocouple bead and lead wires remains very small, and heat is not conducted away from the thermocouple bead through the lead wires. When the thermocouple is positioned horizontally, the temperature of the lead wires can be much less than the temperature of the thermocouple bead, and heat is conducted away from the thermocouple bead through the lead wires, which is illustrated in Figure 12. Consequently, the horizontally positioned thermocouple will generate errors that are much greater than the errors produced by a vertically mounted thermocouple.

Conduction through the lead wires is much less prevalent in a vertically mounted thermocouple (parallel to the isotherms). Thus, in a sand mold, a vertically mounted thermocouple will produce more accurate readings than a horizontally mounted thermocouple.

Conclusions

When using thermocouples to obtain transient temperature measurements, the positioning of the thermocouple relative to the isotherms is crucial. Properly positioning the thermocouple will greatly reduce the error caused by temperature field distortion. For permanent molds, the length of the thermocouple should be situated perpendicular to the isotherms. This configuration produces less overall error in temperature measurements and allows for more control of the distance between the interface and the thermocouple bead. In sand molds, the thermocouple should be positioned parallel to the isotherms, which leads to less conduction through the lead wires and, thus, more accurate temperature measurements.

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