New Method of Dynamical Measurements of Mold Thermal Properties and Applications for Casting Processes

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ABSTRACT

Different mechanisms of non-steady state heat transfer in sand molds can occur during casting processes. These processes include: thermal conduction through a skeleton of solid sand particles, gas conduction in closed pores, air convection in open interconnected pores and, radiation at high temperature. In addition, water vaporization could dramatically change the rate of heat transfer. It is difficult to theoretically take into account all these processes. A novel experimental/computing method was designed for dynamic measurements of the thermal properties of foundry molds. The method is based on generation of a precise energy impulse in mold media by small electrical heater ("micro-heater") and measurement of temperature response near the heat source within the molding media. A computer and data acquisition interface were used for controlling impulse cycles and obtaining high resolution temperature measurements. The device has a 5 mm diameter and easily could be imbedded in different parts of molds. The coefficient of thermal conductivity was calculated on the basis of measured temperature response and non-steady state heat transfer modeling with Fluent software. The small impulse of heat which is applied has a minimal influence on existing thermal processes and properties of sand media, while the short relaxation time after the impulse allows the possibility of frequent sampling measurements of the thermal properties under rapidly changing conditions. The method was used for the measurement of the thermal properties of a green sand mold near the surface of a mold cavity during steel pouring and thin ceramic shell properties during de-waxing.

INTRODUCTION

Mathematical modeling of heat flow in high temperature casting processes has led to improvements in the process control, casting quality, and conservation of energy and material resources. Modeling of the melt flow in a mold cavity, solidification structure, and possible defect formation has a significant effect on the quality of castings. In the on-going development of these models, one of the primary requirements at this time is for accurate values for thermal properties of materials which are used in the processes. The difficulties with making accurate measurements of thermal properties of molding media and molten and solidified metals at high temperatures has led to a limited amount of data on molding media and alloys in the temperature ranges of interest.

Different mechanisms of heat transfer are involved in a vast variety of metal casting process. For example, in an investment casting process, high porosity shell could transfer heat by thermal conductivity through skeleton of solid sand particles, air conductivity in closed pores, with additional air convection in open interconnected pores, and, finally, by radiation at high temperature during firing and pouring. In addition, investment casting patterns are removed in a steam autoclave. Richards et al [1] showed that common models for conductivity of composite materials do not accurately describe the thermal conductivity of the water-saturated investment mold shell. Another example is the heat transfer in a green sand mold which is complicated by water vaporization in surface layer, water vapor migration toward the flask, and condensation in the cold region. In chemically bonded molds, the heat of binder decomposition could also change the intensity of heat flow from solidified castings. Unfortunately, it is difficult to predict all of these processes from first principles.

On the other hand, experimental methods are often used which are based on a steady state measurement technique. During these steady state measurements, a sample is placed between a heat source and a heat sink, and the value of the coefficient of thermal conductivity is determined directly from the temperature gradient after equilibrium has been reached. Because the physical properties of the mold materials can change during these measurements, the steady state methods will not accurately reflect the real non-steady state metal casting processes. For example, steady state condition in sample from green sand with 1” thickness requires at least two-three hours holding time after temperature on hot surface was increased at 100°C. During this time, green sand sample would become completely dry.
In non-steady state methods, the temperature distribution in the specimen varies with time, and measurement of the rate of temperature change determines the thermal diffusivity. The thermal conductivity is then calculated taking into account the density and the specific heat of the material. The non-steady state measurement technique gives results which describe more accurately the metal casting processes when temperature and mold media properties can change significantly during short periods of a process cycle such as pouring a casting or de-waxing an investment shell.

Typically, variations of two main methods are used for non-steady state heat transfer measurements. The first variation, the so-called “Hot Wire” method,[2] generates the known value of heat energy by connecting platinum wire with a programmable electrical power supply. Because electrical resistivity of platinum is a temperature dependent function, the measurement of a voltage drop gives the temperature data. The theory of the hot wire method permits calculation of the coefficient of thermal conductivity (K) of the surrounding media from the slope of temperature-ln(time) line. The second method uses a transient technique, such as the laser flash method. This method measures thermal diffusivity[3] using disk-shaped samples. In general, the adaptation of known non-steady state techniques for measurements of thermal properties of the materials involved in foundry processes presents a lot of difficulties.

In this paper, an alternate method for dynamic measurements of thermal properties of different mold materials used in casting processes is described. We were motivated by the following requirements:

- The possibility of repeated measurements of thermal properties in non-steady state conditions of casting processes;
- The possibility of measurements of different mold media with unstable thermal properties when internal energy sources/sinks take place, such as water vaporization or condensation, binder decomposition, etc.;
- The possibility of analyzing lab scale samples as well as direct measurements in industrial conditions.

**DESCRIPTION OF METHOD**

**EXPERIMENTAL**

The suggested method is based on the following principle: The stable and known value of an impulse of heat energy in the media to be analyzed is generated by passing direct current through the wire micro heater. At the same time the temperature response inside the media near the heat source is continuously measured. In general, the temperature response to the constant value of the heat impulse depends on thermal properties of the media. The applied micro impulse of heat had a minimal influence on existing thermal processes and properties of measured media, while short relaxation time after impulse gave the possibility of frequent sampling measurements of the thermal property data in rapidly changing conditions. The device simultaneously measures the absolute temperature of the media.

A general scheme of the method is given in Fig. 1. Micro-heater, made from Alomega* wire Ø.38 mm, had approximately 15 mm length and was attached to thicker wire (Ø.8mm) from the same material for concentration of heat impulse on the measured space. K-type thermocouple with Ø.38 mm wire was used for temperature measurements. A four-hole, five mm diameter, alumina tube was used for assembling the device. A high resolution 24-bit data acquisition system and programmable power supply were connected to a PC. The LabView8® virtual instrument software was used for programming which supplied precise voltage/current/time parameters of impulses (Figure 1).

The influence of the electrical impulse parameters (current/time) on the value of temperature response was studied using low thermal conductivity material (bulk dry sand) and high thermal conductivity liquid mercury. An example of the measured temperature responses on different parameters of impulse of heat energy is shown in Fig. 2 for bulk dry sand. The amplitudes of the temperature response increased with the increase of the electrical current and the impulse time. The amplitudes of the temperature response had the minimal variations in sequential measurements when the same electrical impulses were applied. Full temperature relaxation time in dry bulk sand increased from 1 min for 1A/3 sec impulse to 5 min for 3A/60 sec impulse. On the contrary, the value of temperature response was many times less and relaxation time was shorter during the test of mercury which has high thermal conductivity (Fig. 2c). The thin ceramic boron-nitride coating was applied during the measurement for prevention of electrical shortening of micro heater in high electro conductive melts.
In general, the relaxation time defines the minimal possible time between sequential measurements. The high resolution temperature measurement system which was used could measure less than 0.1°C response impulse very well which allowed the use of short heat impulse time (1-3 sec) and intervals between measurements as low as 10-20
sec if necessary. The test cycle can be designed using programmable power supply with large variation of parameters.

**COMPUTATIONAL**

Fluent software was used for modeling the non-steady state heat transfer in three-dimensional media with internal volumetric heat source \( q \). The energy transport equation used by FLUENT has the following form:

\[
\frac{\partial}{\partial t} \rho h = \frac{\partial}{\partial x_i} \left( k \frac{\partial T}{\partial x_i} \right) + q
\]  

(1)

where: \( \rho \) is density, \( h \) is sensible enthalpy which equals \( \int_{T_{ref}}^T c_p dT \), \( k \) is conductivity, \( T \) is temperature and \( t \) is time.

Assumed temperature dependent values of heat capacity \( c_p \) could be used for computation. In some non-steady processes, when large changes of \( C_p \) and \( \rho \) of media occur, for example, when water vaporizes and saturates porous bulk sand, the method allows for the computation of thermal diffusivity and consequently conductivity can be computed by the assumption of the heat capacity and density values. The coupled boundary conditions between wire heater and the mold media were applied without additional thermal resistance:

\[
k_{wire} \left( \frac{\partial T}{\partial x} \right)_{wire} = k_{media} \left( \frac{\partial T}{\partial x} \right)_{media}
\]

(2)

The results of modeling for the bulk dry sand with known thermal properties \( (K=0.35 \text{ W/mK}) \) and the comparison to experimentally measured temperature response when 2A impulse was applied are given in Figure 3. The computed hypothetical temperature responses for sand type media with constant density and heat capacity and with different values of the thermal conductivity are shown in Figure 4.

The procedure which was developed for measurement of the coefficient of thermal conductivity of the material consisted of two steps. The first step included the experimental measurement of the value of the temperature response to heat impulses, and the second step was computing the thermal properties. The computation took into account the measured data, the known values of heat capacity and density of media, as well as the test result of the reference material (bulk dry sand) for the same micro heater. For many practical applications, the heat capacity and density could by calculated with using the rule of mixtures. In addition, for non-steady state conditions the special intermediate calculation procedure was used for evaluation of the temperature response value when temperatures before and after relaxation of heat impulse were different.

![Figure 3. Calculated temperature field in dry bulk sand around micro heater (a) and comparison of experimentally measured temperature response with calculated data (b)](image-url)
APPLICATIONS FOR METAL CASTING PROCESSES

BULK SAND MEDIA

On the basis of preliminary trials and adjustments, 2A during 120 seconds heat impulse parameters were chosen. The test results of dry bulk sand and sand with different moisture contents are shown in Fig. 5a. In addition, the mixture of dry sand with mineral oil was tested for analyzing a possible influence of water on circuit shortening and decreasing heat generation during the test. In both cases (Fig. 5b), the method showed significant decrease of the values of the temperature response when the solid sand media had more thermal conductive liquid phase (water or oil). The thermal effect was not sensitive to the electrical conductivity of the liquid phase. The computed values of the coefficient of thermal conductivity (K) of bulk sand with different moisture contents are given in Fig. 5b. In this case, \( C_p \) and \( \rho \) of sand with moisture were evaluated with the rule of mixtures. Increasing moisture leads to the 3-5 times increase of the thermal conductivity of bulk sand.

GREEN SAND MOLD

The sand mold surface and cores are exposed to high temperatures during pouring and casting solidification. The rapidly changed surface temperature can lead to surface defects such as burn-on and mold penetration\(^4\). The prediction of surface defect formation in steel castings is possible based on computing the time periods during which the mold surface is above the critical temperature\(^5\). This analysis requires the thermal properties of the mold surface; binder decomposition, water vaporization, as well as phase transformation in sand particles significantly
change the thermal properties of surface layers when compared to the bulk media\(^3\). There are many technical
difficulties when the traditional methods of thermal conductivity measurements are used in these extreme
conditions. The suggested method has the possibility to measure the thermal properties of the mold/core surface
directly during in casting process. This possibility is illustrated bellow.

Green sand with 3.5-4% moisture and bentonite binder was used for the mold preparation. Medium carbon steel was
poured into an open type mold with 5”x10”x5” cavity. The devise was placed inside the mold wall approximately
\(\frac{1}{2}”\) from the casting surface. The test cycle was designed for non-steady state measurements. The more powerful 6A
impulse was applied with the 5 sec impulse time and the 40 sec delay between impulses. In addition, bulk sand and
initial dry green sand mixture with approximately 1.5% moisture were tested under the same heat impulse in steady
state condition at room temperature.

The results of pouring test are shown in Fig. 6. One can see three different periods. The first one was when mold had
temperature less than 100°C. The temperature responses to heat impulses were near 7.5°C. During the second
period, when the temperature was near the water vaporization interval, the minimal values of temperature response
took place. From the non-steady state heat transfer point of view, water vaporization increased the value of the
coefficient of thermal diffusivity significantly and minimized thermal gradient in the mold. And finally, when
vaporization wave passed the location of the device, the larger values of the temperature response took place, which
indicated the decrease of the coefficient of the thermal conductivity of dried green sand. This measurement showed
that during short period of time after steel was poured in green sand the significant variations in thermal properties
of mold material took place. The average data are shown in Table 1.

### Table 1. The average values of the coefficient of the thermal conductivity of green sand mold, W/mK

<table>
<thead>
<tr>
<th></th>
<th>Dry green sand</th>
<th>Green sand mold</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Period 1</td>
<td>Period 3</td>
</tr>
<tr>
<td></td>
<td>0.41</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>0.53</td>
<td></td>
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</tbody>
</table>

![Figure 6. Plot of the temperature response in green sand mold (1/2” from the casting surface) after pouring of steel](image_url)

INVESTMENT CASTING SHELLS

Shell cracking, which often occurs during the autoclave-dewaxing cycle, leads to surface defects, including heavy
oxidation, fins, and casting distortion. During the autoclave-dewaxing cycle, high temperature steam penetrates the
porous ceramics shell and transfers heat to the wax, causing the wax melt and run out of the shell cavity. The main cause of crack formation is the wax expansion inside relatively weak thin shell. The analysis of these processes requires the thermal conductivity data for different shell conditions, in particular, when shell saturated by water and steam. The suggested method was applied for different types of shells which were built directly in the foundries. One example of the measurements is given bellow.

The shell was built directly on the surface of the device according to the existing multilayer industrial process. The shell was tested in the air, inside a special isolated box filled with saturated steam at 70-90ºC, and submerged in water. The data (Table 2) confirmed that the thermal conductivity of the shell could change by a factor of 2-3 during de-waxing process.

Table 2. Thermal conductivity of shell in investment casting process

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Response, ºC</th>
<th>K, W/mK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial shell</td>
<td>9.3</td>
<td>0.55</td>
</tr>
<tr>
<td>In steam</td>
<td>6.0</td>
<td>1.00</td>
</tr>
<tr>
<td>In water</td>
<td>4.8</td>
<td>1.36</td>
</tr>
</tbody>
</table>

CONCLUSION

A novel method was designed for the non-steady state measurement of the thermal properties of materials used in metal casting processes. The method is based on a generation of a heat impulse and precise measurement of the temperature response inside the investigated media. The thermal properties were determined by computing non-steady state heat transfer. The method was tested on different mold materials. The experimental data showed that significant variations of the thermal conductivity of mold materials take place during metal casting process.

REFERENCES