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Sensitivity Study on the Effect of Thermocouples Positioning on the Heat Transfer Coefficient Determination

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ABSTRACT

Casting is a widely used manufacturing process for complex shaped-parts with high stiffness due to the monolithic integrity. An added value to these demands is high dimensional precision which casting cannot achieve in most cases. To ensure defect-free products and dimensional precision like side walls, radii, the cast has to be cooled according to material type, product size, filling rate and mold design. Nowadays, the cooling control is based mostly on empirical knowledge. To avoid product quality deterioration it is necessary to have an intelligent control system, which adjusts the cooling parameters according to varying casting conditions. To play with the casting parameters, their influence on the cast part is needed to be scientifically known in order to predict it. Numerical simulation is the suitable tool for getting different influences of the casting parameters on the final part shape and dimensions. Instead of costs of test and trials, numerical simulations needs computation time. The present work focuses on the determination of the heat transfer coefficient at the part/mold and part/core interfaces in permanent mold casting, by a gradient extrapolation method. Using adequate equipment, temperature field was monitored during solidification and cooling of a hollow cylinder cast part made of Al-7%Si alloy. By varying the thermocouples positions, the optimal locations of the measurement points were determinad in order to calculate a very accurate heat transfer coefficient.

KEYWORDS: temperature gradient, heat transfer coefficient, gradient extrapolation method, aluminum alloy, permanent mold casting.

1. Introduction

Aluminum alloy casting is one of the common research topic due to the wide applications of the cast parts in different manufacturing industries, especially in automobiles industry. In order to reduce the expenses with the rejected cast parts, the companies focus their own financial resources on numerical and experimental study of the casting process.

Phase transformation of the cast alloy plays a very important role in the solidification process of a cast part and the structural integrity of the part is related to the temperature field evolution with time. The way the heat flows through the part/mold interface affects the cast part quality [1-3].

During the solidification phase, the melt material is cooling and due to shrinkage the air gap between the part and mold occurs. The air gap strongly influences the heat transfer through the part/mold interface because of a very low heat conductivity of the air. At the cast/core interface the contact pressure has an influence on heat transfer. The heat transfer coefficient may be also influenced by the roughness of the mold surface, the type and thickness of the coating layer [4-9]. It is obviously that the solidification process is very long if the heat transfer between the cast and mold is very slow.

The most suitable design mold is needed for assuring the best heat flux between the cast and the mold. In the last years, numerical simulation of the casting process was continuous by developed and improved. Even if there are many numerical software for casting process simulation, these need very performant computers to be used, which, ususally, are not available for the foundry man [2].

Heat transfer coefficient determination is a very difficult task because it depends on the technical and technological parameters of the process. One of the technical parameters which need to be investigated is the position of the measurement points of the thermal field. This may influence the temperature gradient calculation with a direct influence on the final results of the heat transfer coefficient evolution.

There is no reference about any investigation made by other researchers related to this aspect.

2. Experimental Procedure

A hollow cylinder part made of Al-Si-Mg (AC4CH) alloy was cast inside a mold with internal core and external wall both made of steel. The mold (85 mm height) was bottom insulated and the core was cooled by water in order to create an unidirectional temperature gradient on radial direction. During the cast solidification and cooling, the thermal field was monitored using 10 chromel-alumel thermocouples mounted along the radius of core, cast and mold at a depth of 25 mm. The displacement of the external wall of the part was monitored using 3 linear variation displacement transducers (LVDT). The measured values were recorded using a data acquisition system. Having an axisymmetrical part, so a relevant geometry, this model allows an easy determination of the heat transfer coefficient.

3. Numerical Procedure

The heat transfer coefficient calculation is based on the procedure proposed by Hernandez [4]. The method was named gradient extrapolation method or direct method because the heat transfer coefficient is calculated directly using measured thermal field by extrapolating the temperature gradient at the interface between the cast and mold.

For calculation, the radial variation of the temperature in the cast and mold, during solidification and cooling of the cast, was considered to correspond to a second order polynomial equation.

The temperature at the cast/mold interface is impossible to be measured directly. Therefore, the surface temperature of the cast and mold at the boundary was calculated by extrapolating the temperature gradient. Additionally, the temperature gradient in the mold was calculated considering that the temperature variation in the mold corresponds to a fourth order polynomial equation.

In figure 1 it is shown a schematic view of the thermocouple positioning. Thermocouples T_1-T_5 were mounted inside the mold, T_6-T_8 inside the cast and T_9-T_{10} inside the core.

At each time instant, the temperature profiles in different domains are fitted to polynomials one order lower than the numbers of thermocouples:

- for part and mold:

$$T_n(t)=m(t)r_n^2+o(t)r_n+p(t) \tag{1}$$

- for mold only:

$$T_n(t)=a(t)r_n^4+b(t)r_n^3+c(t)r_n^2+d(t)r_n^2+e(t) \tag{2}$$

where:
T_n is the temperature measured by thermocouple [°C];
t is time step [s];
r_n is the radius of the measurement point [mm];
m, o, p, a, b, c, d, e are unknown parameters;
n is the number of the thermocouple considered.

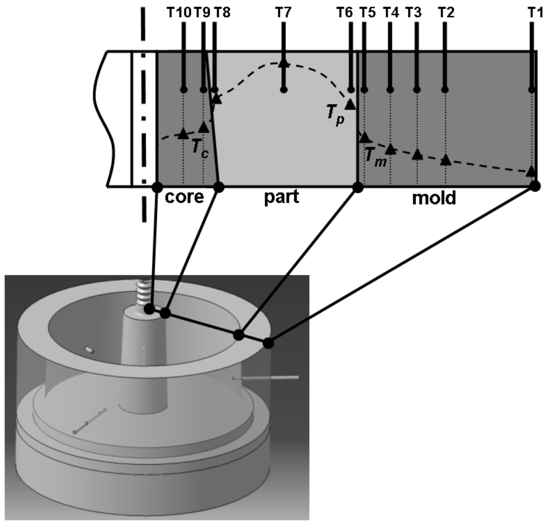

Fig. 1. *Thermocouples distribution along the radius of core, part and mold*

Describing the temperature evolution involved in temperature gradient calculation as it is shown in equations (1) and (2), two linear systems were obtain. By solving the equations systems, coeficients *m, o, p, a, b, c, d* and *e* were calculated.

The surface temperature of the part and mold is calculated relying on equation (3):

$$T_s(t)=x(t)r_s^2+y(t)r_s+z(t) \tag{3}$$

where:

T_s is the extrapolated temperature at the surface of the part/mold [°C];
r_s is the radius of the part/mold interface [mm];
x, y, z are the unknown coefficients.
The temperature gradient was calculated as the partial derivative of temperature with respect to radius, as it is shown in equation (4):

$$\left.\frac{\partial T}{\partial r}\right|_{r=r_s} = 2xr_s + y \tag{4}$$

where:
x and y are the unknown coefficients calculated earlier.
Finally, the heat transfer coefficient was calculated using equation (5):

$$h = \frac{k\left(\frac{\partial T}{\partial r}\right)_{int}}{T_m - T_p} \tag{5}$$

where:
h is the interface heat transfer coefficient [W/m^{2}K];
k is the heat conductivity of the mold material [W/mK];
$(\partial T/\partial r)_{int}$ is the temperature gradient extrapolated at the interface [K/m];
T_m is the mold temperature at the interface [°C];
T_p is the part temperature extrapolated at the interface [°C].

4. Results and Discussions

- Heat transfer coefficient

The heat transfer coefficient curves calculated by gradient extrapolation method were compared with the curve calculated by semi-inverse method. The comparison between the experimental and numerical temperature profiles made by other investigators [12-15] proved that the semi-inverse method is the most accurate. The calculated error between measured and numerical values is lower than 5%.

Heat transfer coefficient was calculated for five situations as it is listed in table 1. For calculating the surface temperature of the mold, 3 thermocouples, different each time, were selected and in the beginning, equation (1) was used. In the end, all five thermocouples in the mold were used for the same calculation, by using equation (2).

The heat transfer coefficient was calculated using equation (5) at the part/core and part/mold interfaces, based on air gap thickness and contact pressure. The numerical results are shown in figure 2.

Table 1. *Thermocouples used for temperature gradient calculation*

Calculation no.	Thermocouples used for calculation
1	T1, T2, T5
2	T1, T3, T5
3	T1, T4, T5
4	T2, T4, T5
5	T1, T2, T3, T4, T5

At the part/core interface, after mold filling, heat transfer coefficient has a certain value. When the part shrinkage occurs, the contact pressure between the internal surface of the part and the external surface of the core will determine a rapid and significant heat transfer.

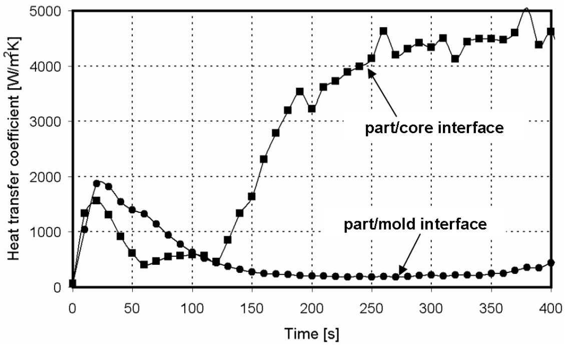

Fig. 2. *Evolution of heat transfer coefficients at the part/mold and part/core interfaces for Al-7Si alloy*

At the part/mold interface, heat transfer coefficient has an ascending variation as long as the alloy is in liquid phase, reaching a maximum value which corresponds to solidus temperature. At this time, the dendritic skeleton is strong enough to withstand the metalostatic pressure and the melt departs from the mold wall.

The part shrinkage is materialized by the formation of air gap at the part/mold interface. Therefore, the heat transfer coefficient value is rapidly decreasing because the air is behaving like a barrier due to its low heat conductivity.

- Air gap formation

The thickness of the air gap which is formed at the part/mold interface was determined by using the part measured displacement and the mold calculated displacement. The air gap dimension is given by the difference between mold and part displacement. For calculating mold displacement using equation (9), it was assumed that the mold has a heat resistance constant at temperature variation and the core does not influence the cast shrinkage.

$$\dot{\delta}_{m,int} = R_{int}\alpha(T(t))\dot{T} \tag{6}$$

$$\delta_{m,int}(t) = R_{int,m}\int_0^t \alpha(T(t))dT(t) \tag{7}$$

$$\delta_{m,int}(t) = R_{int,m}\int \alpha(T(t))dt \tag{8}$$

$$\delta_{m,int}(t) = R_{int,m} \int_{T_0}^{T} \alpha(T(t))dT(t) \qquad (9)$$

$$\delta_w = \delta_{m,int} - \delta_{p,int} \qquad (10)$$

where:

δ_w is the air gap thickness at the cast/mold interface [mm];

$\delta_{m,int}$ is the displacement of the inner wall of the mold [mm];

$\delta_{p,int}$ is the displacement of the outer wall of the part [mm];

$R_{m,int}$ is the mold inner radius [mm];

$T(t)$ is the time-dependent temperature [°C];

t is time [s];

$\alpha(T)$ is the temperature-dependent linear expansion coefficient [K^{-1}].

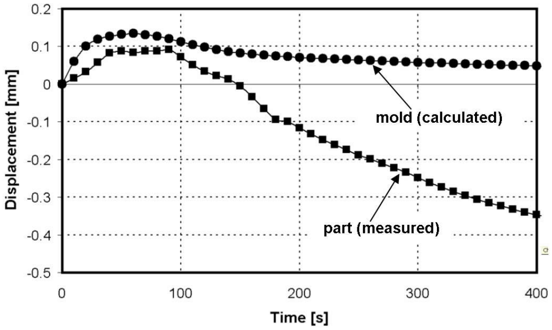

Fig. 3. *Displacement of the mold (calculated) and part (measured)*

In figure 3 is shown the measured radial displacement of the exterior wall of the part and the calculated radial displacement of the inner wall of the mold and in figure 4 is shown the air gap evolution with time.

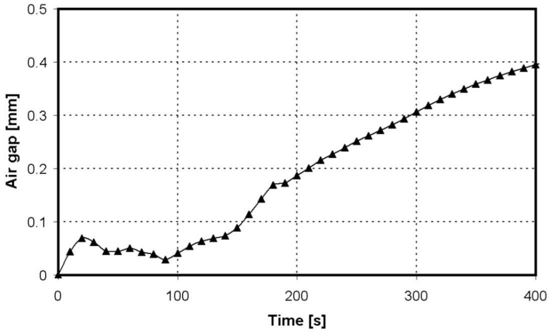

Fig. 4. *The thickness of the air gap which is formed at the part/mold interface due to part shrinkage*

The calculated temperature gradient in the mold, for the situations listed in table 1, is shown in figure 5.

Temperature gradient is a very important variable used for heat transfer coefficient calculation. A very accurate calculation of the temperature gradient will provide very accurate calculation of the heat transfer coefficient. Depending on the position of the measurement points, the value of temperature gradient varies. The heat transfer coefficient evolution calculated using temperature gradient values from figure 5 are shown in figure 6.

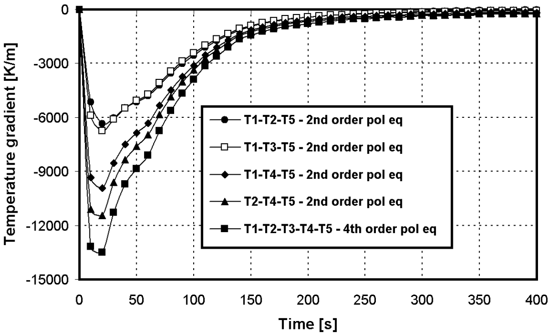

Fig. 5. *Temperature gradient vs. time for mold*

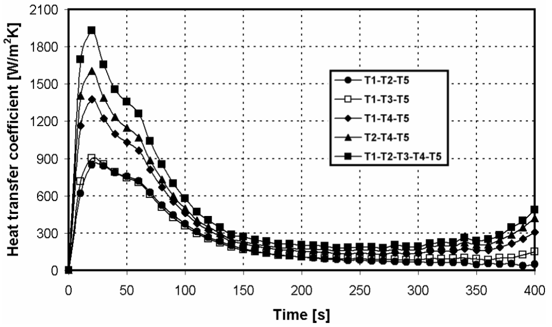

Fig. 6. *Heat transfer coefficient evolution at the part/mold interface calculated by gradient extrapolation method*

Heat transfer coefficient at the part/mold interface was also calculated by a semi-inverse method based on the procedure proposed by Beck [10,11]. Because this method is the most accurate, the result was compared to the curves in figure 6 and it was found that the best thermocouples combination for heat transfer coefficient is the one using thermocouples T_1, T_3 si T_5 as it is shown in figure 7.

The calculation of the temperature gradient variation with time is influenced by the distance at which thermocouples are located over a heat source (the melt). The numerical results obtained for case 2 (T_1, T_3, T_5) (table 1) are in agreement with the numerical results obtained by semi-inverse method. So, the thermocouples used for heat transfer coefficient calculation must be located as it follows: two thermocouples very close to the mold/ambient (T_1), respectively mold/part (T_5) interfaces and one thermocouple (T_3) must be located at 1/3 of the distance between the thermocouples located near the interfaces. This distance will be measured from the thermocouple which is closer to the mold/part interface (T_5 in this case).

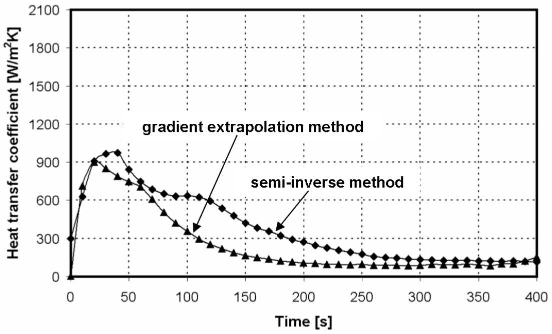

Fig. 7. *Heat transfer coefficient calculation at the part/mold interface calculated by two methods*

5. Conclusions

The research underlined the influence of thermocouples positioning on the heat transfer coefficient determination. The heat transfer is quantified by the temperature gradient at the part/mold interface.

The dimensional accuracy of the part is determined mainly by heat transfer mechanism between the melt and the mold. Heat transfer coefficients at the part/core and part/mold interfaces were determined by a gradient extrapolation method.

Heat transfer coefficient at the part/mold interface was calculated by varying the position of the measurement points in the mold. The calculation of the temperature gradient in the mold is sensitive to thermocouples positions over the heat source.

The results obtained by gradient extrapolation method were compared to the results obtained by a semi-inverse method.

The proper locations and minimum number of thermocouples for an accurate calculation of the temperature gradient in the mold were determined. Therefore, gradient extrapolation method may be also very accurate if the optimal locations for measurement points are found.

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Studiul efectului poziționării termocuplelor asupra determinării coeficientului de transfer termic

Rezumat

Turnarea este un procedeu de manufacturare larg utilizat pentru reperele având forme complexe cu rigiditate ridicată datorită integrității lor structurale.

Pentru a asigura produse fără defecte şi de precizie corespunzătoare în ceea ce priveşte grosimea pereților şi razele de racordare, matrița trebuie să fie răcită în funcție de tipul de material, volumul producției, rata de umplere şi forma matriței.

În scopul evitării deteriorării calității produsului este necesar un sistem de control inteligent care să acorde parametrii de răcire în funcție de condițiile de turnare.

Lucrarea de față tratează determinarea coeficientului de transfer termic la interfața între reper şi matriță, la turnarea în matrițe permanente, prin metoda extrapolării gradientului.