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Application of experimental data for numerical simulation of cast iron solidification

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Abstract

Numerical analysis of cast iron solidification process is presented. The system casting – shell mould is discussed. The parameter controlling the solidification process called a substitute thermal capacity (STC) has been constructed in this way in order to take into account the evolution of latent heats connected with the solidification of austenite and eutectic phases. The information concerning the proper approximation of STC results from the experimental data using the thermal and derivative analysis (TDA).

Keywords: Application of Information Technology to the Foundry Industry, Solidification Process, Numerical Techniques, Thermal and Derivative Analysis

1. Introduction

Numerical simulation of casting solidification constitutes a very effective tool on a stage of optimum foundry technology design. Mathematical model of the process discussed bases on the well known energy equation [1, 2] and the parameters appearing in this equation must be known. In particular the information concerning the thermal processes in the interval $[T_S , T_L]$ (solid and liquid border temperatures) is very essential. It seems, that the credible data concerning the phenomena considered result from the TDA analysis. The complex and difficult for mathematical modelling processes proceeding in a micro scale (nucleation and nuclei growth) are not here discussed. In this place the macro model of solidification is taken into account. In this case the knowledge of function controlling the evolution of latent heat is necessary, at the same time not only the value of this parameter is should be the aim of investigation, the very essential problem is to determine the way of latent heat evolution in the interval $[T_S , T_L]$ – [1, 2, 3, 4, 5, 6, 7, 8]. Experimental data found using the thermal and derivative analysis can be a basic tool for a such information obtainment. This method is often applied to find the data concerning a crystallization of phases appearing during the alloy solidification, first of all the problem of kinetics of solidification can be explained. Cast iron as a typical casting alloy for which during the solidification eutectic transition appears requires a construction of STC for which the real distribution of characteristic phases latent heat (austenite and eutectic ones) will be taken into account.

2. Application of experimental data for calorimetric curve construction

The following energy equation is considered

$$x \in \Omega: \quad c(T)\frac{\partial T(x,t)}{\partial t} = \nabla\left[\lambda(T)\nabla T(x,t)\right] \qquad (1)$$

where c is a volumetric specific heat, λ is a thermal conductivity, T, x, t denote a temperature, spatial co-ordinates and time. Let us assume that this equation determines a temperature field in a casting domain. The similar equation can be taken into account for a mould volume, namely

$$x \in \Omega_m: \quad c_m(T_m)\frac{\partial T_m(x,t)}{\partial t} = \nabla\left[\lambda_m(T_m)\nabla T_m(x,t)\right] \tag{2}$$

where c_m is a volumetric specific heat of mould, λ_m is a mould thermal conductivity.

On a contact surface between casting and mould a continuity condition is given

$$x \in \Gamma_c: \begin{cases} -\lambda(T)\mathbf{n}\cdot\nabla T(x,t) = -\lambda_m(T_m)\mathbf{n}\cdot\nabla T_m(x,t) \\ T(x,t) = T_m(x,t) \end{cases} \tag{3}$$

where $\mathbf{n}\cdot\nabla T$ denotes a normal derivative. On the outer surfaces of the system the Robin condition can be accepted. The initial condition is also known.

Let us assume that the calorimetric curve corresponds to the cooling curve at the control point from casting domain (sensor) for the fictitious material which volumetric specific heat for liquid ($T > T_L$) corresponds to c_L, volumetric specific heat for solid ($T < T_S$) corresponds to c_S, while for $T \in [T_S, T_L]$ the course of $c(T)$ is approximated by a polynomial fulfilling the conditions $c(T_S) = c_S$, $c(T_L) = c_L$ and the derivatives $\mathrm{d}c/\mathrm{d}T$ at the points T_S, T_L are equal to 0. In others words, the function $c(T)$ is a continuous, monotonic and differentiable one. The thermal conductivity of material corresponds directly to the real values of this parameter for cast iron. The calorimetric curve can be found using the numerical methods, in particular the problem described by equations (1) – (4) has been solved using the finite differences method (the real shape of casting-mould system has been considered, of course).

Because the geometry of the system casting-mould (Figure 1) is axially symmetrical therefore the energy equations for successive sub-domains have the following form

$$(r,z) \in \Omega: c(T)\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[r\lambda(T)\frac{\partial T}{\partial r}\right] + \frac{\partial}{\partial z}\left[\lambda(T)\frac{\partial T}{\partial z}\right] \tag{4}$$

and

$$(r,z) \in \Omega_m:$$
$$c_m(T_m)\frac{\partial T_m}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[r\lambda_m(T_m)\frac{\partial T_m}{\partial r}\right] + \frac{\partial}{\partial z}\left[\lambda_m(T_m)\frac{\partial T_m}{\partial z}\right] \tag{5}$$

where $T = T(r, z, t)$, $T_m = T_m(r, z, t)$. The details concerning the construction on FDM equations for the case discussed and problems of regard to boundary conditions are discussed, in details, in [1, 2].

The basic criterion taken into account on a stage of calorimetric curve construction was a conformability of numerical simulation and the real fragments of cooling curves at the control point (sensor) for $T > T_L$ and $T < T_S$. In this place trials and errors method has been used, and in order to achieve the good results, the mould parameters have been modified (the data quoted in literature are rather ambiguous and this approach seems to be accepted). The example of calorimetric curve obtained on the basis of numerical simulation is shown in Figure 2. It should be pointed out that the course of derivative $(\partial T/\partial t)_{cal}$ on a stage of common analysis of real cooling rate and calorimetric cooling rate is a certain way modified (see: [6, 11]).

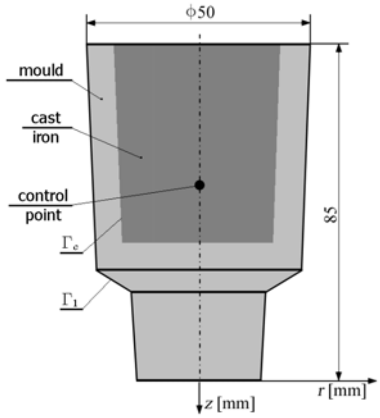

Fig. 1. Casting–mould system

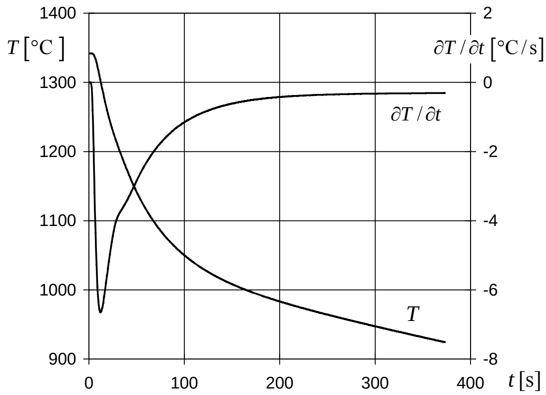

Fig. 2. Cooling and calorimetric curves

3. Substitute thermal capacity of casting material

The shape and form of function determining the evolution of latent heat depends on the alloy considered. Using the macro approach (one domain method [1, 2]) the solidification and cooling thermal effects in the interval $[T_S, T_L]$ are taken into account by substitution of $c(T)$ in equation (1) by the parameter $C(T)$, this means STC. It is a sum of two components, namely

$$C(T) = c_P(T) + c_{sp}(T) \tag{6}$$

where c_P is a volumetric specific heat of mushy zone sub-domain (e.g. $c_P = 0.5\,(c_S + c_L)$), while c_{sp} is a volumetric spectral latent heat controlling the kinetics of solidification.

Generally speaking, the left hand side of equation (1) with parameter $C(T)$ represents the real cooling rate at the point considered and its temporary value results from a course of curve $\partial T/\partial t$ found using the TDA techniques. The same left hand side of equation (1) with parameter $c(T)$ corresponds to cooling rate for which a phase change does not exist. As was mentioned previously, the fragments of cooling curves and differential ones corresponding to $T > T_L$ and $T < T_S$ should be the same both for $c(T)$ and $C(T)$. It should be pointed out that the latent heat is proportional to the area between real curve $\partial T/\partial t$ and cooling rate resulting from the course of calorimetric one [2, 3, 6, 11]. Additionally the kinetics of latent heat evolution can be also observed. In this paper the hypo-eutectic cast iron has been considered.

The charge material has been chosen according to the rules concerning the melting of cast iron in the induction furnace. In a central part of sampling casting a thermocouple PtRh-Pt has been installed. Thermocouple has been connected to the registering apparatus. Thermal and derivative analysis (TDA) has been done to determine the characteristic temperatures associated with the phase transitions. In Figure 3 a typical diagram $T(t)$ and $\partial T/\partial t$ for material considered is shown.

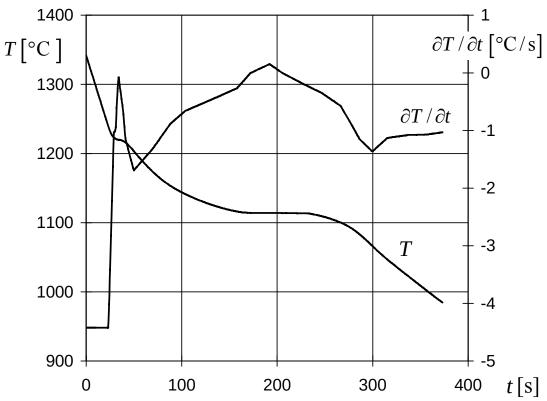

Fig. 3. Cooling curve and its derivative

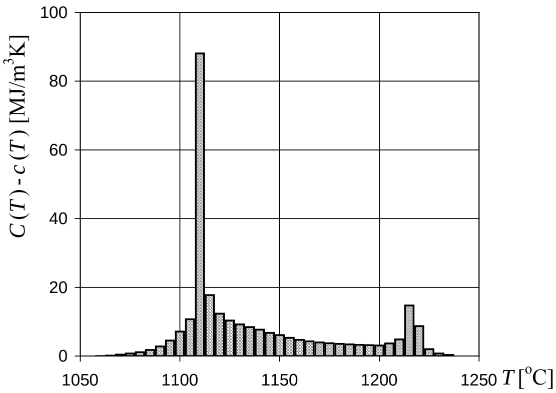

Fig. 4. Temperature dependent evolution of latent heat

On a stage of computations connected with the substitute thermal capacity estimation, the experimental data have been, in a certain way, modified. A local recalescence effect (increase of temperature at the region of eutectic transition) causes the undesirable perturbations of derivative $\partial T/\partial t$. To avoid this effect, the cooling curve $T(t)$ has been initially smoothed at this region. It seems that this simplification does not cause the visible errors of final results.

As was mentioned previously, the course of latent heat evolution results from the differences between real an calorimetric cooling rates. Next this result is transformed on a dependence between the latent heat and temperature. This final diagram constitutes a basis for mathematical description of substitute thermal capacity – Figure 4.

4. Results of computations

The following input data of casting and mould materials have been introduced: $\lambda_L = 20$ [W/(m K)], $\lambda_S = 40$ [W/(m K)], $\lambda_m = 0.7$ [W/(m K)], $c_L = 5.8\cdot 10^6$ [J/(m^{3}K)], $c_S = 5.4\cdot 10^6$ [J/(m^{3}K)], $c_m = 2.1$ [MJ/(m^{3}K)].

Pouring temperature (1340 ºC) and border ones have been found on a basis of TDA diagrams. The computations concerning the calorimetric curve and next the simulation of solidification process for obtained function $C(T)$ have been done using the FDM (explicit scheme for non-linear heat conduction proceeding in an axially symmetrical non-homogeneous domain). Geometrical mesh has been created by the cylindrical elements ($\Delta r = \Delta z = 1$ mm), time step $\Delta t = 0.02$ s.

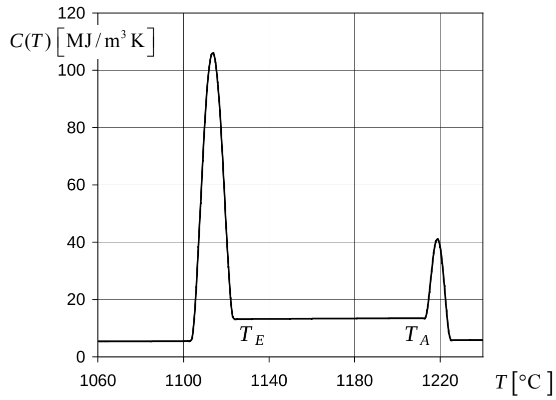

Fig. 5. STC approximation

In Figure 5 the course of assumed STC approximation is presented. The mathematical form of this function is the following [9]

$$C(T)=\begin{cases} 5.86\cdot 10^6, & T \ge 1225 \\ 5.3\cdot 10^{16} - 1.7\cdot 10^{14}T + 2.2\cdot 10^{11}T^2 + \\ -1.2\cdot 10^8 T^3 + 2.4\cdot 10^4 T^4, & 1213 \le T < 1225 \\ 1.33\cdot 10^7, & 1123 \le T < 1213 \\ 1.5\cdot 10^{16} - 5.3\cdot 10^{13}T + 7.2\cdot 10^{10}T^2 + \\ -4.3\cdot 10^7 T^3 + 9.7\cdot 10^3 T^4, & 1102 \le T < 1123 \\ 5.42\cdot 10^6, & T < 1102 \end{cases} \tag{7}$$

Figure 6 illustrates the real cooling curve at the point corresponding to sensor position and this curve found on a basis of numerical modelling. In Figure 7 the examples of simulation results (temperature field in the casting domain for times 50 and 100 s) are shown.

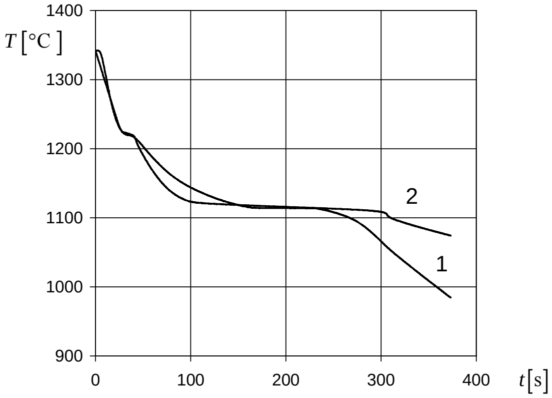

Fig. 6. Cooling curves (1 – real experiment, 2 – simulation)

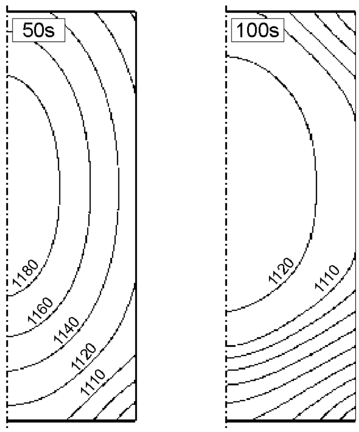

Fig. 7. Temperature fields

5. Conclusions

In the paper the example of cast iron STC estimation is presented. The computations base on the results of real experiment.

The function obtained introduced to the computer program simulating the casting solidification gives the results sufficiently close to the real course of process. The visible differences appear during the last stage of process, this means the cooling of solid.

This effect results not from the wrong approximation of $C(T)$ but from the destruction of mould material which thermal properties are probably quite different than assumed ones. Unfortunately the credible thermophysical parameters of burned mould material are unknown, additionally the shape of mould sub-domain can be also changed.

The macroscopic model of solidification does not assure the possibility of recalescence effect observation. It possible only in a case of more complicated micro/macro solidification models.

Acknowledgements

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