Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 23
ISSUE 2
August
2007

Application of evolutionary algorithms in identification of solidification parameters

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Received 10.04.2007; published in revised form 01.08.2007

Analysis and modelling

ABSTRACT

Purpose: The casting-mould system is considered. Additionally, it is assumed that part of internal parameters determining the course of thermal processes, e.g. volumetric specific heat of mould, mould thermal conductivity, casting thermal conductivity and the like is unknown. Formulated in this way an inverse problem can be solved using different methods and in this paper the possibility of evolutionary algorithms application is presented. To solve the problem knowledge of cooling/heating curves at selected set of points from casting/mould domain is necessary. The evolutionary algorithm allows to minimize the fitness function containing the differences between the 'measured' cooling curves and the same curves found on the basis of boundary initial problem numerical solution for the assumed set of parameters. The calculated cooling/heating curves have been found using explicit scheme of finite difference method. It turned out that the algorithm proposed gives sufficiently exact results of identification and it can be successfully applied in the scope of thermal theory of foundry process.
Design/methodology/approach: In this work numerical modelling of solidification process is applied. A cast iron solidifying in a sand mould is analyzed. The information concerning the courses of cooling/heating curves at the selected set of points from the domain considered is used in order to identify the unknown parameters of the process analyzed.
Findings: Application of evolutionary algorithms gives sufficiently exact results of identification of solidification parameters.
Research limitations/implications: Further work requires an introducing of real temperature measurements to the model presented.
Practical implications: The paper shows the possibilities of solidification parameters identification on the basis of temperature measurements.
Originality/value: The evolutionary algorithms presented allow to identify the parameters of solidification process e.g. volumetric specific heat of mould, mould thermal conductivity, casting thermal conductivity and the like.
Keywords: Numerical techniques; Inverse problems; Parameters identification; Evolutionary algorithms

1. Introduction

The thermal processes proceeding in the system casting-mould-environment are described by the system of partial differential equations supplemented by the adequate boundary, initial, physical and geometrical conditions. The solidification process in domain of casting is described using one domain approach [1, 2, 3, 4, 5]. If the parameters appearing in governing equations are known then the direct problem is considered, while if part of them is unknown then the inverse problem should be formulated [6, 7, 8, 9, 10]. In order to solve the inverse problem the additional information concerning the time-dependent temperature field at the set of points from the domain considered must be used.

In the paper the possibilities of evolutionary algorithms [11, 12, 13, 14, 15] application in identification of solidification parameters are discussed. In the final part of the paper the results of computations are shown.

2. Formulation of the problem

A casting-mould-environment system is considered. A transient temperature field in casting sub-domain determines the following energy equation

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

where $C(T)$ is the substitute thermal capacity [1, 4, 9], $\lambda(T)$ is the thermal conductivity, T is the temperature, x are the spatial co-ordinates and t is the time.

The substitute thermal capacity for metallic alloy is defined as follows [1]

$$C(T) = \begin{cases} c_L, & T > T_L \\ \dfrac{c_L + c_S}{2} - Q\dfrac{\mathrm{d}S(T)}{\mathrm{d}T}, & T_S \le T \le T_L \\ c_S, & T < T_S \end{cases} \tag{2}$$

where the temperatures T_L, T_S correspond to the beginning and the end of the solidification process, respectively, c_L , c_S are the constant volumetric specific heats of liquid and solid state, Q is the volumetric latent heat, $S(T)$ is the solid state fraction at the point considered.

In the case of cast iron solidification the following approximation of substitute thermal capacity can be taken into account (Figure 1) [1, 2].

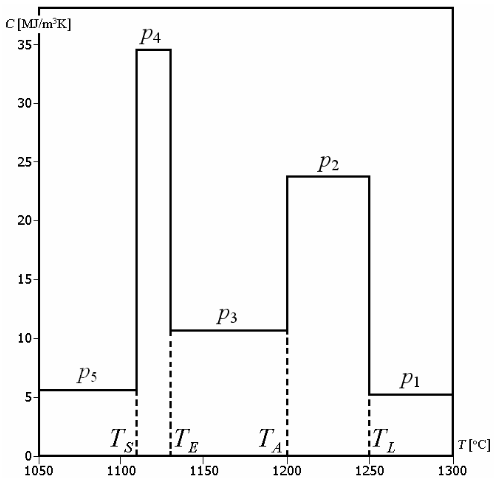

Fig. 1. Substitute thermal capacity of cast iron

$$C(T) = \begin{cases} p_1 = c_L, & T > T_L \\ p_2 = \dfrac{c_L + c_S}{2} + \dfrac{Q_{aus}}{T_L + T_E}, & T_A < T \le T_L \\ p_3 = \dfrac{c_L + c_S}{2} + \dfrac{Q_{aus2}}{T_A - T_E}, & T_E < T \le T_A \\ p_4 = \dfrac{c_L + c_S}{2} + \dfrac{Q_{eu}}{T_E - T_S}, & T_S < T \le T_E \\ p_5 = c_S, & T < T_S \end{cases} \tag{3}$$

where T_A, T_E correspond to the border temperatures, Q_{aus} = Q_{aus1}+Q_{aus2}, Q_{eu} are the latent heats connected with the austenite and eutectic phases evolution, at the same time Q=Q_{eu}+ Q_{aus}.

The thermal conductivity of cast iron can be assumed as follows

$$\lambda(T) = \begin{cases} p_6 = \lambda_L, & T > T_L \\ \dfrac{\lambda_L + \lambda_S}{2}, & T_S < T \le T_L \\ p_7 = \lambda_S, & T_S < T \end{cases} \tag{4}$$

where λ_L, λ_S are the constant thermal conductivities of liquid and solid state, respectively.

A temperature field in mould sub-domain describes the equation of the form

$$x \in \Omega_m: \quad c_m \frac{\partial T_m(x,t)}{\partial t} = \lambda_m \nabla^2 T_m(x,t) \tag{5}$$

where $p_8 = \lambda_m$ is the thermal conductivity, $p_9 = c_m$ is the volumetric specific heat of mould.

On the contact surface between casting and mould the continuity condition

$$x \in \Gamma_c: \quad \begin{cases} -\lambda n \cdot \nabla T(x,t) = -\lambda_m n \cdot \nabla T_m(x,t) \\ T(x,t) = T_m(x,t) \end{cases} \tag{6}$$

is assumed.

On the outer surface of the system the no-flux condition can be accepted, namely

$$x \in \Gamma_0: \quad q_m(x,t) = -\lambda_m n \cdot \nabla T_m(x,t) \tag{7}$$

For the moment $t = 0$ the initial temperature distribution is given

$$T(x,0) = T_0(x), \quad T_m(x,0) = T_{m0}(x) \tag{8}$$

3. Evolutionary algorithm

As was mentioned before, if the parameters appearing in governing equations are known then the direct problem is considered, while if part of them is unknown then the inverse problem should be formulated. In order to identify the unknown solidification parameters, e.g. p_8, p_9, the additional information connected with the course of the process analyzed is necessary.

We assume that the values T_{di}^f at the selected set of points x_i from the domain considered for times t^f are known, namely.

$$T_{di}^f = T_d\left(x_i, t^f\right), \quad i = 1,2,...,M, \quad f = 1,2,...,F \tag{9}$$

In order to solve the inverse problem, the least squares criterion is applied [5, 6, 9]

$$S = \frac{1}{MF}\sum_{i=1}^{M}\sum_{f=1}^{F}\left(T_i^f - T_{di}^f\right)^2 \tag{10}$$

where $T_i^f = T\left(x_i, t^f\right)$ is the calculated temperature at the point x_i for time t^f for arbitrary assumed values of unknown parameters.

Evolutionary algorithm can be very useful in solving of such inverse problems. The algorithm minimizes the fitness function (functional (10)) with respect to parameters p_k [11, 12, 15]. A chromosome (vector) characterizes the solution

$$\mathbf{p} = \left[p_1, p_2, ..., p_k, ..., p_K\right] \tag{11}$$

where p_k are the genes containing information about the solidification parameters.

The genes are the real numbers on which constrains are imposed in the form

$$p_k^L \le p_k \le p_k^R, \quad k = 1, 2, ..., K \tag{12}$$

The evolutionary algorithm starts with an initial population. This population consists of N chromosomes p^n, n = 1, 2,..., N, generated in random way. Every gene is taken from the feasible domain. For the assumed values of p^n, n = 1, 2,..., N, the direct problems described by equations (1), (5), (6), (7), (8) are solved. The next stage is an evaluation of the fitness function (10) for every chromosome p^n and the selection is employed. The selection is performed in the form of ranking selection or the tournament selection [11, 12, 13] and the evolutionary operators: mutation and crossover are applied. In this way the next population is created. The process is repeated until the chromosome, for which the value of the fitness function is zero, has been found or after the achieving the assumed number of populations.

In evolutionary computations the following genetic operators are applied [11, 12, 15]

- uniform mutation operator which changes the genes values in chromosome by choosing the new ones in random way,
- nonuniform mutation operator which changes the genes values in chromosome using the Gauss distribution,
- arithmetic crossover operator which creates new chromosome with genes which are the linear combination of two randomly chosen chromosomes.

4. Results of computations

The casting-mould system shown in Figure 2 has been considered. At first, the direct problem has been solved. The following input data have been introduced: λ_L = 20 [W/(mK)], λ_S = 40 [W/(mK)], λ_m =1 [W/(mK)], c_L = 5.88 [MJ/(m^{3}K)], c_S = 5.4 [MJ/(m^{3}K)], p_2 = 24.384 [MJ/(m^{3}K)], p_3 = 11.32 [MJ/(m^{3}K)], p_4 = 34.75 [MJ/(m^{3}K)] (c.f. equation (3)) c_m = 1.75 [MJ/(m^{3}K)], pouring temperature T_0 = 1300°C, liquidus temperature T_L = 1250°C, border temperatures T_A = 1200°C, T_E = 1130°C, solidus temperature T_S = 1110°C, initial mould temperature T_{m0} = 20°C.

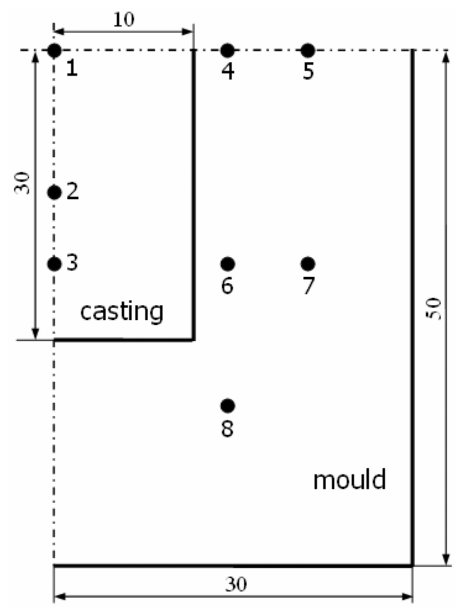

Fig. 2. Casting-mould system

The direct problem has been solved using the explicit scheme of finite difference method [1]. The regular mesh of dimensions 25×15 with constant step h = 0.002 [m] has been introduced, time step Δt = 0.1 [s].

In Figure 3 the cooling curves at the control points 1, 2, 3 from casting sub-domain (see: Figure 2) are shown, while Figure 4 illustrates the heating curves at the points 4, 5, 6, 7 and 8 from mould sub-domain.

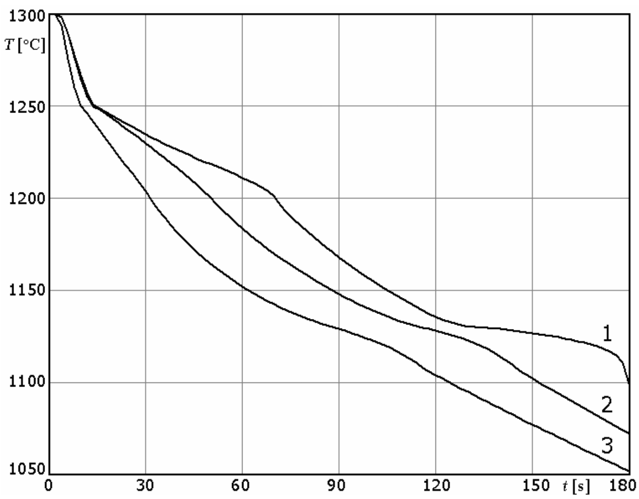

Fig. 3. Cooling curves at the points 1, 2, 3

In the Table 1 the evolutionary algorithm parameters are collected. The part of the results obtained is presented in Tables 2 and 3. The first problem concerns the identification of substitute thermal capacity coefficients (c.f. equation (3)) using the cooling curves from casting domain (Figure 3). In the second example the mould parameters $p_8 = \lambda_m$, $p_9 = c_m$ (c.f. equation (5)) have been identified using the cooling curves from mould domain (Figure 4).

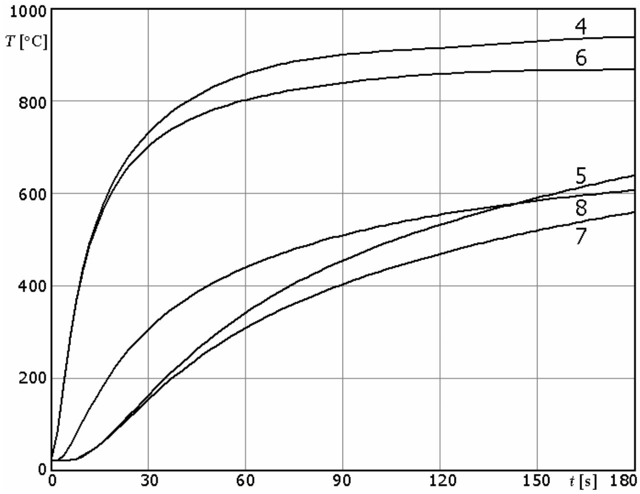

Fig. 4. Cooling curves at the points 4, 5, 6, 7, 8

Summing up, the evolutionary algorithm is a good identification tool and always the solution of inverse problem is obtained.

Table 1.
Evolutionary algorithm parameters

Number of generations	200
Number of chromosomes in each population	50
Probability of uniform mutation	30%
Probability of nonuniform mutation	40%
Probability of arithmetic crossover	30%
Probability of cloning	10%

Table 2.
Result of computations using the EA – example 1

design variable	exact value [MJ/(m^{3}K)]	found value	error %
p_1	5.88	5.7509	2.19
p_2	24.384	24.7149	1.36
p_3	11.32	11.1012	1.93
p_4	34.75	34.7077	0.12
p_5	5.4	5.8073	7.54

Table 3.
Result of computations using the EA – example 2

design variable	exact value	found value	error %
p_8 [W/(mK)]	1	0.9996	0.04
p_9 [MJ/(m^{3}K)]	1.75	1.7497	0.02

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