Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 20 ISSUES 1-2 January-February 2007

Derivative-gradient thermal analysis in casting properties forecasting

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Received 07.11.2006; accepted in revised form 15.11.2006

Analysis and modelling

ABSTRACT

Purpose: The aim of this work was to show possibilities and conception of more accurate structure and mechanical properties forecasting with use of modified derivative – gradient thermal method.
Design/methodology/approach: The main restriction in standard thermal and derivative analysis is one point measurement of temperature in casting with assumed geometry. In this work a modified method is described in which restrictions present in TDA method are overcame and more accurate diagnostic of the liquid material can be conducted.
Findings: Structural relations have been shown for local conditions of solidification defined by two derivatives dT/dt and dT/dl. Presented method incorporates up-to-date knowledge about structure influence on operating properties of metallic materials.
Research limitations/implications: Proposed methodology can be used for cast metal matrix composite and alloys properties diagnosis and forecasting. However accurate forecasting requires more detailed mathematical description.
Originality/value: Proposed conception enables possibility of structure and operating properties forecasting basing upon one physical measurement – temperature measurement.
Keywords: Composites; Solidification; Thermal and derivative analysis TDA; Simulation

1. Introduction

Conception of described method resulted from studies on structure forecasting for metal matrix composite with dispersive reinforcement. Local differences in heat flow kinetics near the ceramic reinforcing particles were shown with use of computer simulation. These ceramic particles with thermal properties significantly different from metallic matrix create heat resistance and strongly disturb heat flow. Such state has no analogy in cast metallic alloys. Scale of heat flow differences in cast alloys is incomparably smaller, however for castings with changing wall thickness problem of structure forecasting is still up-to-date and is not always taken into account in legal documents.

In today applied diagnostic techniques for alloys and metal matrix composites dominate methods based on thermal and derivative analysis. These methods consist of solidification process kinetics evaluation (T, dT/dt) referred to constant volume of model casting with specific geometry. Mould is prepared from materials with known geometrical and thermal properties. such methods of solidification analysis are easy to apply but have many restriction resulting from the method concept. From practice it is known that structure of a casting in its volume can differ in wide range.

Forecasting of metal structure in regions with different solidification kinetics basing on one-point measurement of temperature is very complicated. In practice very often we face situation when structure is significantly different from evaluated.

In literature relations can be found, which describe relation of solidification parameters with structure and operational properties [1 – 28].

In respect of structure forecasting simulation methods are way ahead from rapid diagnostic methods for alloys. Simulation methods require additional experimental validation. Besides experimentally determined derivative dT/dt, second parameter is thermal gradient dT/dl – very often neglected in industrial practice.

This work describes experimental method for simulation results validation, which is based on connected analysis for both parameters : dT/dt and dT/dl – which enclose physical sense of formulation "local conditions of solidification". Temperature measurement in several points enables evaluation of both derivatives in range of solidification modulus typical values and typical solidification rates. Possibility of data registration and its mathematical transformation enables conditions for effective control of castings quality. To make the method most effective and universal it is necessary to capture the widest range of solidification conditions by using proper casting – model system for selected casting technology.

In literature relations showing connection between solidification kinetics and structure, and also between structure parameters and operational properties are widely described. These are, among others, empirical Hall – Petch relations describing influence of dominant phase crystals, Marckrott relation for two phase, Voigt and Reus for several phases and for synergy of matrix crystals. Indicated relations describe conditions for primal crystallization for basic alloys and are incorporated in post-processing procedures in simulation software. Problem of structural and mechanical properties forecasting for hypoeutectic AlSi alloys is described in work [23]. Structure refinement can be interpreted on base of dendrite number for α phase in volume unit, but only for conditions when dendrite morphology is also analyzed. Analysis described in this work included dendrites orientation and significance of thermal gradient in that matter.

Application of this work is directed to simulation analysis with use of neural network algorithms. Favorable specific mechanical properties (related to mass density) for AlSi alloys are undeniable. One of the limitation in wider application of these alloys is rather low fatigue strength. In work [28] a relation for morphological characteristics of the structure are correlated with fatigue strength of hypoeutectic AlSi alloy. Methods of structure control in perspective can enable distinct improvement of this properties. Example of relation between morphology of structure obtained in technological process and fatigue strength.

Modern low – silicon aluminum alloys create possibilities obtaining very favorable mechanical properties:: Rm≤510 MPa, Rp0,2≤390 MPa at elongation of A5≤16% [29]. These alloys can be used as cast or after mechanical working. At low silicon content alloys are susceptible to changes in solidification and cooling rates occurring by castings with high solidification modulus. In such cases precise structure and mechanical properties forecasting and diagnosis method is especially needed.

Most of the manufactured composites contain ceramic reinforcement materials, which are characterized by significantly different (from the metal matrix) thermal properties. Composite solidification has radically different heat flow kinetics from classical alloys.

Experimental evaluation of both derivatives would enable determination of structural or operating property with use of optional theory and relations connecting both values.

This work is a continuation and a consequence of studies on components selection in respect of technological and operation properties for resulting cast composite. The main aim of diagnostic method development for liquid alloys and also liquid composite is improvement of construction material manufactured with use of casting techniques.

2. Validation studies for presented method conception

Studies of temperature measurement were conducted with use of traditional TDA sampler consisting from shell mould and Ni – NiCr thermocouples. Schematic diagram of test stand is shown in figure 1.

In the modified TDA sampler six thermocouples were placed (figure 2) along helix and direction of main heat flux – in plane perpendicular to sampler axis containing heat center of the casting.

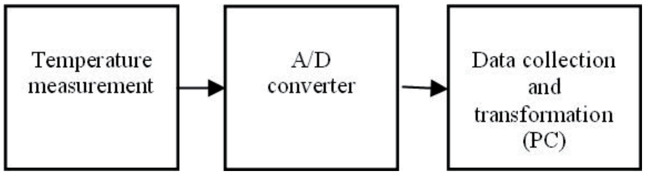

Fig. 1. Functional diagram of the test stand

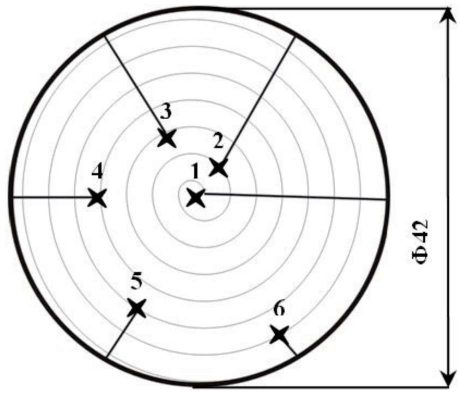

Fig. 2. Distribution of the thermocouples on casting section

In presented studies AlSi alloys were poured at 720°C. In figure 3 the relations T=f(t), dT/dt=f(t) and dT/dl=f(t) were shown for particular thermocouples (figures a, c, e) and for indication of maximum differences only for casting axis and near the mould cavity (figures b, d, f). The significant differences occurring in solidification kinetics need a solid theoretical explanation. Further experimental studies should give the answer to question whether obtained characteristics can be utilized for structure and mechanical properties forecasting in casting selected region.

In every diagram characteristic oscillations of studied parameters in function of time can be seen. Similar oscillation have been observed in previous experimental and simulation studies of dispersive composite solidification [25]. One of the explanations is that they are connected with occurrence of "reverse heat fluxes" and are one of the additional aims of thermal and derivative and gradient analysis.

In micrographs from figure 4 (a, b) non – modified eutectic can be seen (α + Si), where in α phase lamellar Si crystals occur. In following micrographs increasing dispersion for eutectic silicon in α phase is observed.

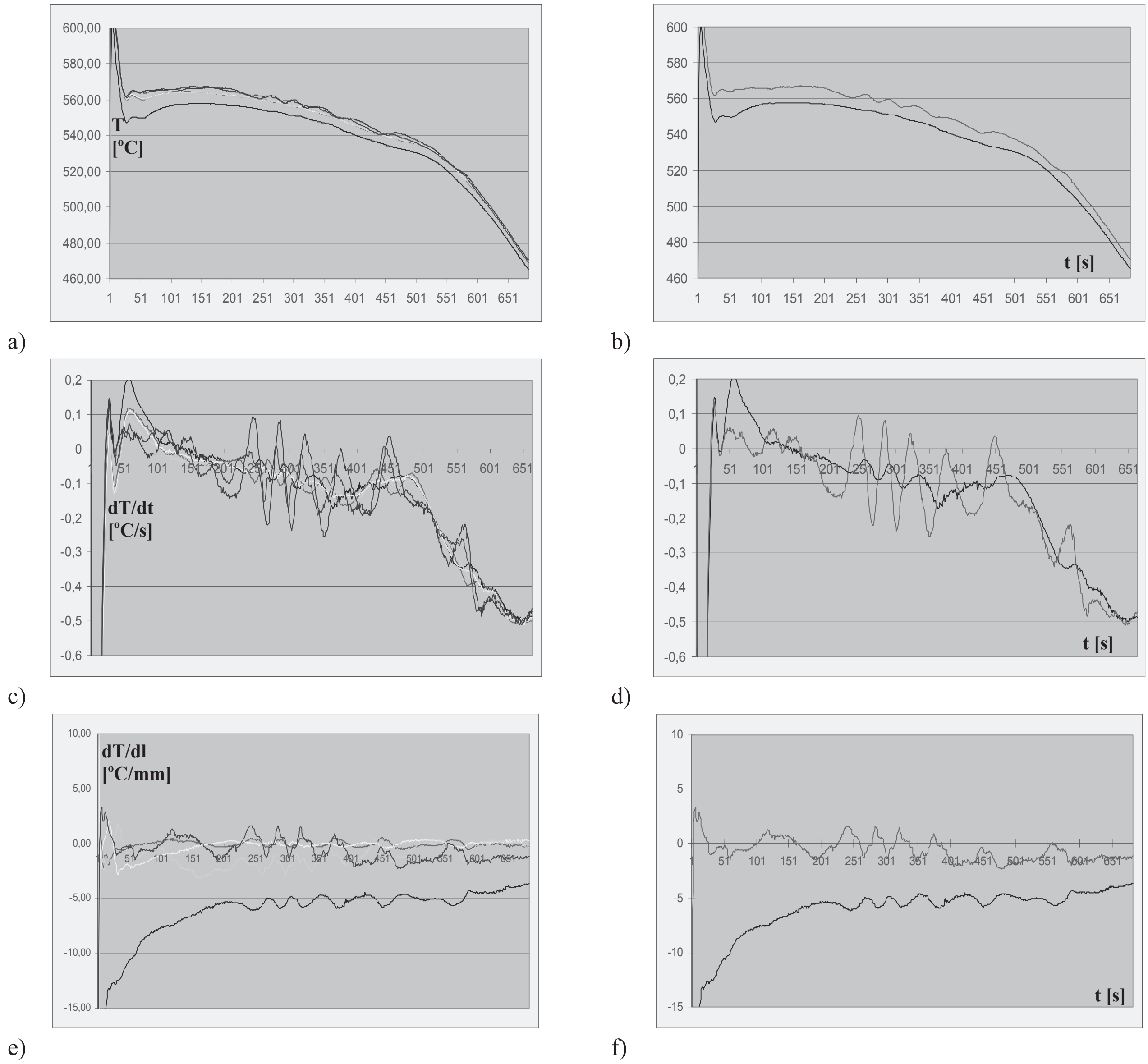

Fig. 3. Relations: T=f(t), dT/dt=f(t) and dT/dl=f(t) obtained for six thermocouples placed along the radius of sample casting (fig. a, c, e) and for extreme positions, that is in the center and near the surface of the mould (fig. b, d, f)

Fig. 4. AlSi11 micrographs taken along the radius of horizontal section of the sample casting. As can be seen dispersion of the eutectic components grows from the center to the surface of the casting. a), casting center, b) casting surface; a) Microstructure from center region, b) Microstructure near the mould region

3. Results discussion

Results have shown differences in structure along the radius of the casting. Dispersion of structure is correlated with solidification kinetics described by functions: T=f(t), dT/dt=f(t) and dT/dl=f(t). This relations need to be described by qualitative and quantitative analysis. It is necessary to work out a method for studies of materials with thermal properties and structural components from wide range – also composites with dispersive reinforcement.

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