

New approach to cast dispersive composite engineering

M. Cholewa*

Division of Foundry, Institute of Engineering Materials and Biomaterials,
Silesian University of Technology, ul. Towarowa 7, 44-100 Gliwice, Poland

* Corresponding author: E-mail address: miroslaw.cholewa@polsl.pl

Received 15.03.2006; accepted in revised form 30.04.2006

Materials

ABSTRACT

Purpose: The aim of this work was to show possibilities of numerical simulation software, based on heat transfer model, commonly used in foundry industry in cast composite properties engineering.

Design/methodology/approach: The main restriction in most of used software systems is lack of heat transfer, which may occur at composite creation. In this work the reinforcing particle morphology and size were expressed by one quantity – morphological modulus M_m and were examined for influence on heat transfer and conductivity up to the Newton's and Fourier's laws.

Findings: The main restrictions for using Fourier's model based software for composite engineering are shown. The way for crystallization control was presented including influence of morphology, transition zone and thermophysical properties of components.

Research limitations/implications: Proposed methodology can be used for cast composite properties engineering in cases, where relative motion of components is negligible. In other cases heat transfer coefficient is justified only if the software used is based on Fourier's model and the source code is accessible.

Originality/value: Proposed assumptions create possibility for components selection verification in terms of technological and operating properties of cast composite. An example of such approach was shown in work [1].

Keywords: Composites; Solidification; Reinforcing particles morphology; Simulation

1. Introduction

Identification and analysis of restrictions occurring in solidification process examination is connected with experimental methods and physical models used in numerical simulation software. Proper interpretation of assumptions can enable attaining high properties of cast composites.

THE COMPONENTS EFFECTIVE PROPERTIES AND TECHNOLOGICAL PARAMETERS

The most common state in industrial conditions is when reinforcement temperature is lower than matrix temperature. From proper wettability point of view the opposite case is more beneficial. The particular case is when both components have the

same temperature. This state is momentary in technological process. To minimize temperature difference between the components the melt should be intensively stirred. To obtain metal stirring in the mould the force field can be used (electromagnetic etc.).

If the heat conductivity of the reinforcement is lower than the matrix, then even with neglected statistically small heat resistance, for a moment, determined by specific temperature and time, the reinforcing particles create volumes with the highest temperature. In most cases these volumes have smaller heat capacity than the matrix, which emits crystallization heat in short time. When the heat conductivity of reinforcement is higher than the matrix the heat can flow from the matrix to the particles (reversed heat transfer) only when the technological process does not enable real temperature equalization. Such case is most desirable for suspensive casting with so-called internal micro-

chills. This requires precise calculation of heat diffusion in function of time and in range of matrix solidification.

The amount of heat accumulated in elementary volumes can be controlled by technological treatment. Among these relatively easy one can control the temperature. Other factors, like thermal properties: density and specific heat of components can be controlled in small range because of negligible variation. The difference of heat conductivity for reinforcing materials reaches three orders of magnitude (10^{-1} – 10^1 W/mK). Specific heat and mass density differ in range of the same order. Significant difference in heat conductivity restrict in experimental procedure use of statistically symmetrical models of experiment. While the heat capacity b can represent basic thermal properties of reinforcing particles as well as properties of matrix. As an alternative the heat accumulation coefficient can be indicated. The main factor influencing the heat accumulation factor (1) is the crystallization heat:

$$b_o = \sqrt{\lambda_o \rho_o \left(c_{po} + \frac{L_o}{\Delta T} \right)} \quad (1)$$

where: b , λ , ρ , c_p , L , T are, respectively: heat accumulation coefficient, heat conductivity, mass density, specific heat, crystallization heat, temperature, index o refers to the matrix.

In other cases – where is no phase change, heat accumulation factor is described by relation (2):

$$b_z = \sqrt{\lambda_z \rho_z c_{pz}} \quad (2)$$

where: index z refers to reinforcement particles in solid state, without phase changes.

Other physical quantity, which may also describe basic thermal properties, is heat diffusivity (3, 4):

$$a_o = \frac{\lambda_o}{\rho_o \left(c_{po} + \frac{L_o}{\Delta T} \right)} \quad a_z = \frac{\lambda_z}{\rho_z c_{pz}} \quad (3, 4)$$

where: a is the heat diffusivity.

In works [2, 3] basic thermal properties of components are correlated.

PARTICULARITY OF SOLIDIFICATION PROCESS NUMERICAL ANALYSIS

Numerical analysis is complementary to experimental methods. Its precision depends on engaged physical model for studied phenomena. Calculations are mainly based on central located reinforcing particle and assigned to it volume of the matrix. Such approach enables zero heat flux assumption on, for example two heat flow directions. Analyzed is only one main

direction of heat flow. Numerical analysis for particle located on heat flow direction is justified. Although such analysis for spherical particle is simple, the experimental validation is not.

In cast composites reinforced with ceramic particles the solidification process differs from solidification of pure matrix. Relative movement between the components intensifies the heat transport. Verification of interactions between the components must be conducted with use of Newton – Fourier's model (6). The state previous to solidification is characterized by unstable liquid flow round the particle. Heat flux density taken by the liquid from solid surface in Newton's model is described by (5):

$$q = \alpha(T_s - T_p) \quad (5)$$

where: heat convection coefficient, W/(m²K); T_s – solid surface temperature, T_p – liquid matrix temperature.

Heat flux density in direction perpendicular to solid surface (reinforcement) also can be described by Fourier's law. Connecting both models, the thermal gradient in reinforcement near the surface can be shown with relation (6):

$$\left(\frac{\partial T}{\partial n} \right)_z = -\frac{\alpha}{\lambda_z} (T_z - T_o) \quad (6)$$

Decrease of temperature and relative velocity connected with growing viscosity and order of ions before solidification causes decay of movement. For matrix this can be described by (7):

$$\left(\frac{\partial T}{\partial n} \right)_o = -\frac{\alpha}{\lambda_o} (T_o - T_z) \quad (7)$$

Heat flux taken through contact surface of matrix and reinforcement is equal to liquid metal enthalpy decrease with mass flux m' :

$$m' = dm/dt \quad (8)$$

where mass flux density is:

$$\mu = dm'/dA \quad (9)$$

$$\alpha(T_z - T_o)dA = -m'c_p d(T_z - T_o) \quad (10)$$

$$\int \alpha dA = A \bar{\alpha} \quad (11)$$

$$A \bar{\alpha} = -m'c_p \ln \frac{(T_z - T_o)_2}{(T_z - T_o)_1}$$

where: $\bar{\alpha}$ – average coefficient on exchange surface, $(T_z - T_o)_1$ and $(T_z - T_o)_2$ – temperature differences between components, $T_{z,o}$ – temperature of reinforcement and matrix, dA – elementary surface of components contact, A – sum of elementary contact surfaces – heat transfer surface, c_p – specific heat for

liquid matrix, which in narrow range of solidification is constant, m' – mass flux.

Mass flux connected to heat transfer between matrix and reinforcing particle flows to the particle through intersection equal to particle projection on plan perpendicular to mass flux direction. In case of convex particle projection section will be equal to maximum intersection of the particle. The quantity of mass flowing through depends on size of the section and its shape. Hard to determine value of this quantity one can calculate with use of equation (12):

$$m' = m \cdot v \cdot \frac{F}{O} \quad (12)$$

where: m – portion of liquid metal flowing round the particle until the relative movement decays, v – relative velocity, F – surface area of particle projection, O – perimeter of particle projection.

Velocity value can be evaluated basing on difference of mass density of components. At forced convection the force fields influence must be taken into account. From technological point of view it is necessary to create in liquid metal shear stresses by intensive stirring. It improves the wetting. As an example the use of inductive furnace for heating and stirring of components and creating relative velocity between them. When components in composite creation phase are subjected to force fields action resulting difference in relative velocity can be evaluated base on specific permeance. Value of m coefficient can be calculated using reinforcement content in the composite. Projection surface F and its perimeter O are easily evaluated from quantitative analysis of reinforcing material. Quotient F/O is equal to M_m^{-1} . Then average value of exchange coefficient will be:

$$\alpha = - \frac{m' c_p}{A} \ln \frac{(T_z - T_o)_1}{(T_z - T_o)_2} \quad (13)$$

$$\alpha = - \frac{m \cdot v \cdot c_p}{M_m A} \ln \frac{(T_z - T_o)_1}{(T_z - T_o)_2} \quad (14)$$

where: M_m – is a morphological modulus.

Connecting Newton's and Fourier's laws there is possibility to evaluate thermal gradient in matrix and reinforcement. On heat transfer coefficient significant influence has the unstable metal movement. Heat transport has dynamic character. Metal movement is decelerated and this deceleration is hard to evaluate. By intensive stirring cavitation may occur. Solidification of matrix causes significant change in its heat transfer coefficient [4, 5]. Order of magnitude for heat transfer coefficient of liquid metal is $10^2 - 10^4$ W/(m²K) [6, 7]. By phase change from gas to liquid it can exceed 10^5 . Such state not always is connected with significant relative velocity of components. For many solutions free convection may be sufficient.

By dispersive composite creation there are three characteristic states (from heat exchange point of view):

1. State of different initial components temperature, accompanied by relative movement of components. Simultaneously there is heat give up to the mould and surroundings. Initial temperature state can be defined on two manners: $\Delta T_{comp} > 0$; $\Delta T_{comp} < 0$;
2. Instantaneous state of equal temperature in components $\Delta T_{comp} = 0$, by which heat exchange does not exist;
3. State, in which with temperature decrease and growing viscosity movement decays and heat transfer coefficient decreases to 0.

Mentioned states can be described by relation:

$$\alpha (T_z - T_o) dA = -m' c_p d(T_z - T_o) \quad (15)$$

Assuming small change in heat exchange surface in range of solidification we get:

$$\alpha = \frac{-m'}{A} c_p \ln \frac{(T_z - T_o)_1}{(T_z - T_o)_2} \quad (16)$$

In analyzed state 1 $\Delta T_{kompon.} = |T_z - T_o|$ also reaches maximum, which leads to maximum value of heat transfer coefficient. Momentary state 2, which duration is inversely proportional to difference in thermal conductivity of components and direct proportional to reinforcement content and takes value in range 1 – 0. For simplification the relative velocity change can be taken as a linear and, as a consequence also for the m' value with maximum value in state 1 going to 0 in state 3. The last state duration depends on heat give up from the whole system to the surroundings. In practice there is significant difference between permanent mould and ceramic mould casting. Mainly by higher cooling rates is a possibility for reversed heat flow – to reinforcing particle from the matrix – by low thermal conductivity of reinforcement and its high heat accumulation.

Broadly discussed problem is the evaluation of simulation results reliability based on thermal gradient determination precision [8 – 10]. Crystallization analysis is based on stochastic models describing phase morphology with Monte Carlo method or cellular automaton [11]. Size and shape of crystallizing dendrites is considered in function of thermal gradient and fractal dimensions [12].

2. Conclusions

In many publications [9, 14 – 16] describe micro and macroscopic modeling of crystalline structure. Microscopic simulation is based on nucleation, crystal growth and crystallization heat give up. Utilization of presented assumptions enables use of numerical simulation based on Fourier's law for composite properties modeling. Together with validation experiments and macro – scale simulation the composite morphology can be described in complete volume of the casting.

References

- [1] M. Cholewa, Simulation of solidification process for composite micro region with incomplete wetting of reinforcing partile, 13 th Intern. Sci. Conf. AMME. Gliwice, 2005, p. 67.
- [2] S. Pawłowski, S. Serkowski, Fireproof materials for metallurgical applications, part I, Nr 1892, Gliwice, 1995 (in polish).
- [3] Z. Jura, Simulation software CasTech. Scientific works of Silesian University of technology KMtSt. v.30, Gliwice 1997, p. 119 (in polish).
- [4] Z. Poniewierski, Crystallization, structure and properties of AlSi alloys, WNT, Warsaw, 1989 (in polish).
- [5] S. Pietrowski, AlSi alloys, Wyd. Pol. Łódzkiej, Łódź 2001. (in polish).
- [6] J. Składzień, Thermokinetics and thermodynamics, Pol. Śl., nr 1213, Gliwice, 1985. (in polish).
- [7] S. Wiśniewski, Heat transfer, PWN, Warsaw, 1998. (in polish).
- [8] Z. Ignaszak, P. Mikołajczak, Discretization influence on gradient parameters in solidification process simulation, Arch. Techn. Masz. i Autom., v. 18, 1998, p. 163. (in polish).
- [9] W. Kapturkiewicz, Modeling of cast iron castings crystallization, Wyd. Nauk. Akapit, Cracow, 2003. (in polish).
- [10] Z. Ignaszak, Validation of virtual engineering systems applied in foundry industry, Konf. Sprawozd. Kom. Hutn. PAN, Krynica, 2002. (in polish).
- [11] D.M. Stefanescu, H. Pang, Modeling of casting solidification stochastic or deterministic?, Canadian Metallurgical Quarterly, v. 37, nr 3-4, 1998 p. 229.
- [12] R. Sasikumar, R. Kumar, The Strength Of The Coupling Between Macroscopic Heat Flow And Equiaxed Grain Formation In Castings, Acta.Metall. Mater., v. 43, no 12, p 4387.
- [13] Ph. Thevoz, Desboilles, M. Rappaz: Modeling of equiaxed microstructure formation in casting, Metall. Trans. A., v. 20A, 1989, p. 311.
- [14] Kapturkiewicz, Model and numerical simulation of casting crystallization, Publ. of the Academy of Mining and Metallurgy, v 109, p. 10.
- [15] C.A. Gandin, M. Rappaz: Couplet Finite Element-Cellular Automaton Model for The Prediction of Dendritic Grain Structures in Solidification Processes, Acta Metall. Mater., v. 43, 1994, p. 2233.
- [16] P. Thevoz, M. Gaumann, M. Gremaud, The numerical simulation of continuous and investment casting, J.of Mater., 2002, p.343.

Further reading

- [17] E. Majchrzak, B. Mochnacki, J.S. Suchy, Solidification of cast composite – numerical analysis of heat transfer between spherical particle and metal matrix, 7 th Intern. Sci. Conf. AMME. Gliwice, 1998, p. 329.
- [18] S. Kumai, Hu J. Higo Y., Effects of dendrite cell size and particle distribution on the near- threshold fatigue crack growth behavior of cast Al-SiCp composites, Materials Processing, Elsevier Science, 1995, s. 376.
- [19] H.J. Brinkman, J. Duszczyk, L. Katgerman, Produktion of aluminum composites by P/M router, 7 th Intern. Sci. Conf. AMME. Gliwice, 1998, p. 49.
- [20] A. Olszówka-Myalska, J. Śleziona, Surficial phenomena on Sic – Al alloy interface as composite manufacturing and exploitation factors, 7 th Intern. Sci. Conf. AMME. Gliwice, 1998, p. 395 (in polish).
- [21] L.A. Dobrzański, M. Piec, Structure and properties of aluminum alloys reinforced with the Al₂O₃ particles, 12 th Intern. Sci. Conf. AMME. Gliwice, 2003, p. 271.
- [22] L.A. Dobrzański, A. Włodarczyk, A. Adamiak, Composite materials with AlCu4Mg1 matrix reinforced with ceramic particles, 12 th Intern. Sci. Conf. AMME. Gliwice, 2003, p. 297 (in polish).
- [23] J. Hemanth, K.S. Shashi Shekar, Effect of heat transfer on strength and fracture behavior of Al/Al₂SiO₅ hybrid MMCs, 12 th Intern. Sci. Conf. AMME. Gliwice, 2003, p. 371.
- [24] M. Cholewa, Simulation of composite microregions solidification process, 13 th Intern. Sci. Conf. AMME. Gliwice, 2005, p. 63.