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Kinetics of composite solidification taking movement of components into consideration

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ABSTRACT

Purpose: of this paper is evaluation of influence relative movement rate of components during solidification on heat movement kinetics. Following assumptions have been made, relative movement of components favour the thermal homogenisation of system, and what follows improving structural and utilitarian properties of composite.

Design/methodology/approach: Real rate of forced relative movement of component is hard to measure. But it analytical estimation in temperature and time function is possible. In presented researches as kinetics of heat movement determinants, dependences of temperature and temperature on time and heat movement direction derivative in time and direction of thermal axis are assumed. Next the computer simulations have been made.

Findings: In comparison with relative movement rate of components cooling rate have dominant influence on kinetic of composite region solidification. Along with increasing of cooling rate similar and about double increasing of time and direction derivatives of temperature were observed.

Research limitations/implications: Quantitative analysis of field of force influence on components movement in solidificating composite is purposeful. In planed researches potential field of force will be electromagnetic field.

Practical implications: Individual selection of character of relative components movement in depends of sand mould's thermal properties, which was used to casting composite, is necessary. Even small relative components movement, on level 1 [cm/s], during composite solidification causes thermal homogenization of composite microregion, what may in prospect, improves structural homogeneity of composite, in the same time decreases thermal stresses on matrix – reinforcement boundary.

Originality/value: It is show that apart from other, typical variants of metal-ceramic composites use also component with high thermal conductivity to creating composite casting generating in particles surroundings high local cooling rates and temperature gradients.

Keywords: Composites; Casting; Computer simulations; Solidification

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ENGINEERING MATERIALS

1. Introduction

The matter of researches is elementary microregion of composite contained single particle with irregular geometry near to real particle geometry, which has been placed in matrix with assumed components fraction. Fraction of particles in composite is 8%. The basic aim of investigations is evaluation of influence relative movement rate of components during solidification on kinetics of heat movement. Following assumptions have been made, relative movement of components favour the thermal homogenisation of system, and what follows improving structural and utilitarian properties of composite. Relative movement of components during solidification without forced convection are disputable, like significance of its influence on utilitarian properties. When movement is caused mainly by gravitational segregation. Movement rate, which is result from gravitational segregation decreases along with morphological modulus of reinforcement particles increasing (M_m=F/V [1/µm]) [4] and along with temperature of liquid matrix decreasing. If during solidification movement of liquid dispersion are forced then as a result of differences matrix and reinforcement physical properties relative movement of components occurs [11-13]. Difference of mass density or difference of electric and magnetic properties depending on way of movement forcing causing relative component movement existence what may have essential influence on kinetics of heat movement in solidifying composite. Real rate of forced relative movement of component is hard to measure. But it analytical estimation in temperature and time function is possible. In presented researches as kinetics of heat movement determinants, dependences of temperature and temperature on time and heat movement direction derivative in time and direction of thermal axis are assumed ($T = f(t,l)$, $\frac{dT}{dt} = f(t,l)$, $\frac{dT}{dl} = f(t,l)$). Took into consideration temperature and time ranges covering solidification of composite matrix. Relations of solidification rate and temperature gradient with alloys microstructure and also with basic mechanical properties are presented among others things in works [1,2,5-10,14,15]. Moreover in earlier authors works [2,3] analytical Fourier-Kirchhoff-Newton model of heat movement was presented. This model for significant value of relative component movement rate may be turn out particularly useful owing to taking into consideration coefficients of thermal conductivity and heat exchange on particle – matrix boundary. Relations illustrate equations (1-3):

$$\left(\frac{\partial T}{\partial n}\right)_o = -\frac{\alpha}{\lambda_o}\left(T_o - T_z\right) \tag{1}$$

$$\alpha = -\frac{m \cdot v \cdot c_p}{M_m A} \ln \frac{(T_z - T_o)_2}{(T_z - T_o)_1} \tag{2}$$

$$M_m = \frac{F}{O} \tag{3}$$

where:

α – average value of heat transfer coefficient on exchange surface,

λ_o – thermal conductivity coefficient of matrix,

$(T_z - T_0)_1$ and $(T_z - T_0)_2$ – temperature differences between components on side inflowing and outflowing metal stream with regard to particle,

$T_{z,o}$ – reinforcement, matrix temperature,

A– summary area of component contact, heat transfer area,

c_p – specific heat of liquid matrix,

m – mass portion of metal flowing pass particle to time when relative movement is steady,

v – relative velocity,

M_m– morphological modulus of reinforcement particles,

F – surface of particle view area,

O – circumference of particle view.

2. Researches conception and methodology

In carried out experiment (computer simulation) assumed composite material made of aluminum – siliceous (AlSi11) matrix, with high thermal conductivity coefficient and metallic particle (CrFeC) also with significant high thermal conductivity in comparison to traditionally used ceramics. Originally presented system is characterized by not big sensitivity on analyzed parameters. Proved existence of differences in system about maximum near thermal properties gives basis to carrying out similar analysis for composites with ceramic particles where the differences in thermal properties are significant bigger. Moreover proposed component set have important utilitarian feature. CrFeC particles contain chromium carbides that are crucial importance for tribological processes.

2.1. Start and boundary condition assumed for simulation

As a matrix material AlSi11 alloy with CrFeC particles was assumed. Model microregion is a square about side dimension 3 mm, in which center immovable particle was placed. In Figure 1 simulated region with axis, along which analysis of heat movement kinetic in solidificating matrix was carried out, are presented. Simulation was carried out for 12 cases of matrix movement rate and cooling rate: v_l=0; 0.01; 0.02; 0.03 [m/s] and v_t=0.5; 1; 1.5 [K/s]. For each simulations start temperature was: T=993 [K].

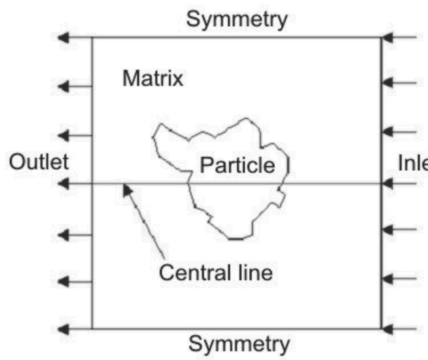
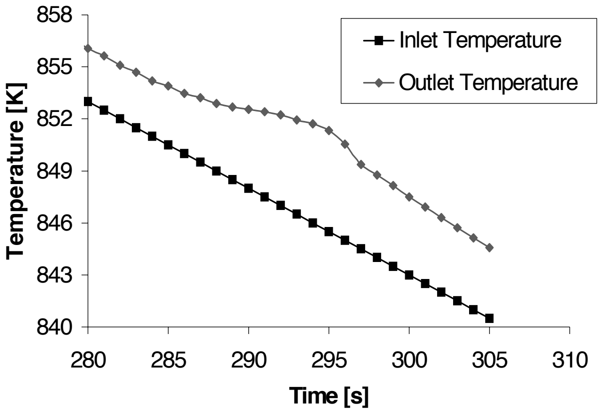
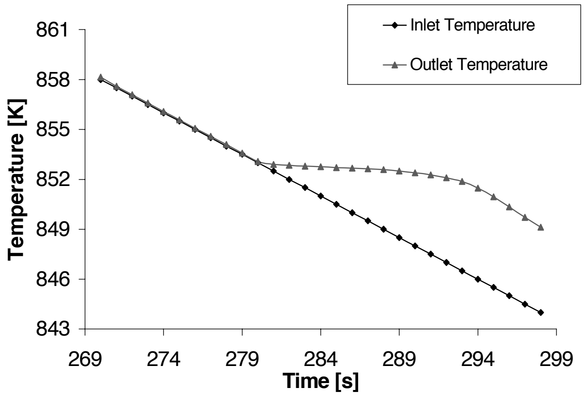


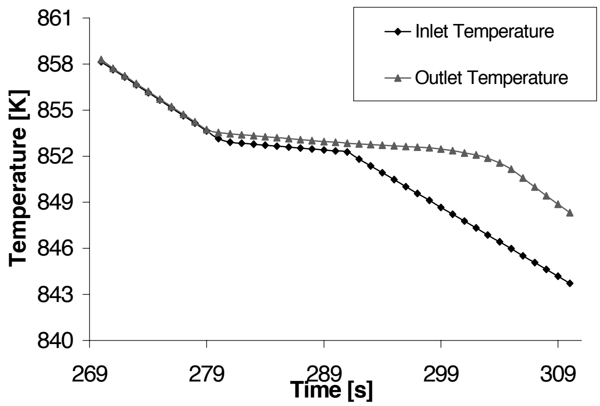
Fig. 1. Simulated composite microregion



a) v=0 [m/s] and DT 0.5 [K/s]



b) v=0.01 [m/s] and DT 0.5 [K/s]



c) v=0.01 [m/s] and DT 0.5 [K/s]

Fig. 2. Example diagrams shows averaging temperature drop for minimum values of movement rate and cooling rate: a) for zero movement rate, a) and b) without taking into account temperature arrest on inlet, c) with taking into account temperature arrest on inlet

In first series „initial" simulations linear temperature drop on inlet of analyzed region was assumed. Such state fulfils constant rate of heat receiving by mould. For this aim the end movement rate, for which metal still flow before end of solidification, is determined from linear dependence, took into account time after which the first crystals appears and assumed a priori start rate. It must be emphasize that, for the lack of data about components relative rate, values of start rate (first column of Table 1) are intuitive. End rate estimation in dependence of time after which the first crystals of solid phase appears (not for: for example 50% solid fraction) was made in order to prove significant influence of component movement rate even with passing over the rate which occurs during solid fraction increase up to 100%. In table 1 determined values of rate v_l connected with matrix temperature drop in time function are presented. Example results of rate change in outlet in dependence on assumed parameters shows in Figure 2.

Table 1.
Determined end rate on system inlet

Start rate v_{lp}[m/s]	Cooling rate v_t [K/s]	Time after which the first crystals of solid phase appears t [s]	End rate v_{lk} [m/s] 10^{-3}
0.01	0.5	281	0.035
	1	142	0.07
	1.5	94	0.1
0.02	0.5	281	0.07
	1	142	0.14
	1.5	94	0.21
0.03	0.5	281	0.1
	1	142	0.21
	1.5	94	0.32

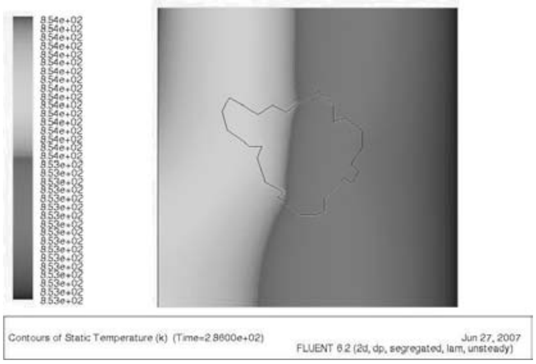
Obtained results were use for carried out essential simulations with taking into account temperature arrest on inlet connected with composite matrix crystallization.

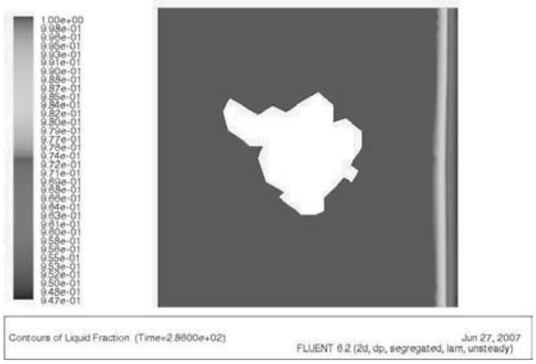
3. Results

Example simulations results as image of temperature and liquid phase friction distribution in analyzed microregion are presented in Figure 3.

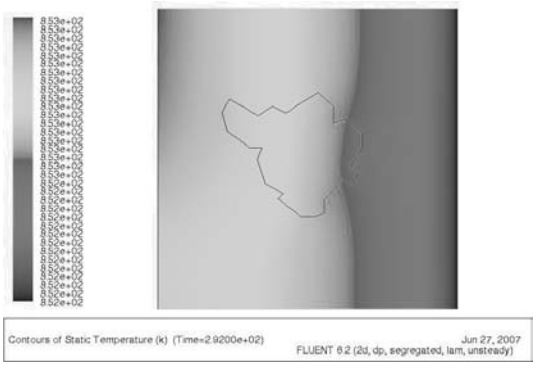
Obtained results show that after 6 sec. along with increasing cooling rate and increasing relative movement rate faster general temperature drop follows in analyzed microregion. Accompanying it shortening time of transformation matrix from liquid to solid phase. Result is consistent with expectations, and for quantitative description and further kinetics of solidification analysis, temperature change and its time derivative and heat movement direction derivative taking into account they value along heat axis of region during composite matrix solidification were analyzed. In first order temperature changes in point placed on heat axis side by side with distant about 0.03 mm (axis length is 3 mm), with sampling time equal 1 sec. was recorded. On the basis of obtained results the temperature time derivative and direction derivative was estimate. Surface of dependences on surface diagram are presented in Figures 4 and 5.

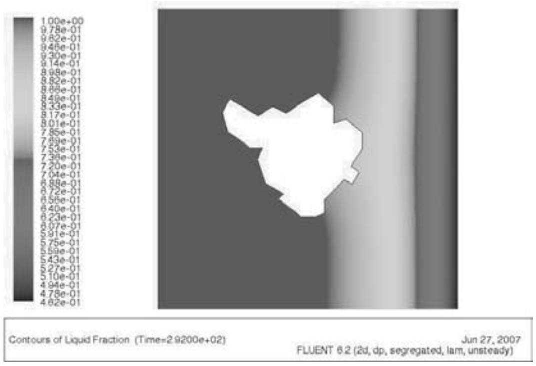
a) v=0.01 [m/s] and ΔT 0.5 [K/s]





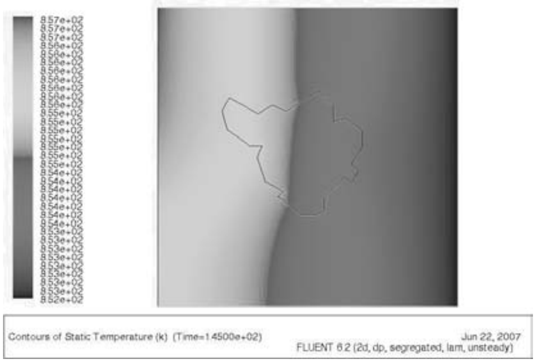
After 286 seconds

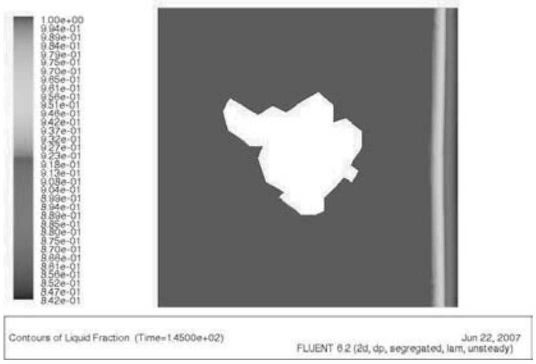




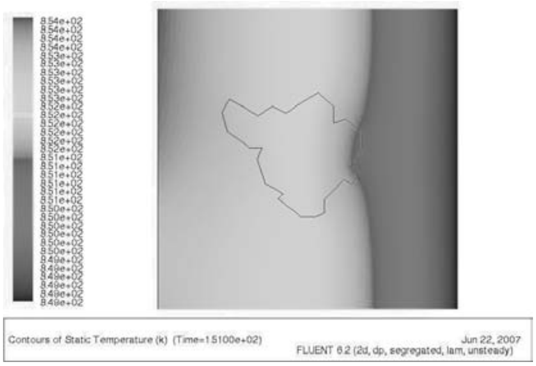
After 292 seconds

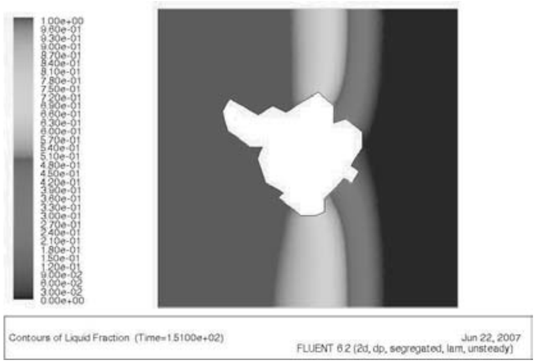
b) v=0.02 [m/s] and ΔT 1 [K/s]





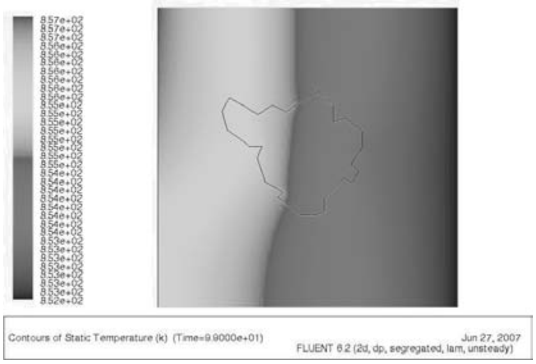
After 145 seconds

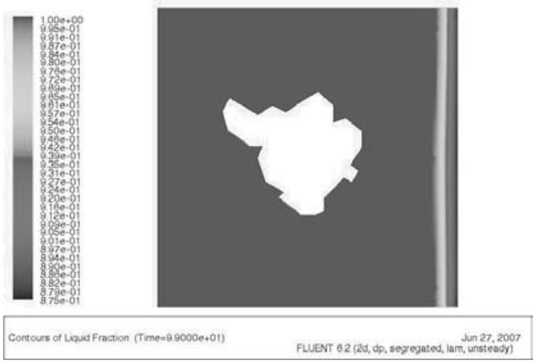




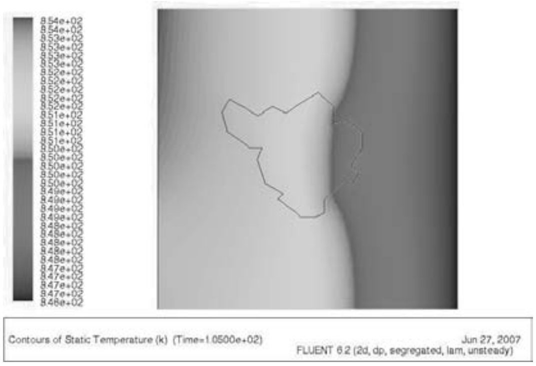
After 151 seconds

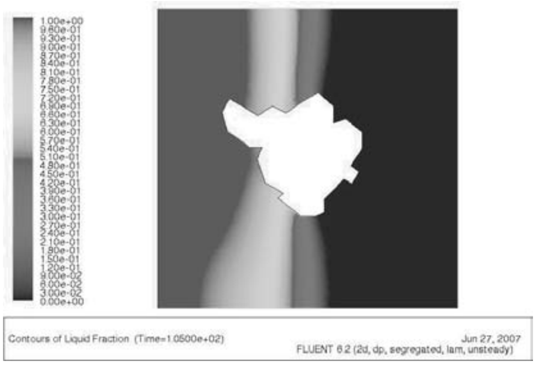
c) v=0.03 [m/s] and ΔT 1.5 [K/s]





After 99 seconds





After 105 seconds

Fig. 3. Example temperature (left column) and liquid phase friction (right column) distribution in analyzed composite microregion

On the basis of diagrams presented in Figures 4 and 5 it is possible to specify values of both derivatives in particle direct surroundings. The strongest influence on they values range exist on side outlet and inlet liquid matrix. It is possible to estimate the influence both variables in analyzed process – components movement rate v_l and cooling rate v_t – on heat movement kinetics. Along with increasing both variables increasing intensity of temperature time and direction derivatives change. In particle surroundings values of temperature gradient shows bigger diversity than solidification rate. Even smallest relative component movement rate cases significant decreasing values both derivatives of temperature. For comparison, reaction intensity, diversity time and assumed direction of heat movement, collinear with direction relative components movement rate, derivative of temperature are illustrated in the form of bar chart in Figures 6 and 7. In analyzed range for assumed cooling rate characteristics and for constant relative components movement rate was found that:

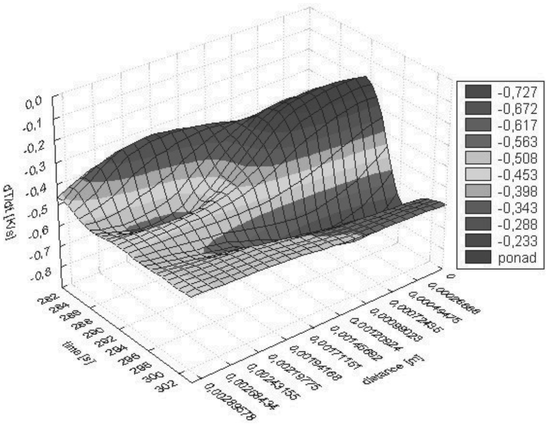
- Cooling rate v_t with relation to relative components movement rate v_l have dominant influence on solidification kinetics,
- Along with increasing of cooling rate v_t is observed, apart from relative movement rate v_l, similar about double increase of time and direction derivatives values dependences of temperature on time and on direction. Values of both derivatives for rest matrix are the biggest consistent with expectations, and analogous increasing of derivatives is over double (2.16 – for gradient and 2.29 – for solidification rate).

In Table 2 are presented in percentage maximum decrease temperature gradient and solidification rate for altering cooling rate v_t and relative rate v_l in compare to microregions with rest matrix.

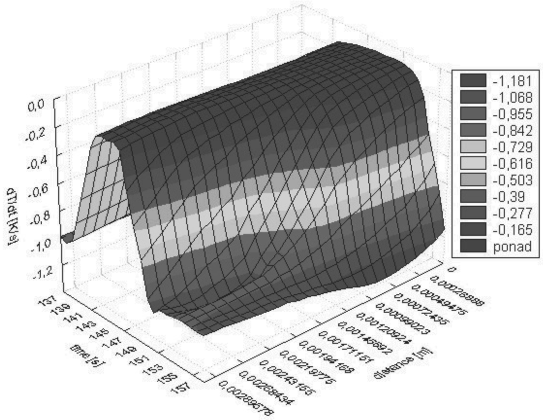
Table 2.
Influence of components movement rate on kinetics parameters decrease

Value of direction derivative of temperature decrease in relation to lack of components movement (vl=0 [m/s]) in [%]*			
	v_l=0.01 [m/s]	v_l=0.02 [m/s]	v_l=0.03 [m/s]
v_t=0.5 [K/s]	17	15.5	10
v_t=1 [K/s]	25	16.5	23
v_t=1.5 [K/s]	35.5	39	35
Value of time derivative of temperature decrease in relation to lack of components movement (v_l=0 [m/s]) in [%]*			
	v_l=0.01 [m/s]	v_l=0.02 [m/s]	v_l=0.03 [m/s]
v_t=0.5 [K/s]	22	18	13
v_t=1 [K/s]	19	6.5	18
v_t=1.5 [K/s]	20	20	20

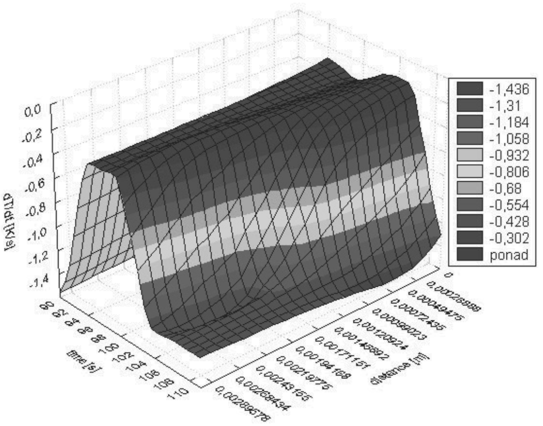
*) Results relate to maximum values recorded along heat axis of analyzed microregion.



a) v_l=0 [m/s], v_t=0.5 [K/s]

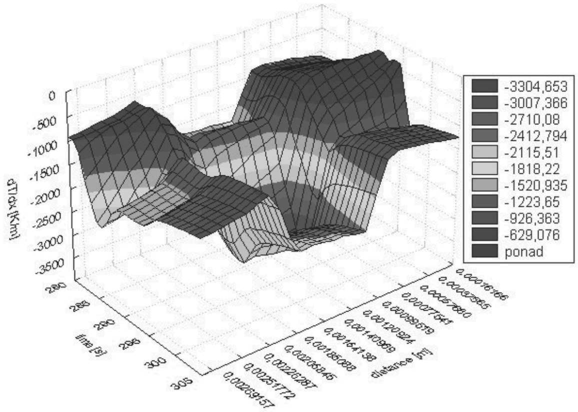


b) v_l=0.02 [m/s], v_t=1.0 [K/s]

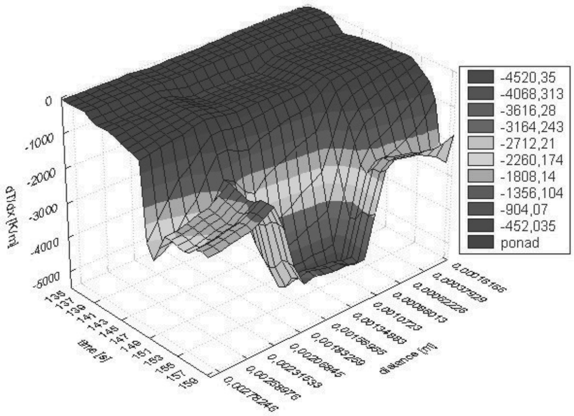


c) v_l=0.03 [m/s], v_t=1.5 [K/s]

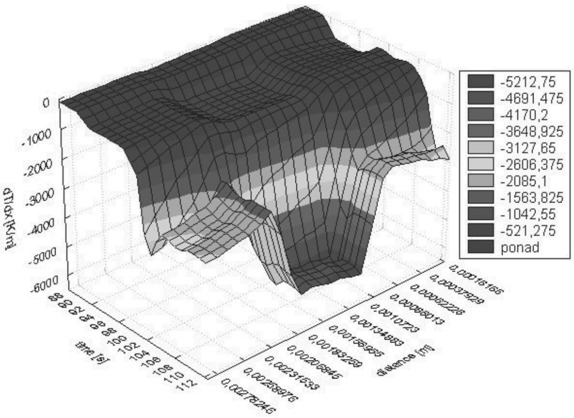
Fig. 4. In diagrams temperature time derivatives $\frac{dT}{dt} = f(t,l)$ [K/s] for altering relative component movement rate $\boldsymbol{v_l}$ and cooling rate $\boldsymbol{v_t}$



a) v_l=0 [m/s], v_t=0.5 [K/s]



b) v_l=0.02 [m/s], v_t=1.0 [K/s]



c) v_l=0.03 [m/s], v_t=1.5 [K/s]

Fig. 5. In diagrams temperature direction $\frac{dT}{dl} = f(t,l)$ [K/m] for altering relative component movement rate $\boldsymbol{v_l}$ and cooling rate $\boldsymbol{v_t}$

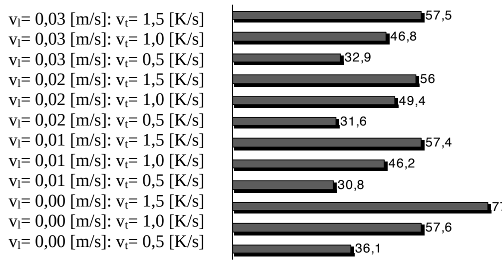


Fig. 6. Statement of maximum values of absolute temperature gradient, [10^{-2}K/m]

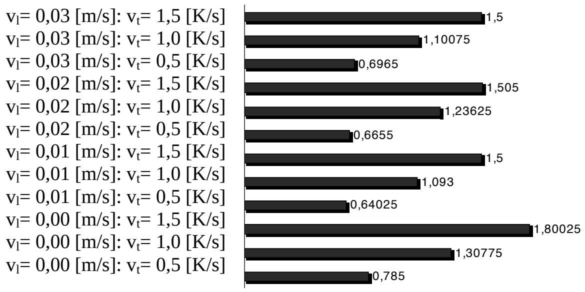


Fig. 7. Statement of maximum values of absolute temperature time derivatives, [K/s]

Along with increasing of relative components movement rate decreasing of temperature gradient is the bigger, the bigger cooling rate is. The biggest effectiveness, in comparison with stationary state of components, is observed even for assumed minimum relative component rate. However for maximum cooling rate and relative movement reduction for temperature gradient is similar and amounts at least 35%. Influence of input variable on cooling rate is analogous but effectiveness in comparison with stationary stat is lesser and amounts about 20%.

It's necessary to emphasize that local temperature changes and its derivatives, that occurs around the particles are so complicated that it demands individual analysis at first on direction perpendicular to instantaneous rate vector direction and direction of heat movement, next on direction under angle amount 45^o. In general angle of 45^o sims to be the most suitaple ffor statistical evaluation of influence relative movement rate on crystallization kinetics.

4. Conclusions

In researched range:

1. In comparison with relative components movement rate cooling rate have dominant influence on kinetic of composite region solidification.
2. Along with increasing of cooling rate similar and about double increasing of time and direction derivatives of temperature were observed.
3. Components movement causes significant decreasing kinetic parameters of solidification: time derivatives to about 20%, and direction derivative to about 35%.

Obtained results lead to practical conclusions:

- It is show that apart from other, typical variants of metalo-ceramic composites use also component with high thermal conductivity to creating composite casting generating in particles surroundings high local cooling rates and temperature gradients, that may be effective reduced by use of liquid metal movement during solidification.
- Even small relative components movement, on level 1 [cm/s], during composite solidification causes thermal homogenization of composite microregion, what may in prospect in macro scale, improves structural homogeneity of composite, in the same time reducing thermal stresses on matrix – reinforcement boundary.
- Individual selection of character of relative components movement in depends of sand mould's thermal properties, which was used to casting composite, is necessary
- Quantitative analysis of field of force influence on components movement in solidificating composite is purposeful. In planed researches potential field of force will be electromagnetic field.

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