

Experimental and Simulated Temperature Gradient During Growth α -phase of Al-Si Alloy Castings

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A numerical simulation of solidification process for AlSi8,7 alloy castings has been carried out. Numerical simulation with experimental temperature gradient and local solidification time have been compared for different boundary condition. A numerical simulation of solidification process have been executed by the program PAMCAST Simulor. The paper presents the investigations results of the temperature gradient distribution during solidification α -phase in the castings.

Keywords: castings, Al-Si alloys, temperature gradient, simulation.

1. INTRODUCTION

Appropriate forecasting of crystalline structure and mechanical properties of castings, according to exploitation requirements, is one of more important tasks pertaining to designing of manufacturing of castings made of various alloys. Very often procedures have only intuitive or barely qualitative meaning with regard to particular walls of the whole casting. Application of available knowledge on thermal conditions to be met during formation of a structure in accordance with defined casting methods, without suitable quantification of the conditions, is not complete.

Therefore, for forecasting of structure and mechanical properties of the castings with the use of empirical equations particular information is required, e.g. local solidification time and temperature gradients, obtained from expensive and time-consuming experimental studies, with the use of suitable mold equipment. A more rapid and less expensive method for gaining the information consists in simulation of the casting solidification process. However, in order to ensure good consistency with actual casting conditions a validation condition of the simulation model should be satisfied.

Validation procedures of the model, considered as physical & mathematical formulation of the engineering task to be solved with numerical methods, consist of looking for an effective adjustment of model components to the parameters of the actual process. This is related with testing of various variants of the set of parameters, enabling determining of error margins occurring during the simulation calculations. Among usually applied procedures may be reckoned: a global (balancing) energetic validation and a dynamical temperature validation [1]. The present paper includes the attempt to enlarge the validation procedure providing good approximation of solidification time and temperature gradients in selected points of the casting. To achieve this goal the results of experiments were used.

The simulation studies of the casting solidification process were performed by means of a simulation code PAMCAST Simulor.

2. SIMULATION STUDIES - IDENTIFICATION OF CONDITIONS FOR CASTING SOLIDIFICATION

The studies under real conditions and simulation research of solidification process have been performed for the castings in the form of a cylinder made of AlSi8,7, of the diameter 30 mm and height 100 mm, casted in vertical position, with upper riser of the height 55 mm, solidifying in a mold made of homogeneous quartz sand (1) and in a mold of quartz sand with copper chill placed at the bottom face of the cylindrical casting (2).

Such values as the local solidification time and average temperature gradient during crystallization of the α -phase, determined based on self-cooling curves, served as a basis for defining the simulation conditions and thermal parameters of the material. A simplified iteration method was applied. Therefore, the direct problem (the PAMCAST simulation) was repeatedly solved until achieving satisfying conformity of solidification time of the casting in the simulated (S) and experimental (E) solidification processes. The first derivative of self-cooling curves (E and S) for selected points of the castings served for evaluation of convergence of the process.

The simulation calculations were carried out for the following values of characteristic temperatures, defined on the base of experimental self-cooling curves of the castings:

- initial temperature of the alloy in the mold 660 °C,
- liquidus temperature 602 °C,
- eutectic temperature 574 °C,
- solidus temperature (termination of solidification according to PAMCAST formula) 572.5 °C,
- initial temperature of the mold and the environment 25 °C.

Other parameters assumed for the simulation calculation, corresponding to the conditions of actual process, were as follows:

- heat of solidification 419000 J/kg;

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– linearly variable increment of solid phase: for the eutectic temperature 574 °C $f_{SE}=0.31$, while for the solidus temperature 572.5 °C $f_{SS}=1$;

– specific heat of the alloy: liquid phase $c=1290$; solid phase $c=1000$; chill $c_{OCH}=421$; molding sand $c_M=1016$ J/kgK;

– alloy density: liquid phase $\rho'=2600$; solid phase $\rho=2700$; chill $\rho_{OCH}=8940$; molding sand $\rho_M=1590$ kg/m³.

Average coefficient of heat exchange between the casting and the Cu-chill was identified based on the simulation of solidification process that gave the best conformity of 5 values of solidification time, comparing the simulated and experimental processes. In result the coefficient $\alpha_{O-OC}=4500$ W/m²K was obtained.

The coefficient of heat exchange between the casting and the quartz sand, assumed as $\alpha_{O-M}=10^6$ W/m²K (meaning a quasi-ideal contact), does not significantly affect the process. On the other hand, the coefficient of heat exchange between the mold and environment is $\alpha_{M-OT}=20$ W/m²K.

Moreover, the values of thermal conductivity of the alloy were assumed from the PAMCAST Simulor data base: $\lambda_L=125$ W/mK for the liquid phase and $\lambda_S=170$ W/mK for the solid one. For the molding sand the coefficient $\lambda_M=0.69$ W/mK was assumed - according to [2].

The method of choice of material parameters for the simulation was based on the experience attained during the activity of the Material Technology CAD CAE Laboratory in the Institute of Materials Engineering of the Poznań University of Technology. Satisfying conformity was achieved between the solidification times, i.e. the simulated and experimental values (excepting the distance between cylinder basis $y=45$ mm of the casting obtained from the mold No 2) with considerable difference between simulated and experimental temperature gradients in a casting solidifying in the mold No 2 (Table 1).

Table 1. Values of local solidification time of the casting and the average temperature gradients in y and x direction during crystallization of the α -phase (from the experience and the simulation). Stage I

Mold	Co-ordinates of the point of a casting ($y; x$) in mm									
	5; 0	15; 0	25; 0	35; 0	45; 0	5; 0	15; 0	25; 0	35; 0	25; 9
	Solidification time, s					Temperature gradient, °C/cm				
1 E	67	92	104	112	123	5.9 ¹	3.4 ¹	1.8 ¹	1.4 ¹	2.7 ²
S	65	88	101	114	125	4.6 ¹	2.3 ¹	1.3 ¹	0.9 ¹	2.4 ²
2 E	4	11	21	31	46	36.5 ¹	17.3 ¹	11 ¹	9.3 ¹	5.4 ²
S	6.3	13	21.1	29.4	38.6	18 ¹	7.6 ¹	3.9 ¹	2.2 ¹	2.7 ²

¹gradient component in y -direction (cylinder axis) G_y , ²gradient component in x -direction (cylinder radius) G_x , y – denotes the distance from the bottom face of cylindrical casting being in the pouring position, $x=0$ – axial coordinate of the cylinder (Fig. 2).

The next series of simulation calculations were related to the goal consisting in improving the consistence between simulated and experimental temperature gradients. Further simulations were carried out, showing the differences in the following parameters:

– mold No 1: constant values $\alpha_{O-M}=10^6$ W/m²K, $f_{SL}=0$, $f_{SE}=0.31$ and variable ones $\lambda_M=0.69-0.95$; $\lambda_L=70-125$; $\lambda_S=70-210$ W/mK;

– mold No 2: constant values $\alpha_{O-M}=10^6$ W/m²K, $f_{SE}=0.31$ and variable ones $\alpha_{O-OCH}=3.5 \cdot 10^3 - 3 \cdot 10^4$ W/m²K, $\lambda_M=0.69-0.90$; $\lambda_L=70-125$; $\lambda_S=90-210$ W/mK, $f_{SL}=0-0.29$.

It was shown for the castings solidifying in the mold No 1 that for the 1-st data set (No 1: $\alpha_{O-M}=10^6$ W/m²K, $f_{SL}=0$, $f_{SE}=0.31$, $\lambda_M=0.9$, $\lambda_L=90$, $\lambda_S=210$ W/mK) the best conformity between the simulated and experimental temperature gradients does not correspond to the best consistence between respective solidification times (Fig. 1a, curves 1). On the other hand, the best conformity between simulated and experimental temperature gradients for the casting from the mold No 2 was obtained (Fig. 1b, curves 3) for the 3-rd data set (No 3: $\alpha_{O-M}=10^6$, $\alpha_{O-OCH}=10^3$ W/m²K, $f_{SL}=0$, $f_{SE}=0.31$, $\lambda_M=0.74$, $\lambda_L=90$, $\lambda_S=130$ W/mK). Both the approximation of simulated and experimental temperature gradients and the conformity of local solidification time for the part of the casting being adjacent to the chill, i.e. at the distance $y=25$ mm, were improved as compared with the data of Table 1. However, the simulation studies with the use of other test data did not improve approximation of simulated and experimental results.

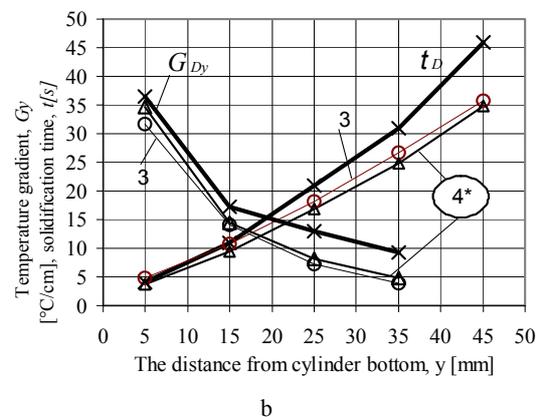
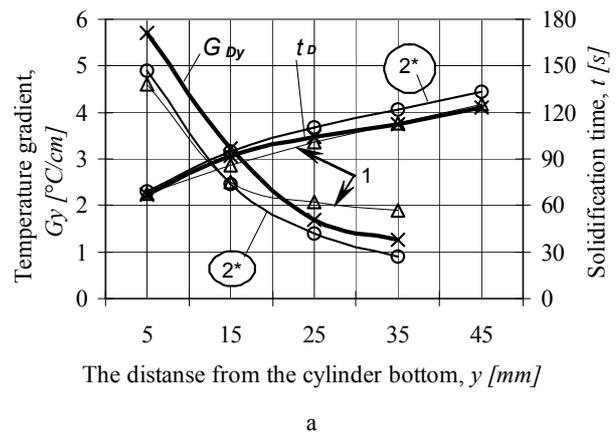


Fig. 1. Values of local solidification time and temperature gradient obtained from experiments (t_D , G_{Dy}) and from simulation (according to the above mentioned data No: 1, 3, and 2*, 4*) along the axes of the castings solidifying: a – in the mold No 1, b – in the mold No 2

In order to improve the identification method presented here, aimed at finding the parameters defining solidification conditions based on repeated solving of the direct problem (the iterations carried out with a simplified method - a trial-and-error method), and enabling good simultaneous conformity of solidification time and temperature gradient, further simulations would be required, with the use of greater number of combinations of thermophysical properties of the casting and mold materials. However, such an approach does not guarantee quick reproduction of optimal sets of these properties.

No literature items have been found that would be devoted to validation of the model stating the problem of simultaneous conformity of solidification time and temperature gradient with the use of simulation methods and appropriate experimental values. Taking into account the above mentioned difficulties and the data from the work [2], further studies and selection of simulation data, i.e. thermophysical properties of the casting and mold materials in the simulation process of casting solidification, were carried out with the use of a specialist program Calcosoft 2D [3]. The program includes an integrated procedure for solving inverse problems and is considered to be one of the best software products of the type [4].

Table 2. Values of local solidification time of the casting and the average temperature gradients in y and x direction during crystallization of the α -phase (from the experience and the simulation). Stage II

Mold	Co-ordinates of the point of a casting ($y;x$) in mm											
	5; 0	15; 0	25; 0	35; 0	45; 0	5; 0	15; 0	25; 0	35; 0	25; 5	25; 9	
	Solidification time, s					Temperature gradient, °C/cm						
						G_y				G_x		
1 E	67	92	104	112	123	5.9	3.4	1.8	1.4	2.5	2.7	
S2*	69	95	110	122	133	5.0	2.4	1.4	1.0	1.7	2.1	
2 E	4	11	21	31	46	36.5	17.3	11	9.3	4.1	5.4	
S4*	3.7	9.4	16.8	24.7	34.9	37.2	11.7	5.8	3.2	2.3	3.2	

In order to perform the inverse problem calculations with the use of the Calcosoft program were used the same thermophysical values as the ones used before for the calculation of the direct problem. At the same time, one of the values was indicated as a sought parameter (beta value). The file **.mesu_plot* included experimental values corresponding to time sequences of temperature recorded in examined points of the casting. The value of the coefficient λ_M calculated with Calcosoft amounted to $\lambda_M = 0.66$ W/mK. The value λ_M reproduced this way was reintroduced to the simulation calculation of solidification process carried out with the help of PAMCAST Simulor. Average values for examined castings, from the simulation and experimental [5] ones, corresponding to the best simultaneous conformity of solidification time and temperature gradient, are shown in Table 2 and Fig. 1 (lines 2* and 4* differ from the values 1 and 3 by the values $\lambda_M = 0.66$ W/mK and $\alpha_{O-M} = 10^4$ W/m²K). As can be seen, the values obtained from the simulation differ from the experimental ones, similarly as previously.

However, the differences of the gradients are less than the ones obtained from the calculations of the stage I.

3. SIMULATION STUDIES – FINAL CALCULATIONS

The simulation data identified at the Stage II enabled carrying out simulation calculations in selected points at the surface of axial cross-section of the cylinder ($x = 5; 9; 12, y = 5; 15; 25; 35$ mm). The values of average resultant temperature gradient $G = (G_x^2 + G_y^2)^{0.5}$ and its position angle with regard to the casting axis $\beta_G = \arctan G_x / G_y$ were determined.

The results obtained are shown in Fig. 2. The values of average resultant temperature gradients G_S and their position angles β_{GS} (Fig. 2) differ from the ones found experimentally (E).

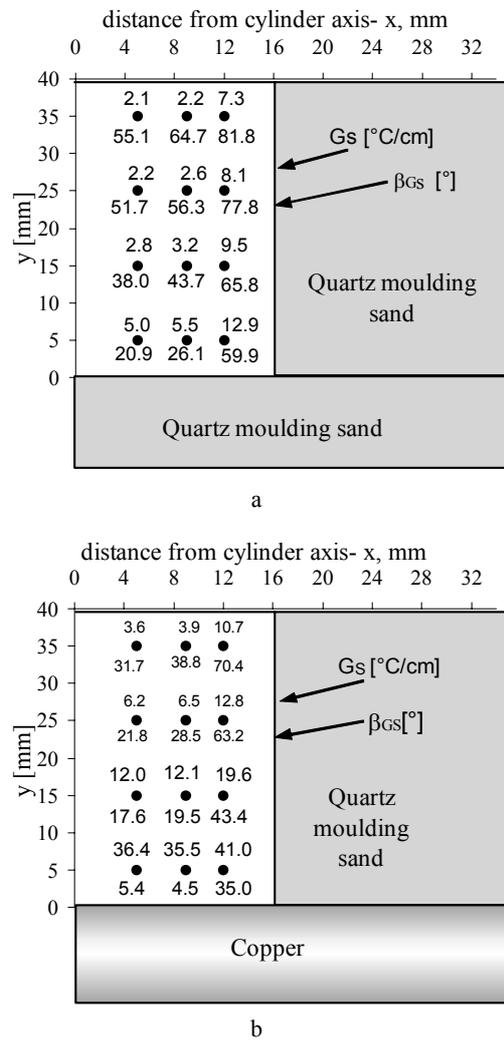


Fig. 2. Temperature gradient calculated from simulation (G_S) and its direction angle (β_{GS}) at the cross-section of the casting made of AlSi8,7, solidifying: a – in the mold No 1, b – in the mold No 2

Improvement of conformity with the experiments may be achieved with the help of correction factors (e.g. for the distances $y = 25$ and 35): for temperature gradient $k_G = G_E / G_S$ and its position angle $k_\beta = \beta_{GE} / \beta_{GS}$. Corrected values (indexed with k) of the average temperature gradient and its position angle are then given by the formulas:

- for the casting from the mold No 1
 $G_{Sk} = 1.32 G_S, \quad \beta_{GSk} = 0.92 \beta_{GS},$
- for the casting from the mold No 2
 $G_{Sk} = 2.43 G_S, \quad \beta_{GSk} = 0.84 \beta_{GS}.$

Better approximation of the average value of temperature gradient (at the casting cross-section) achieved by simulation with correction to the experimental data was achieved for slower solidifying casting (the mold No 1) and such a conformity, near the level of 5 %, is acceptable. On the other hand, rather poor approximation for the casting characterized by important heat exchange rate (the mold No 2 with a chill) requires further analysis.

4. CONCLUSIONS

Taking into account the studies of simulation of casting solidifying process, aiming at achieving good simultaneous conformity of solidification time and temperature gradient during increasing of the phase α , obtained from simulation and from experiments, the following conclusions may be formulated:

1. Better conformity of the parameters obtained by simulation carried out with the help of PAMCAST Simulor software and the ones found by experiments may be achieved for the castings of low solidification rate, i.e. for $G < 5.5 \text{ }^\circ\text{C}/\text{cm}$ (in the molds of quartz sand). For the castings of higher solidification rate (e.g. in chilled molds) the conformity is worse (approaching 5 %, which is not sufficient).
2. Strict conformity of G_y and G_x between the simulation and experiments is not necessary. Only constant value of the differences $G_{yE} - G_{yS}$ and $G_{xE} - G_{xS}$ at the casting cross-section is required.

3. Poor conformity between resultant temperature simulation and experiment imposes the use of gradient G and its position angle β_G obtained from the correction factors $k_G = G_E / G_S, \quad k_{\beta G} = \beta_{GE} / \beta_{GS},$ respectively.
4. Further studies are foreseen, aiming at explaining the lack of expected conformity between the actual and virtual trials. Such a situation, in the opinions of the authors, is caused by the methods of solving the inverse problems (up to now the values of thermophysical parameters of the materials and heat resistance between the casting and the chill were considered as constant).

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