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Effect of Contact Gap in Directional Solidification of AlSiFe Alloys

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Abstract

One of the methods to study solidification of alloys and metals is directional solidification. In the paper the effect of the contact gap between the analyzed specimen and the bottom heater was analysed. The occurring contact gap caused the increase in planned solidification velocity. For the facility calibration the methodology with *M* coefficient was applied. The experiments revealed efficient values of *M* and allowed to conduct efficiently the directional solidification of AlSiFe alloys in wide range of growth rates. The effect of the contact gap seems to be random phenomena and most difficult factor influencing precisely planned directional solidification.

Keywords: Directional solidification, Aluminium alloys, Calibration, Fe-rich intermetallic phases, β-Al_5FeSi

1. Introduction

Directional solidification technology enables formation of materials during directional transition from liquid to solid state along direction specified trough thermal gradient [1]. As first directional solidification was applied to prepare turbine blades, and can be used to improve functional and structural characteristics of materials, such as single crystal super alloys, high temperature intermetallic compounds, in-situ eutectic composites. Directional solidification technique is also an important research instrument to study solidification theory of metals and alloys, because it helps to achieve controllable cooling rate in a broad range, solidification structure from near-equilibrium to far-from equilibrium, interface evolution, solute redistribution, phase selection, crystal growth instability [2]. From directional solidification well known are instruments of Czochralski [3], Bridgman-Stockbarger [4] and Chalmers.

One of the methods for conduction of directional solidification is the aerogel based power down method that uses two controlled heaters [5,6,7]. The method applies control of each heater independently introducing in the specimen the projected temperature gradient, cooling rate and velocity of the solid/liquid interface. Application of the aerogel crucible allows to control the position of solidification front in time (because of its transparency) and extremely low thermal conductivity maintain plane solidification front in processed specimens.

Aluminium alloys are characterized by good application characteristics and are replacing traditional materials in many areas e.g., aerospace and machinery. One of the impurities in AlSi alloys is iron causing formation of Fe-rich intermetallics, with especially detrimental β-Al_5FeSi phases.

In the current paper we have concentrated on the calibration method of Artemis [5,7] to control temperature and gain planned solidification conditions in the specimens. The effect of contact gap and it influence on solidification velocity was discussed.

2. Methodology

This study comprises calibration of Artemis [5,6,7] special facility, that is Bridgman-like furnace for directional solidification. In the centre of Artemis two heating elements are located with a cylindrical specimen (8 mm diameter and 120 length) between (Fig. 1). The specimen is surrounded by a piece of silica aerogel as crucible and thermal insulator [5,6]. Bottom heater was equipped with a cylindrical cooling element attached to cooling system (copper plate cooled with water). The heat flows between heaters trough specimen and leaves them trough cooling system. Thanks to construction and vacuum only small part of the heat radiate to facility chamber [6,7]. The aerogel crucible with excellent insulating properties secure almost flat isotherm in the specimens and directional solidification. The heaters are controlled with PID unit allowing solidification with supposed constant velocity, temperature gradient and cooling rate [7,8]. Because the silica aerogel is transparent, it is possible to record the brightness intensity with special CCD camera. Analysing brightness course allows to determine the solidification front in time and solidification velocity.

The experiments with AlSi alloys were conducted by temperature gradient G=3 K/mm and growth rate v=0.02-0.12 mm/s with and without fluid flow induced inside the specimen by a rotating magnetic field (RMF) with 6 mT.

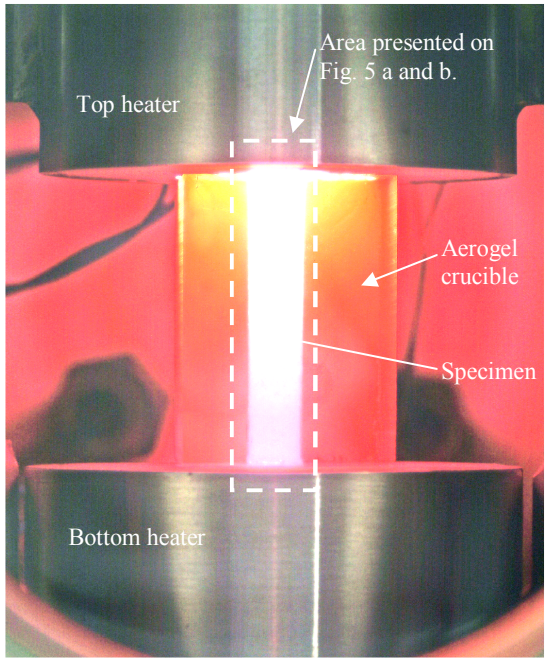

Fig. 1. Photo of the Artemis-3 facility [7].
The specimen with 8 mm diameter installed in the aerogel crucible (transparent) between bottom and top furnace.

3. Results and Discussion

Artemis allows for solidification according to planed thermal conditions thanks to fully controlled top and bottom furnaces and aerogel crucible. For solidification with expected thermal gradient, velocity and cooling rate, in the heaters we need to assume temperature profile in time. Ratke [5] described the thermal processes in Artemis with help of Stefan condition

$$\Delta H_V \frac{dy}{dt} = \lambda_S \left.\frac{\partial T^S}{\partial x}\right|_y - \lambda_L \left.\frac{\partial T^L}{\partial x}\right|_y \tag{1}$$

where λ_L λ_S are the thermal conductivity in the liquid and solid, ΔH_V is the enthalpy of fusion per volume and $T^{L,S}$ are the temperatures in the liquid and solid, $dy/dt=v$ is solidification velocity. For the determination of the proper temperature profile it is necessary to know thermal properties of processed alloy ρ, ΔH, λ_L, λ_S and the effective gradient length L. Steinbach [7] has proposed the determination of L trough iterative experiments, whilst Ratke [8] has proposed the special formulas for bottom heater cooling rate dT_{bot}/dt. Solidification experiments for the AlSi alloys with Fe-rich intermetallics solidifying with the same [9,10] or various solidification velocities v required precise determination of v_{ini}. In [11] was introduced the coefficient M:

$$T_{bot}(t) = T_m - \left(\frac{\rho \Delta H v}{\lambda_S} + G_L \cdot \frac{\lambda_L}{\lambda_S}\right) v \cdot t \cdot M \tag{2}$$

Using M coefficient it was possible to establish the temperature in the top and bottom heater (Fig. 2) and minimize number of experiments. The coefficient M initially assumed as M=1 was changed to M=0.9 and M=1.1. The measurement of solidification velocity was performed as the measurement of intensity [5] in functions of time of the specimen surface trough aerogel crucible. The measured intensity curves with a peak pointing on solidification front are well visible on Fig. 3.

From the results gained in experiments with growth rate 0.02-0.12 mm/s we observed the increase of the velocity in comparison to the planned values (Fig. 4). The solidification of specimen is determined by temperatures in bottom and top heater which influences the temperatures in the specimen. During solidification the top part of the specimen is liquid and has good contact with the top heater, whilst bottom part of the specimen is solid and this can mean the worse contact between specimen and the heater and that the temperatures in bottom part of the specimen might differ from temperatures in bottom heater. In the bottom heater the specimen touches the heating element and the cooling element. The occurrence of the contact gap between bottom part of the specimen and bottom heating element and especially cooling element can cause disturbance in the heat flow from the specimen. The occurrence of the contact gap seems to be the most difficult element to control in directional solidification. Cooling rate according to the formula equals R=G · V, where G is the temperature gradient in the specimen and V growth rate. The occurrence of the contact gap can cause slower cooling in the bottom part of the specimen (the bottom profile on the Fig. 2 has higher temperatures), and this can cause the lower temperature gradient When assuming e.g. about 10% smaller gradient, this may cause only about 5% decrease of cooling rate because R depends on both the bottom heater and also upper heater in which the temperatures has not changed. In this way the occurrence of

the contact gap causes the increase of the growth rate that we have observed in experiments.

The proposed *M* coefficient resulting from experiments (Fig. 4) amounts 0.9-1.0 as effect of the contact gap between the bottom part of the specimen and bottom heater (its heating element and cooling element).

The solidification in the Artemis facility was calculated with ProCast [12]. The results of the structures presented Fig. 5. The microstructure in experimental specimens revealed among other things: Secondary Dendrite Arm Spacing SDAS 110 μm [11] and Eutectic lamellae 5.20 μm [11]. The simulation results showed SDAS 98-114 μm, Eutectic lamellae 2.03-2.50 μm and are in good conformity with experimental data and confirmed the proper calibration of experimental directional solidification.

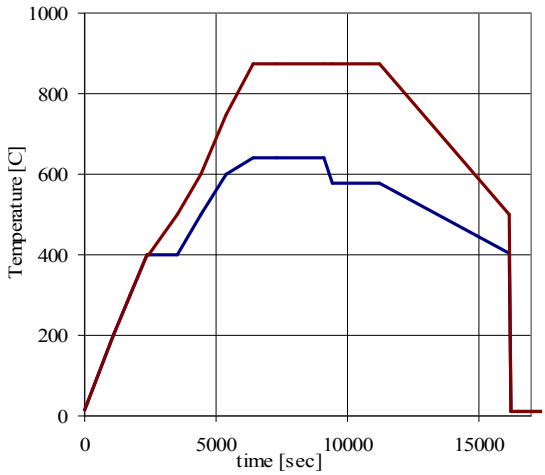

Fig. 2. Temperature profiles in the top and the bottom heaters for growth rate *v*=0.04 mm/s.
Solidification of Al-5 wt.% Si-0.5 wt.% Fe alloy.

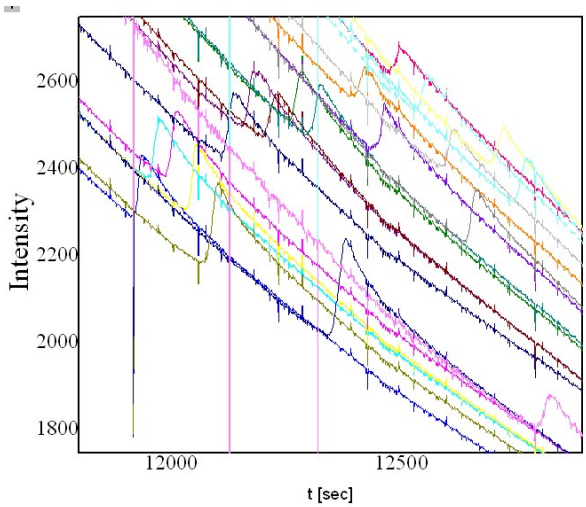

Fig. 3. Intensity in function of time recorded from the specimen sample trough the transparent aerogel crucible with help of the CCD-camera. Solidification of Al-5 wt.% Si-0.5 wt.% Fe alloy, growth rate *v*=0.04 mm/s, gradient *G*=3 K/mm

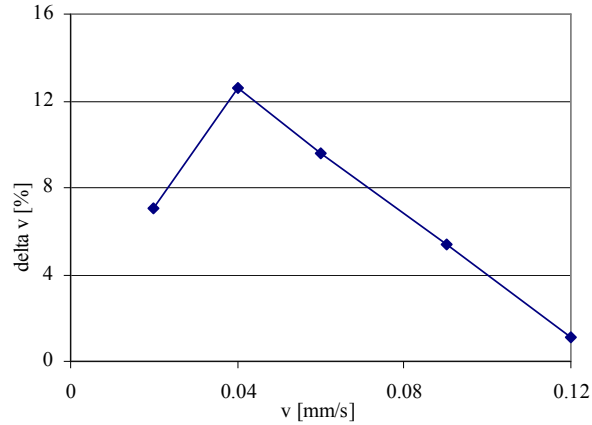

Fig. 4. Difference [in %] of growth rate between planned and real values. The values gained as average from many conducted experiments

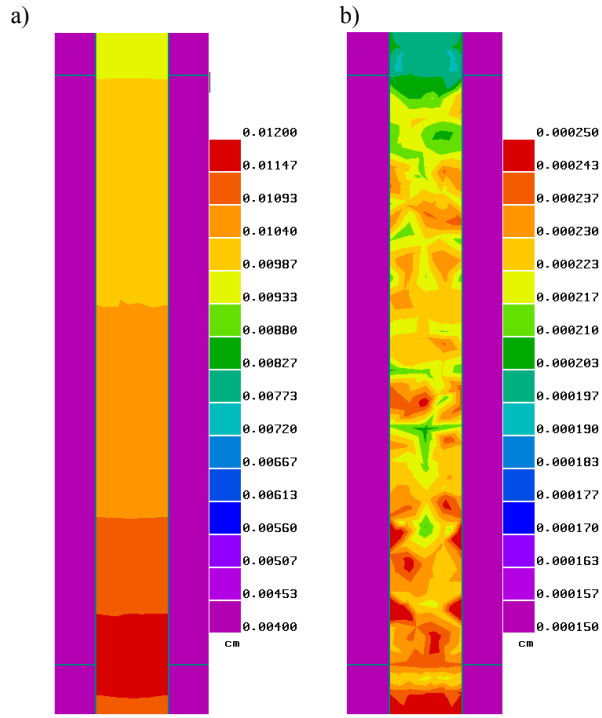

Fig. 5. Solidification simulation in Artemis with ProCast [12]: a) Secondary dendrite arm spacing and b) Eutectic lamellae for Al-7 wt.% Si-0.0 wt.% Fe alloy and growth rate *v*=0.04

The obtained *M* values were helpful by planning of the solidification experiments with growth rates in the range 0.02-0.12 mm/s. Using calibration with received *M* values it was possible to conduct solidification of AlSi alloys with presence of β-Al_5FeSi needles. The specimens cross sections (Fig. 6) presented Fe-rich phases with mainly dendritic and also with cellular microstructure. Fig. 6a showed specimen cross section by growth rate 0.02 mm/s and allowed to gain cellular microstructure in neighbourhood of fully shaped dendrites.

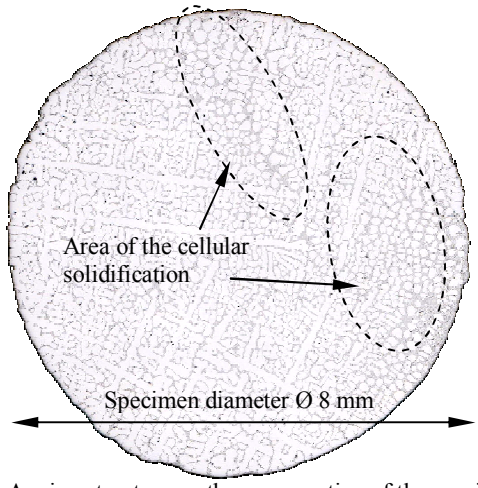

Fig. 6a. A microstructure on the cross section of the specimen of Al-5wt.%Si-1.0wt%Fe alloy solidified without fluid flow. Growth rate v=0.02 mm/s, G=3 K/mm

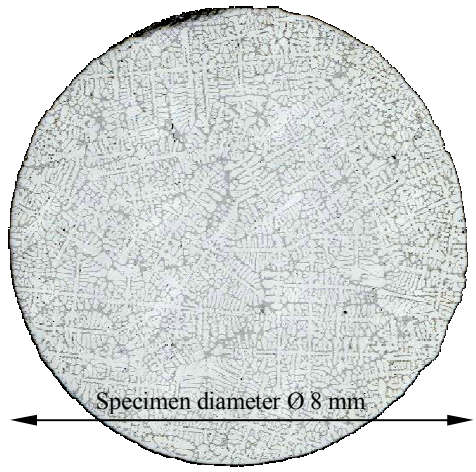

Fig. 6b. A microstructure on the cross section of the specimen of Al-5wt.%Si-1.0wt%Fe alloy solidified without fluid flow. Growth rate v=0.09 mm/s, G=3 K/mm

4. Conclusions

One of the methods in analysing the formed in castings microstructures is the planned and controlled directional solidification in special furnaces.

In the paper we have analyzed the effect of contact gap between directionally solidified specimen and the bottom heater on the calibration of the special facility Artemis. The effect of contact gap seems to be random phenomena occurring on different surfaces and times and is most difficult factor influencing precisely planned directional solidification. The estimated experimentally and confirmed by simulation values of M coefficient allowed to conduct efficiently the directional solidification of AlSiFe alloys in wide range of growth rates.

Acknowledgements

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