TRAVELLING MAGNETIC FIELD MIXING FOR PARTICLE DISPERSION IN LIQUID METAL

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Abstract: The experimental Bridgman type furnace combined with travelling magnetic field Bitter coil mixing arrangement is used to investigate the solidification structure and the additive particle distribution dynamics. Supporting numerical models combine time dependent fields, developing turbulent flow fields, moving free surface, solidification front and the Lagrangian dynamic particle tracking.

1. Introduction

In order to enhance the mechanical properties of the material the transition from columnar to equiaxed grains should be promoted and the grain size reduced. For this purpose, the use of inoculants such as TiB_2 microparticles as grain refiners is very efficient [1-3]. The introduction and distribution of the particles inside the material represents always a challenge especially when the particle size is decreased. Different methods have been developed such as mechanical stirring, pulse magnetic fields or ultrasound. The advantage of using magnetic field is the completely contactless influence on the liquid metal. In the case of a traveling magnetic field (TMF) the flow direction and its intensity can be easily controlled to produce required distribution of the inoculant particles within the matrix material. The TMF can be used to increase the number of nucleation points which will enhance the reduction of grain size in the alloy [4,5] and to homogenize the temperature of the melt. The electromagnetic mixing helps to produce equiaxed dendrites and prevent the growth of cellular dendrites [6,7]. Melting light metal alloys (Al, Mg, etc) in the presence of electromagnetic (EM) field can help to diffuse inclusions of various sizes in the liquid volume or oppositely concentrate these on the surface of the solidified melt. Barnard et al. [8] demonstrated experimentally that melting in a high frequency AC field indeed brings particles to selected locations on the surface of consequently solidified metallic sample. Bubbles and inclusions are observed to move selectively in the presence of EM field during the steel casting [9]. Materials of special properties, like an increased concentration of additive particles near the surface, are produced in the presence of the imposed electromagnetic field [10]. Numerically the particle paths can be predicted [11,12] accounting for the added electromagnetic force effects. The electromagnetic force acts directly only on electrically conducting inclusions, however the electromagnetic force in the surrounding fluid creates a gradient of pressure giving additional integral force even on the non-conducting inclusions of various sizes and composition. The gravity induced buoyancy acts vertically, but the EM 'buoyancy' acts in the direction opposite to the EM force. In addition to this, the large scale electromagnetically driven flow circulation exerts a drag force, torque and shear, which contribute to the particulate transport. The paper presents results obtained using a TMF of low intensity during the melting of aluminum alloy 357 with TiB_2 microparticles added with the purpose of grain refining.

2. Experimental procedures

Experiments were carried out using a Bridgman furnace equipped with a bitter coil. The furnace VB2 (Vertical Bridgman 2 inches) manufactured by Cybestar is characterized by a

zone of a controlled temperature gradient. The hot and cold end zones are equipped with graphite resistors for heating. This bitter coil provides a traveling magnetic field of 10 mT and frequency of 50 Hz. The phase shift is set as 60 degrees between the coil sections.
The material used as matrix material was Aluminum 357. This alloy is commonly used in casting of aerospace structures. TiB_2 microparticles were selected to be mixed with aluminum 357. The diameter of the particles was 8.6μm and its density 4.52 g/cm^3 .The percentage in weight added to the aluminum alloy was 0.85 %. The final weight of the specimen is 730 g. The material is introduced in the furnace inside a crucible made of quartz which is supported by a graphite container. Microparticles and aluminium are introduced at the same time in the furnace. A block of the filling material was made using a stack of the plates filled with the TiB_2 microparticles (Figure 1). The amount of material of the specified weight permits to obtain a final specimen 15 cm high and 5 cm in diameter.

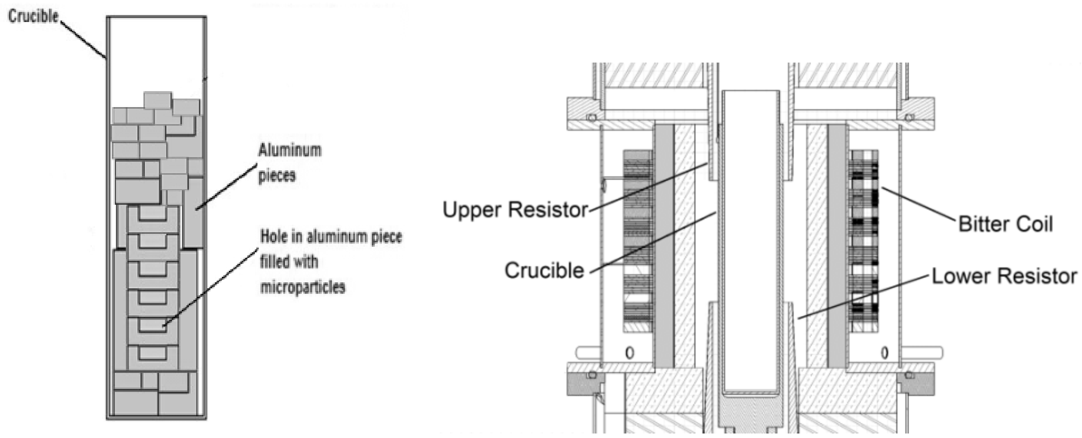

Figure 1: Crucible filling and the furnace cross-section of the experimental device with the Bitter coil at SIMAP, Grenoble.

The aluminum has a very high reactivity with the oxygen and forms aluminum oxide in milliseconds. In order to avoid an oxide layer over the surface of the crucible, the furnace is subjected to vacuum conditions, of 10^{-3} mbar at the beginning of the experiment. Afterwards, an open cycle of argon flow of 2.3 l / min is maintained during the totality of the experiment. The pressure inside the furnace is maintained in this way at 1200 mbar.
The aluminum alloy was heated to a temperature of 800°C imposed in upper and lower resistors. This temperature was maintained during 1.5 hours. Electromagnetic stirring started when this temperature was attained. Upwards and downwards TMF was alternated every 10 minutes and set to upwards direction during the cooling period until the solidification of the material. The temperature of the lower resistor was brought to 700 °C creating a gradient of 660 K/m which was kept until the end of the cooling. The rapid cooling would enhance the reduction of the grain size, therefore, the cooling rate selected was 0.25 K/s.

3. The mathematical model and results
The mathematical basis of the present model is the time-dependent Navier-Stokes and continuity equations for an incompressible fluid, and the thermal energy conservation equations with the Joule heating term for the fluid and solid zones of the metal charge [14]. The turbulent viscosity and the effective thermal diffusivity is the subject of the turbulence model accounting for the EM effects. The numerical solution of the coupled problem is obtained using the pseudo-spectral collocation method, employing the continuous co-ordinate transformation for the shape tracking. The time-dependent fluid flow problem is set with appropriate boundary conditions: at the free surface of the liquid the normal hydrodynamic stress is compensated by the surface tension, whilst at the solid walls the no-slip condition is

applied to the velocity wherever there is a contact at any given time. The free surface contact position moves as determined by the force balance and the kinematic conditions. During the melting or solidification, the solid-liquid interface is traced automatically as the solidus temperature surface $T = T_S$ moves with the coupled effects of the solid fraction-modified specific heat function. The temperature field corresponds to the thermally insulating side wall and the linearly decreasing in time hot top/cold bottom condition. The EM mixing and the additive particle distribution is investigated using the numerical models combining the time dependent EM fields, developing flow fields, the moving free surface and solidification front. The EM mixing is achieved by the Bitter type coil arranged in separate sections with a prescribed phase shift. The device schematic is shown in the Figure 1 and the numerical model with a computed velocity field - in the Figure 3.

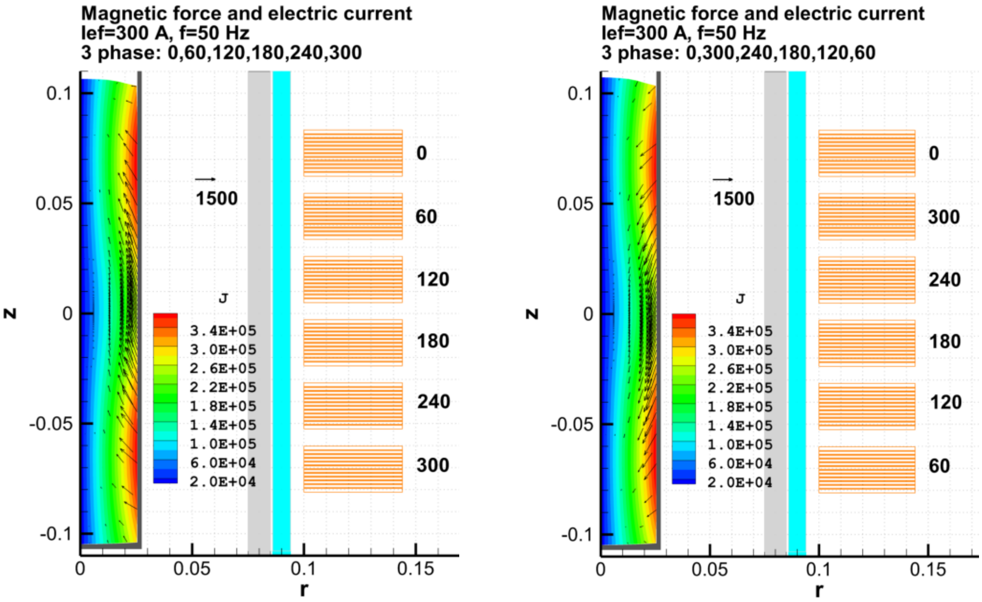

Figure 2: Upwards (left) and downwards (right) travelling magnetic field electric current and force distribution in the aluminium sample.

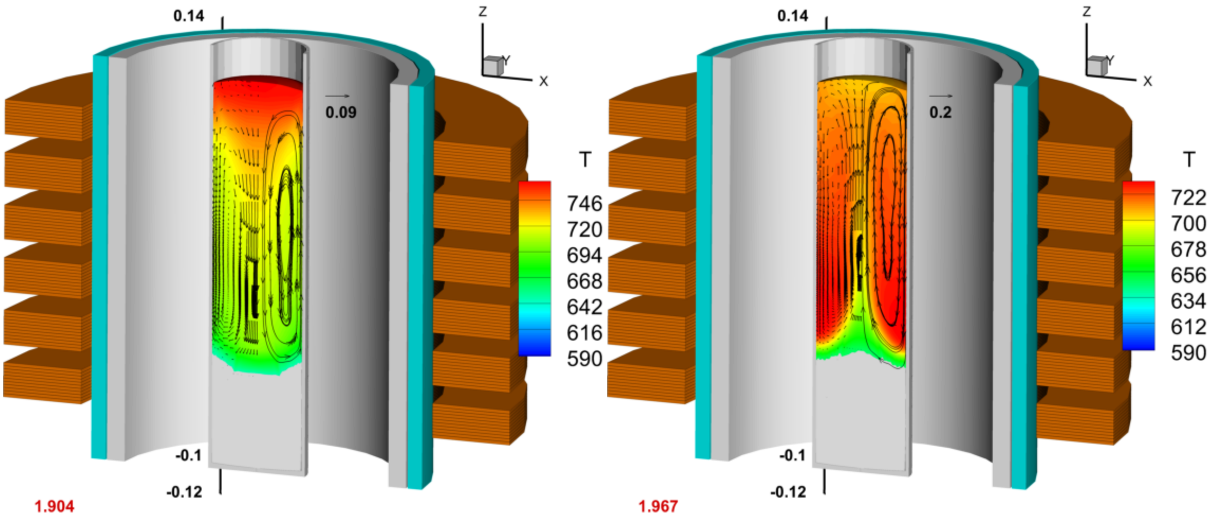

Figure 3: The velocity field in aluminium samples due to the upward (left) and downward (right) travelling magnetic field.

The AC phase shift permits to create the travelling magnetic field either upward or downward (Figure 2 shows the time average EM force distribution), which permits a variety of the mixing patterns affecting the solidification front and various scenarios of the particle motion.

The particles of micro to nano-size are added at desired locations in order to follow their paths and concentration, following their distribution in the gradually solidified metal ingot. Larger particles (> 10 µm) are the most sensitive to the buoyancy and the EM force effects, while smaller size particles follow closely the fluid flow pattern, only deviating in the regions of the higher EM force density and being entrapped when reaching the solidification front. The choice of flow pattern ensures the desired distribution of the particles. The upward EM field favors the fast entrapment of the particles at the bottom solidification front (Figure 4, left). On the contrary, the downward traveling field creates the flow, shown in the right of the Figure 3, leads to enhanced particle concentration at the top part of the melt (Figure 4, right), thus delaying or even preventing the additive supply to the solidification front.

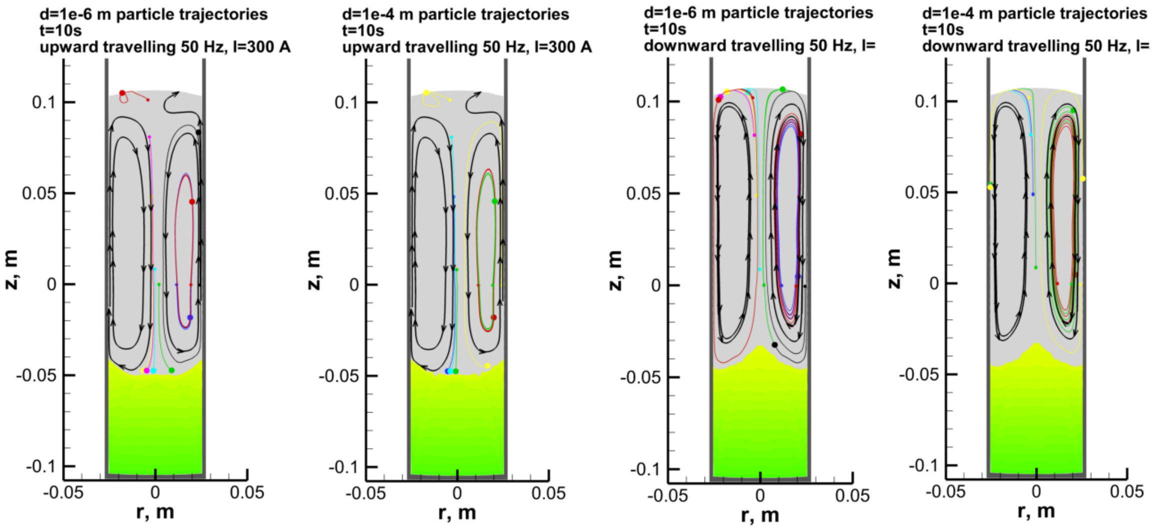

Figure 4: Various size particle trajectories in **aluminium** melt for the upward (left) and the downward (right) travelling magnetic field.

The results presented are preliminary and a full experimental verification is expected. The numerical model show areas in which the magnetic field is more intense and the optimum flow direction for the particle dispersion to the solidified metal matrix. The highest intensity of the magnetic field is located at the middle of the bitter coil area. In consequence, the particles would be more effectively dispersed if they are positioned there at the beginning of the experiment.

4. Experimental results and discussion

The microscopic study of the solidified specimens revealed an apparently good dispersion of the particles. Agglomeration and settling can easily occur due to the difference in density between aluminum and TiB2. The images obtained from the analysis of material from the lower part of the crucible showed no signs of agglomeration. The extraction of the particles could have been the result of the polishing performed on the samples. The upper part of the specimen showed different results. The number of particles found during the optical inspection was higher than on the lower part. Signs of possible TiB_2 agglomerates were found. The characterization of the specimens is still in process and the number of particles will be determined accurately in future work. The following images were taken from samples of the lower part of the specimen. The images show equiaxial grains at distances of less than 1 cm from the wall of the crucible. There are clear signs of refining the aluminum 357 stirred with the TiB additive (Figure 5, left) and the aluminum 357 solidified without refining (right).

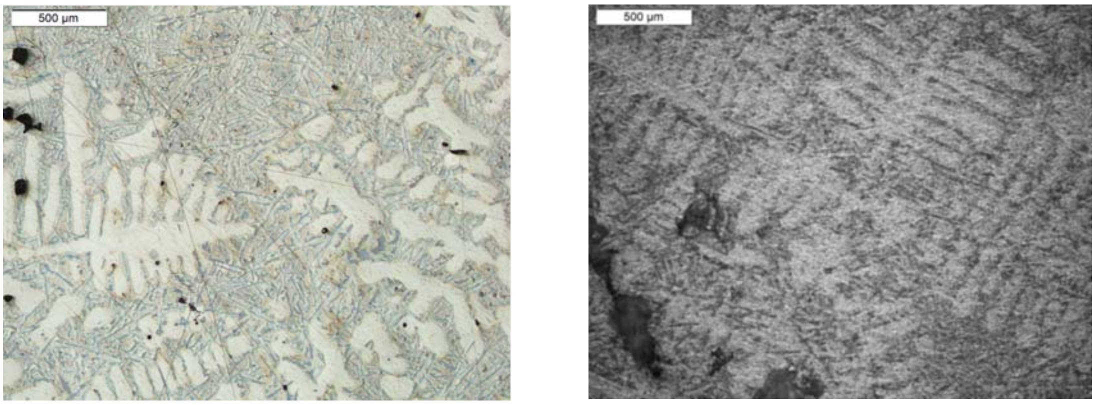

Figure 5: Micrographs of the solidified samples: (left) aluminum 357 stirred with the TiB additive. (Right) Equiaxial dendrites and signs of porosity without refining.

5. Conclusions

Intense mixing can be achieved using both upwards and downward travelling magnetic field. The melt front shape is strongly affected by the flow direction and the type of side wall thermal conditions. The particle paths and the concentration can be optimised to the desired outcome manipulating the EM field. The combined use of grain refiner and low intensity traveling magnetic field has shown positive results in the refining of the material.

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