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HIGH FREQUENCY ELECTROMAGNETIC SEPARATION OF INCLUSIONS FROM ALUMINUM

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Abstract

Removal of inclusions from aluminum is a critical step during the production of high quality aluminum alloys. Electromagnetic purification method for the removal of inclusions has been proposed to complement the existing methods, and many researchers have devoted a lot of effort to studying the electromagnetic inclusion removal process. It has been widely published that high frequency electromagnetic field is limited in the depth of penetration into the molten metal thereby rendering the separation method ineffective. The contribution of the high circulatory fluid flow associated with such high frequencies has also been reported to be negative. The effect of wall temperature to the electromagnetic inclusion removal process has also not been clearly established. This study presents new results that show that, fluid flow contributes greatly in the presence of lower wall temperature to remove particles during high frequency (63 kHz) EM purification of aluminum, contributing to overcoming skin depth effect in small and large crucibles.

Introduction

The detrimental effect of nonmetallic inclusions on the chemical, mechanical and processing properties, and demand for high quality aluminum and its alloys has motivated many researchers to devote considerable amount of effort to finding cost effective and clean methods to rid the metal of inclusions. Several methods including flotation, sedimentation, centrifugal separation, filtration, and electromagnetic separation have been proposed.[1-5] Among these methods filtration requires the least capital investment,[1] but has the limitation of low removal efficiency for inclusions smaller than 10 μm and the disadvantage of filter clogging at high inclusion concentrations. Since the work of Leenov and Kolin [6-7] who first proposed the principle underlining electromagnetic separation, many researchers have devoted considerable effort to studying this method relative to the removal of inclusions from metals. Electromagnetic separation is one method with the potential to remove much smaller particles [8-10] and also has no inclusion concentration dependence.[11-12] AC electromagnetic separation is the easiest for industrial implementation and continuous separation among the available options for this separation technology. However, the skin depth effect of high frequency electromagnetic systems imposes a limitation on this potential inclusion removal technology as has been reported.[2] Associated with the AC electromagnetic system is the high fluid flow velocity in the melt which results in electromagnetic stirring of the molten metal. The effect of electromagnetic stirring during the application of AC magnetic fields for inclusions removal has been reported to be negative due to the strong fluid velocity induced close to the wall where particles are trapped, resulting in the re-entrainment into the melt of the particles at the wall.[11] However, there are some positive effects of the induced fluid flow by the electromagnetic field, since it can carry inclusions from the melt to the vicinity of the wall of the crucible where the electromagnetic Archimedes force is effective to trap the inclusions. This positive effect is yet to be emphasized. Additionally, the effect of wall temperature to the electromagnetic process has also not been clearly stated though a previous study [11] considered cooling of the crucible wall during EM separation.

This study investigates the high frequency electromagnetic inclusions separation process from molten aluminum in relatively small and large crucible with cooling.

Experimental Procedure

Figure 1 shows the schematic of the experimental set-up used during the electromagnetic separation of inclusions from aluminum. The set-up includes the induction coil powered by a 100 kW capacity power supply with a frequency range of 50 - 200 kHz, the crucible containing the aluminum-SiC particulate composite (~15 wt% of particles), and cooling coil made from Teflon or copper tubing. The Teflon cooling coils were used to inject water directly to the crucible during separation while in the case of the copper cooling coil, the crucible was in direct contact with the coil, which was water cooled.

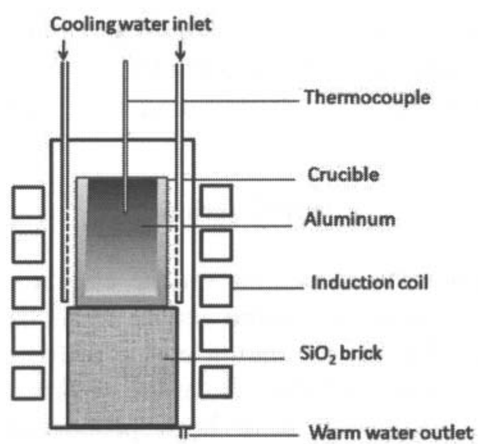

Figure 1. Experimental set-up for EM separation of inclusions from aluminum with water cooling

The purpose for cooling was to study the effect the wall temperature has on the EM separation process, as it determines the viscosity distribution within the molten metal close to the wall. Table I gives details about the experimental schemes and the parameters used in this study. Four experiments were made under the same frequency and coil current at 63 kHz and 280 A respectively. The experiments were designed to investigate the effect of temperature, the size of crucible and fluid flow on the high frequency EM separation process.

Table I Experimental materials and condition

Exp. #	Crucible material (diameter)	Cooling Conditions	Temperature outside crucible (^oC)	Parameters
Al-EM–1	Al_2O_3 (15 mm)	Non cooled	680	f = 63 kHz i_{rms} = 280 A t = 15 s
Al-EM–2	Al_2O_3 (15 mm)	Water cooled	300	
Al-EM–3	SiO_2 (40 mm)	Half water cooled	300 – 680	
Al-EM–4	SiO_2 (40 mm)	Cu coil cooled	630	

During the experiments the designed amount of composite material was put in the crucible as in the set-up and the power supply turned on. After melting was complete the temperature was allowed to rise to about 850 ^oC. The separation parameters are set at this stage, with simultaneous cooling (for the case where cooling is need) and the experiment monitored for 10 – 15 s. The outside crucible wall temperature was estimated based on measurements with a thermocouple immediately when the power supply and cooling water were turned off. In the case involving direct water cooling of the crucible (i.e. experiments Al-EM–2 and Al-EM–3), there was complete solidification of the metal after this time. Samples were cut and polished to study the particle distribution under the microscope.

Results and Discussions

Particle separation from Experiments

The Al-15 wt% SiC particulate composite used in this study contained well dispersed particles with size range of 1 – 15 μm within the matrix of aluminum as showed in the optical micrographs showed in Fig. 2. The average area fraction of particles determined with the help of image analysis software, ImageJ is ~29.2 %.

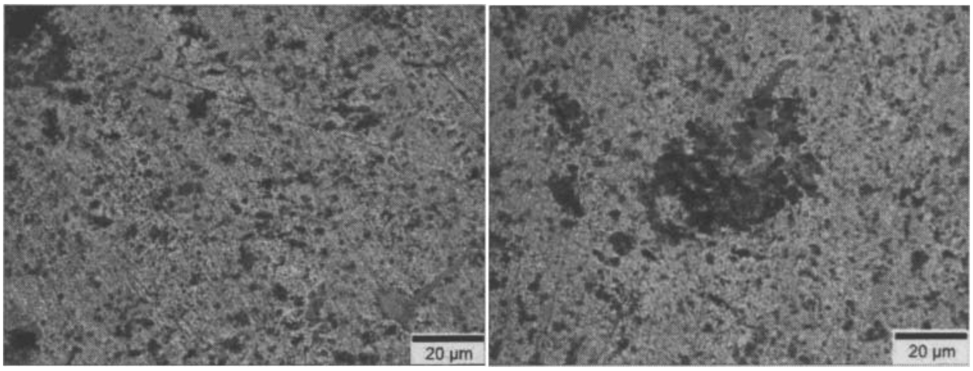

Figure 2. Micrograph of the Al-15 wt% SiC composite material as procured for the EM separation experiments.

The results from experiment Al-EM–1 in which no cooling was employed is shown in **Fig. 3.** No clear separation of particles can be observed at the wall off. However, accumulations of larger particles were observed close to the wall of the crucible and other parts of the sample. This indicates some force acted on the particles but was not enough to keep them at the wall of the crucible to give the desired separation.

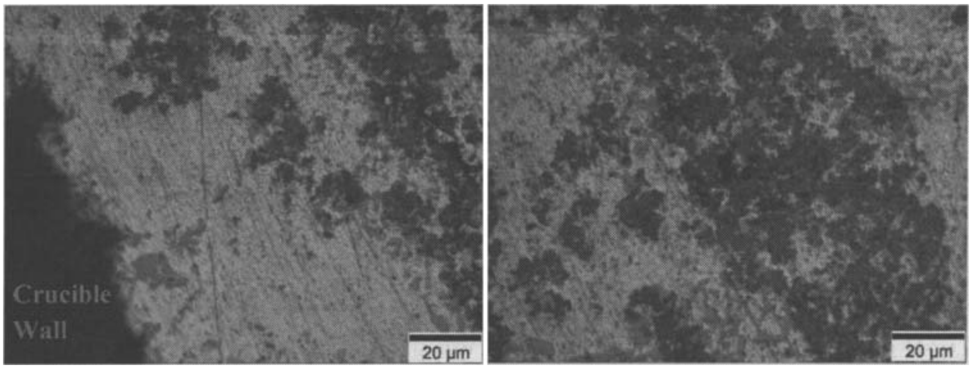

Figure 3. Accumulation of larger particles in the vicinity of the crucible wall where fluid viscosity is not high enough to trap them to the wall due to wall high temperature observed from experiment Al-EM–1 – no clear separation of particles.

Figure 4 shows the separation results obtained from experiment Al-EM–2 in which the wall of the 15 mm MgO crucible was kept approximate at 300 °C during the separation period. A particle accumulated layer of thickness averaging about 2 mm was observed all around the sample with an estimated area fraction of 53 % within the layer. Beyond the particle layer into the sample the matrix of the metal was much cleaner with a small particles observed at certain parts. Figure 5 gives a more complete view of the sample, showing the cross-section and the separated layer of both the picture of the polished cross-section and an almost complete assembly of optical images of the layer (about 220 pictures of the layer put together). Optical micrographs within the central part of the image in Fig.5 are a collection of a few pictures of the center and not the actual pictures of the center though it gives a good representation of the view of the parts of the sample away from the particle layer. A separation efficiency of 84.1 % was calculated for this experiment.

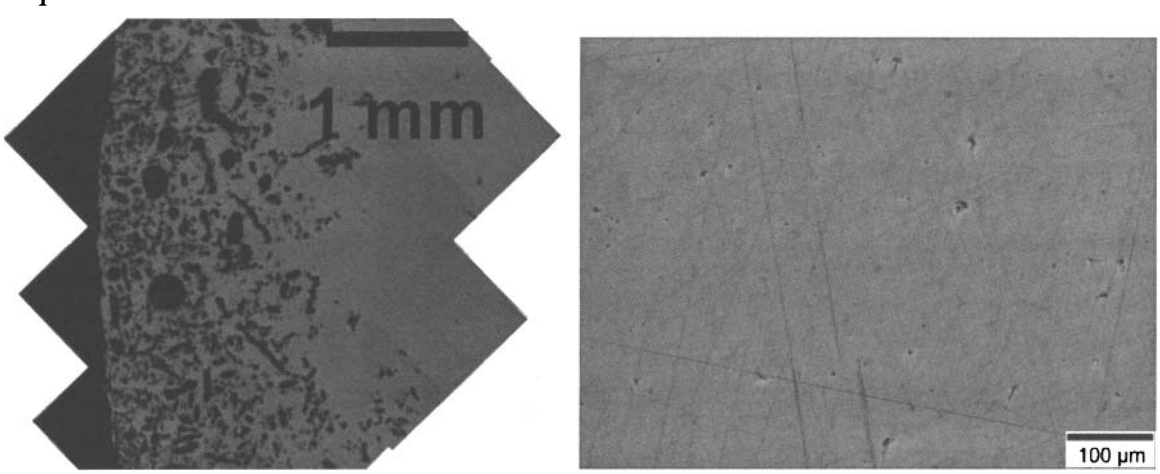

Figure 4. Thick accumulation of particles at the wall of the crucible (left) and a cleaner aluminum matrix close to the center of the crucible observed from Exp. Al-EM–2

In experiment Al-EM–3, a 40 mm SiO_2 crucible was used and cooled half way from the bottom of the crucible. The outside temperature of the crucible was held at approximately 300 °C as in experiment Al-EM–2. Figure 6 is a scanned image of the polished vertical cross-section of the sample from experiment Al-EM–3. It shows that the cooled part had particles separated from the inner matrix to the wall of the crucible which the un-cooled portion (top of sample) had well dispersed particles within the metal.

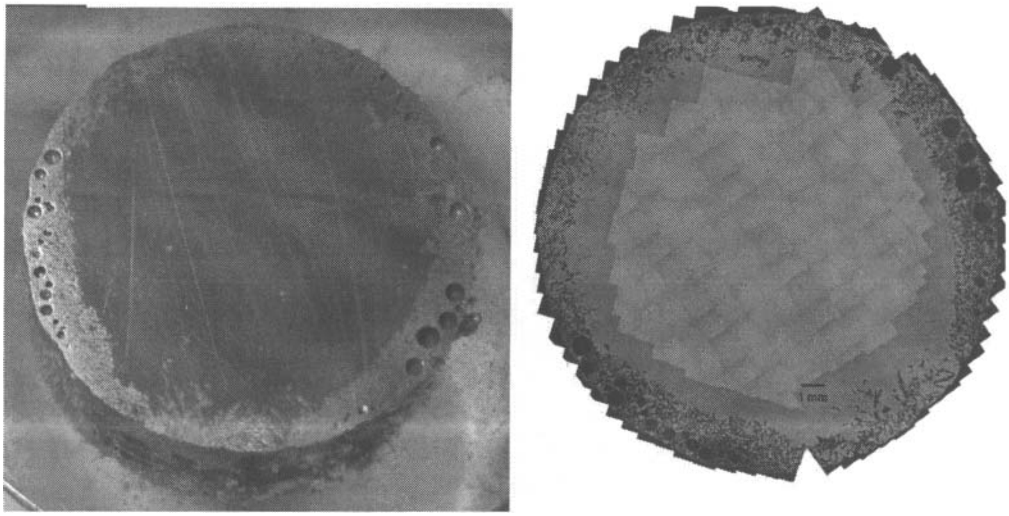

Figure 5. Complete view of the cross-section of the sample from Exp. Al-EM–2 showing thick accumulation of particles at the wall of the crucible and a cleaner aluminum matrix close to the center of the crucible observed. A separation efficiency of 84.06% was recorded.

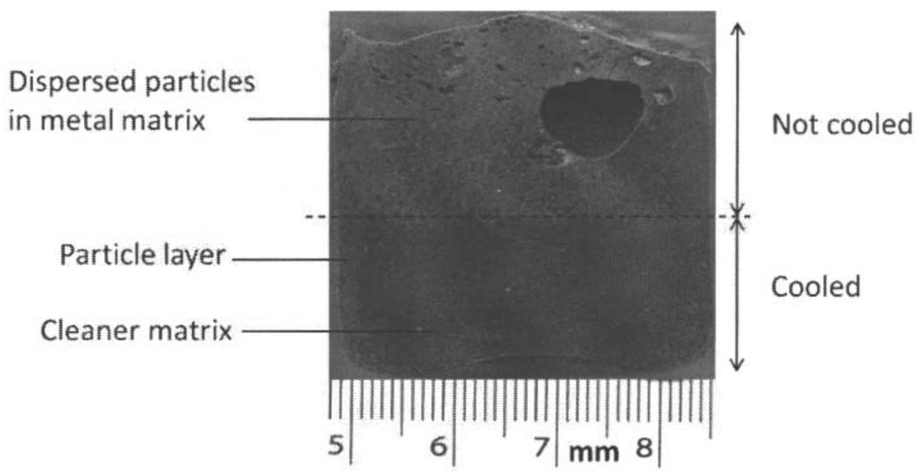

Figure 6. Scanned vertical cross-sectional image close to the center of the crucible from experiment Al-EM–3 (40mm SiO_2 crucible), which was water cooled on the bottom half showing a cleaner matrix and separated particle layer in the bottom half and a well distributed particle in the matrix of aluminum in the upper half.

This is an indication of the important effect the temperature has on the EM separation process. Comparing the separated region to the results of experiment Al-EM–2 can be seen that the separation is uniform throughout the matrix of the sample and was not limited by the skin depth which is a 0.99 mm (990 μm) from the surface at a frequency of 65 kHz. There must therefore be another mechanism different from the effect of EM Archimedes force by which particles a transported from the melt. This is the influence of the induced circulatory fluid flow of molten metal by the EM field. The induced fluid flow is demonstrated by the result from experiment Al-EM–4 showed in Fig. 7. In experiment Al-EM–4 copper coil cooling was employed, in which a water cooled copper tubing was wound round the crucible to provide some EM shielding effect in order to allow for the induced flow pattern to be observed. Figure 7 shows close to the bottom part, which is the bottom of the crucible the sweeping effect of fluid flow on particles and a print of the circulatory flow pattern. The picture at the bottom of Fig. 7 is the optical microscope view of a section of the separated wall revealed by the fluid flow effect. Thus the induced flow carries the particles from the molten metal stream closer to the wall of the crucible where the EM Archimedes force is effective and if the metal is viscous enough close to the wall particles are trapped.

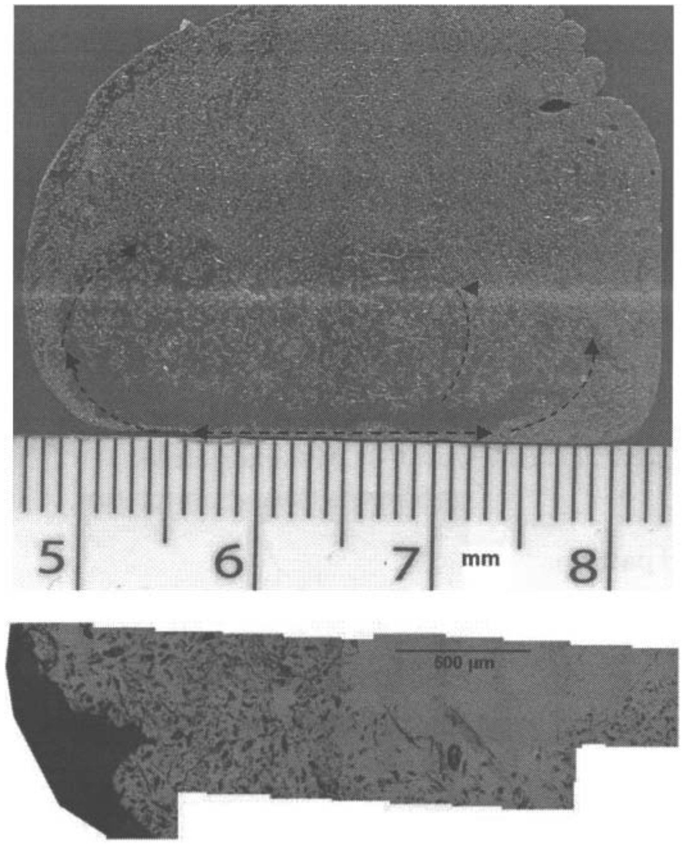

Figure 7. Particle distribution in the metal after experiment Al-EM–4 showing the path of fluid motion during the experiment. The upper photo is a scanned cross-sectional image close to the center of the sample, while the bottom photo shows the microstructure of part of the separated layer revealed by the flow pattern.

In principle, increasing the current will increase the EM field strength and thus the induced fluid flow, which has the tendency to increase the separation efficiency. However, there is limit to how much fluid flow is allowed due to possibility of washing already separated particles by turbulent fluid flow.

Temperature and Viscosity Distribution

As an example calculation, a general solidification model (see Eq. (1)) may be solved analytically considering the Al_2O_3 crucible to predict the temperature distribution within the metal for various outside crucible wall temperatures after a time of 10s separation time. For the development of the model refer to the reference [13].

$$T = T_m + \frac{1}{erf\left(\phi\sqrt{\frac{\alpha_s}{\alpha_l}}\right) - 1}\left[T_\infty erf\left(\phi\sqrt{\frac{\alpha_s}{\alpha_l}}\right) - T_m + \left(T_m - T_\infty\right) erf\left(\phi\frac{x}{2\sqrt{\alpha_l t}}\right)\right] \qquad (1)$$

$$\phi = f\left(T_o, T_\infty\right)$$

where T_0, T_m, and T_∞ are temperature of the outside crucible wall, melting point of metal and the molten metal respectively, α is the thermal diffusivity, subscripts "s" and "l" stand for solid and liquid metals respectively, and x is the distance from the crucible wall. Table II gives the material properties used in the calculations.

Table II Material properties for the crucible and aluminum

Property	Al_2O_3 Crucible	Solid Al	Liquid Al
Thermal Conductivity (kW/mK)	0.023	0.211	0.091
Density (Kg/m^3)	3950	2555	2368
Specific heat (kJ/kgK)	1.90	1.19	1.09
Latent heat of fusion (kJ/kg)	-	398	-

The Arrhenius type viscosity model was used and the parameters of activation energy 12.4 kJmol^{-1} and pre-exponential factor 0.2293 mPa.s were taken from the reference [14]. The results are showed in Fig. 8. It is seen that the thermal conditions outside the crucible have serious implications on the conditions inside the crucible, which may lead to freezing of the metal below its melting temperature of 933 K (660 °C). Beyond the frozen layer the temperature increases steadily toward the center of the crucible until the stream temperature is reached. For a 15 mm Al_2O_3 crucible maintaining the outside wall temperature at 300 °C lead to complete freezing after 15 s, which is explained by the calculation. Changes in the temperature affects the viscosity of the melt very much as seen in the viscosity distribution, therefore designing to keep the surface temperature of the crucible wall around the melting temperature of the molten metal may generate a good enough viscosity to keep the particles trapped to the wall of the crucible while preventing freezing of the molten metal during the EM purification process.

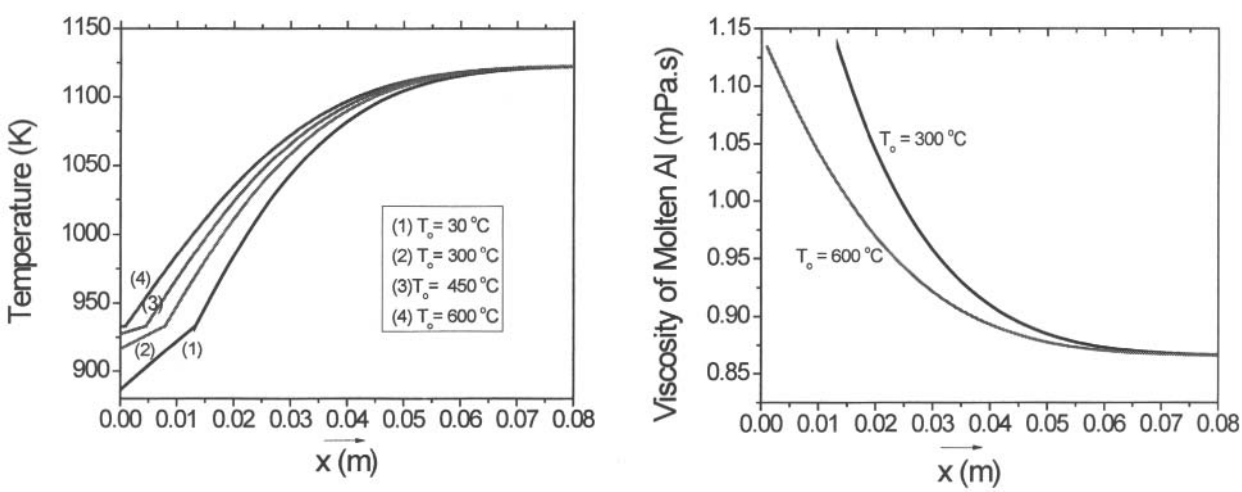

Figure 8. Temperature and viscosity distribution distribution within the metal for various outside wall temperatures, T_o of Al_2O_3 crucible after a time of 10 s. The viscosity distribution is after the results in the literature [14]

This result may be useful for future industrial design of an electromagnetic separation unit for removing nonmetallic particles from molten metals

Summary

High frequency EM separation of inclusions from aluminum was investigated on an Al – 15 wt% SiC particulate composite with particles sizes ranging 1 – 15 μm. Experiments using a smaller and bigger crucible were carried out with and without cooling. It was found that, without cooling it is impossible to retain particles at the wall of the crucible due to very high EM induced circulatory flow of molten metal which sweeps particles away. With cooling a more viscous fluid is generated close to the wall of the crucible which helps to trap the particles as they are transported by fluid flow close to the wall where the Archimedes force is effective. Freezing of the metal may occur close to the wall if the temperature of the wall is not well controlled. It is recommended that controlling the inner surface wall temperature about the melting point of the metal could help develop the requisite viscosity to trap particles at the wall. The size of the crucible did not matter in the separation process.

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