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Effect of turbulent flow on electromagnetic elimination with high frequency magnetic field

GUO Qing-tao(郭庆涛), LI Ting-ju(李廷举), WANG Tong-min(王同敏),
JIN Jun-ze(金俊泽), CAO Zhi-qiang(曹志强), ZHANG Qi(张 琦)

State Key Laboratory of Materials Modification by Laser, Ion and Electron Beams,
School of Materials Science and Engineering, Dalian University of Technology,
Dalian 116024, China

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Abstract: The results of experiments and simulations show that there is a turbulent flow in the molten aluminum and it is hard to be restrained in the thin tubule (diameter of 6 mm) when the electromagnetic body force is applied. The electromagnetic elimination experimental results show that the flow has serious effect on the elimination of 5 μm alumina inclusions, but has little effect on the 30 μm and 100 μm primary silicon. The effects of the electromagnetic field and the turbulent flow on the electromagnetic elimination are discussed.

Key words: molten aluminum; electromagnetic elimination; flow; high frequency magnetic field; non-metallic inclusions

1 Introduction

The application of the electromagnetic body force to separate non-metallic inclusions was proposed by ALEMANY et al[1,2]. And ASAI et al have measured the migration velocity of polystyrene particles in a sodium chloride aqueous solution, in which a DC electric field and DC magnetic field were simultaneously imposed. They found that the direction of migration is opposite to the electromagnetic force and the migration velocity agrees well with the values calculated from the theory of LEENOV and KOLIN[3, 4].

The theory of electromagnetic elimination with high frequency magnetic field is: the electromagnetic body force can be generated by the interaction between alternating magnetic field and induced current in the molten metal. Because of the different electric resistance between the metal and the non-metallic inclusions, non-metallic inclusions will migrate opposite to the electromagnetic body force and then can be wiped off. Non-metallic inclusions can be eliminated with the electromagnetic body force, but the elimination efficiency will be decreased if there is violent turbulent flow in the molten metal. Base on the theory of LEENOV and KOLIN and Stokes drag force[5], Eqns.(1) and (2) can be got:

$$F_{\mathrm{p}}=-\frac{3}{4}\frac{\pi d_{\mathrm{p}}^{3}}{6}F \tag{1}$$

$$F_{\mathrm{D}}=\zeta\frac{S\rho v^{2}}{2} \tag{2}$$

where F is the electromagnetic body force; F_{p} is the electromagnetic pinch force; ζ is the damping coefficient; ρ is the density of particles; F_{D} is the viscosity resistance; d_{p} is the diameter of particles; S is the area of particles; and v is the relative velocity.

From Eqn.(1) it can be seen that F_{p} decreases with the decrease of d_{p}^{3}. The Eqn.(2) shows that F_{D} is related to ζ, v and S, where $S=\pi d_{\mathrm{p}}^{2}/4$. It can be seen that the flow of the metal can affect the viscosity resistance, then the result of the electromagnetic elimination. Verifying the existence and the model of the flow in the molten metal is vital in the electromagnetic elimination research. It can also be seen that the diameter of the non-metallic particles will affect the viscosity resistance and the electromagnetic pinch force. Then verifying the elimination effects of various diameter inclusions with

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Corresponding author: GUO Qing-tao; Tel: +86-13604259195; E-mail: mystone_2002@tom.com

high frequency magnetic field is necessary.

In this investigation, the experiment on the turbulent flow in the molten aluminum with electromagnetic field has been done first. The simulation results also showed that the turbulent flow was aroused with non-uniform electromagnetic body force in the molten aluminum. In order to verify the effect of the turbulent flow on various diameter non-metallic inclusions, the electromagnetic elimination experiments have been done with 5 μm alumina inclusions, 30 μm and 100 μm primary silicon respectively. The effects of the flow and the various diameter inclusions on the electromagnetic elimination have been discussed finally.

2 Verification of existence of turbulent flow in molten metal

2.1 Experiment

2.1.1 Experimental apparatus

Fig.1 shows the schematic view of experimental apparatus. The 9-turn solenoid loop is made up of copper tubes with 10 mm in diameter. The inner diameter of the solenoid loop is 66 mm and its length is 140 mm. The solenoid loop is powered by the IGBT-type electrical source power that is capable of producing alternating electric currents with a frequency of 20 kHz. The ceramic tubule with 6 mm in inner diameter is placed in the center of the solenoid loop. The constant temperature of the molten aluminum is kept with both the function of forced air-cooling and Joule's heating. The aim of applying air-cooling is to dispel the Joule's heating in the molten aluminum.

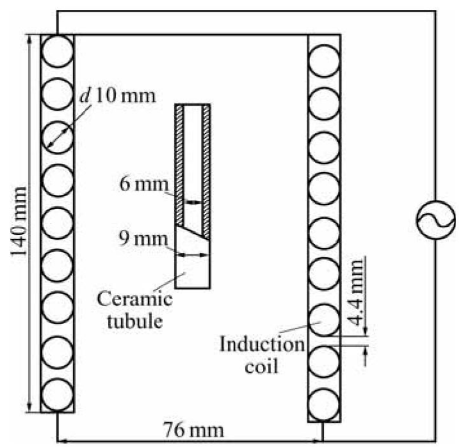

Fig.1 Schematic view of experimental apparatus for electromagnetic elimination

2.1.2 Experimental method and results

Molten aluminum is poured into ceramic tubule and kept at 720 ℃. 5 μm alumina inclusions that are enwrapped on iron core (0.7 mm) with aluminum foil are added into molten aluminum in position *A* (center of the metal), *B* (1.5 mm to the brim) and *C* (0.5 mm to the brim) respectively, as shown in Fig.2. Applying the electromagnetic field for 2, 3, 5, 10 and 60 s respectively when surface magnetic induction intensity of the molten aluminum (*B*) is 0.03 T. Then 15 samples can be got.

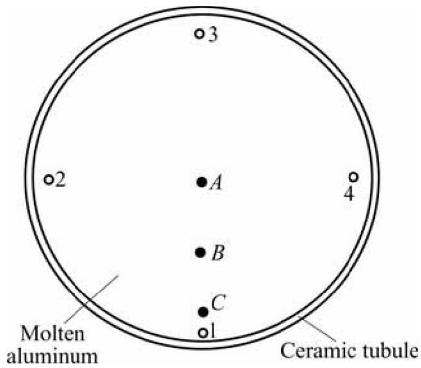

Fig.2 Schematic view of position of iron in molten aluminum

Fig.3 shows the microstructures of the solidified sample when alumina inclusions are added in the position *A* and the time of applying the electromagnetic field is 2 s. There are alumina inclusions both in the periphery and in the inner of the sample. In fact, the alumina inclusions can almost be found throughout the surface of the sample. And the distribution of the alumina inclusions of the other 14 sample is also shown in Fig.3. When alumina inclusions are added into the molten aluminum in position *A* and the time of applying the electromagnetic field is more than 2 s, alumina inclusions can be found in area 1, 2, 3, 4 and *A* in the solidified samples. When inclusions are added in positions *B* and *C*, alumina inclusions can also be found in area 1, 2, 3, 4 and *A* 2 s later with the electromagnetic field. It is to say that alumina inclusions can be moved to the whole surface of the samples in 2 s with the high frequency magnetic field.

Without the electromagnetic field, 2 s late alumina inclusions can be found in area 1 but seldom in area 2, 3 and 4 when the alumina inclusions are added in position *B*. When the time is more than 5 s there are few inclusions in area 2, 3 and 4 in the across section of the sample.

From the above, it can be concluded that the electromagnetic body force can easily arouse the turbulent flow in the molten aluminum in the thin tubule.

2.2 Simulation

Fig.4 shows the simulation model. The geometry is the same as the experimental apparatus.

Fig.5 shows the electromagnetic body force in the molten aluminum with the high frequency magnetic field. Because of the skin and margin effects, the electromagnetic body force is not uniform and mainly

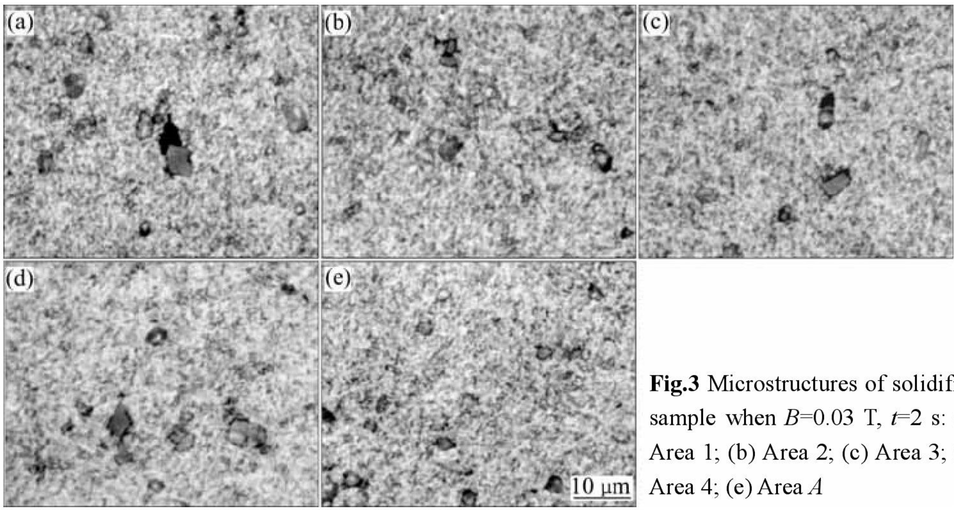

Fig.3 Microstructures of solidified sample when B=0.03 T, t=2 s: (a) Area 1; (b) Area 2; (c) Area 3; (d) Area 4; (e) Area A

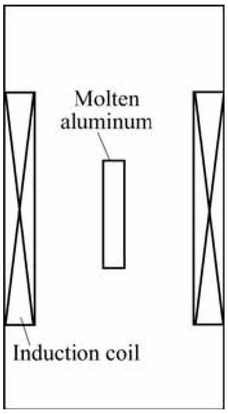

Fig.4 Simulative model of magnetic field

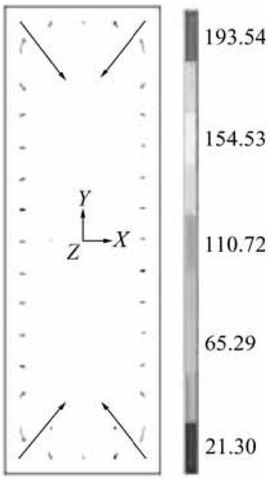

Fig.5 Electromagnetic body force in molten aluminum

distributes in the corner in the cases. Fig.6 shows the flow of the molten aluminum in the tubule. In fact, even if the electromagnetic body force is uniform, the turbulent flow in the thin tubule can also be aroused by the asymmetry of the tubule. With the increase of the EMF, the turbulent flow will become more violent. It is meaningless to pursue the uniform electromagnetic body force in the electromagnetic elimination because the turbulent flow in the molten metal is hard to avoid. How to use the flow to increase the efficiency of the electromagnetic elimination in the molten metal should be studied further.

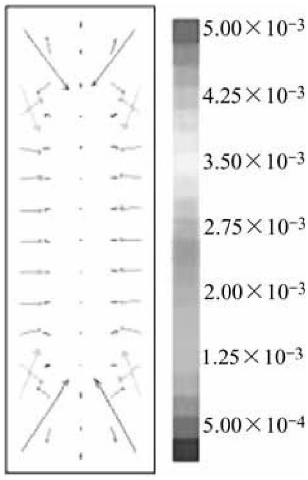

Fig.6 Velocity vector in molten aluminum with electromagnetic field

3 Effect of turbulent flow on elimination

3.1 Elimination experiment with 5 μm alumina inclusions

The electromagnetic elimination experiments that have been done with lots of alumina particles in aluminum molten cannot validate the verity of elimination because of the agglomeration of the particles [6−9]. In the investigation, in order to prevent alumina particles from agglomerating, alumina particles (5 μm) are enwrapped on iron core with aluminum foil and added into molten aluminum. The iron core is taken out when alumina inclusions dispersedly distribute in the molten aluminum. Then the elimination experiments can be done with the molten aluminum.

In the elimination experiment, *B* is 0.03, 0.04 and 0.06 T, Time is 2, 5, 10, 60 and 120 s respectively and the temperature of the sample is kept constant.

Fig.7 shows the microstructure of the solidified sample when *B* is 0.03 T and the applying time with the electromagnetic body force is 60 s. The alumina inclusions distribute both in the inner and in the periphery of the sample. The distribution of the alumina inclusions of the other samples is also shown in Fig.7. Fig.8 shows the microstructure of the sample when *B* is 0.06 T and elimination time is 120 s. Fig.8(a) shows that some alumina inclusions have reached the periphery of the metal and Fig.8(b) shows that some inclusions have been squeezed out of the metal. But there are still some alumina inclusions in the inner of the metal.

From the microstructure of the solidified samples, it can be seen that alumina inclusions distribute everywhere on the surface when *B* is 0.03 T and elimination time is 2 s; when *B* is 0.06 T and elimination time is 120 s, there are also some alumina inclusions in the inner even if some can be squeezed out from the molten aluminum. It can be concluded that 5 μm alumina inclusions can be eliminated, but the elimination efficiency is very low in the experiments.

3.2 Elimination experiment with 30 μm inclusions

Simulative elimination of non-metallic inclusions that formed in molten metal is the other means in researching electromagnetic elimination[10−13]. In order to get smaller primary silicon, Cu-14%P (mass fraction) alloy has been added into the Al-18%Si (mass fraction) alloy. The final composition of the alloy in the experiments is 0.1%P and 0.62%Cu with balanced Al-18%Si (mass fraction) alloy.

Fig.9 shows the solidified sample in the atmosphere, and the primary silicon in 30−100 μm distributes in the whole cross section of the sample. Fig.10 shows the structure of the solidified sample with forced electromagnetic field and air-cooling synchronously when *B* is 0.03 T and elimination time is 30 s. The aim of applying air-cooling during electromagnetic elimination is to dispel the Joule's heating and to decrease the temperature of the molten alloy from 720 ℃ to 570 ℃. It is seen that most primary silicon distribute in the periphery but little in the inner of the sample. Fig.11 shows the microstructure of the electromagnetic elimination sample. It is seen from the experiment that most non-metallic inclusions which is larger than 30 μm can be eliminated effectively in 30 s under the experimental condition.

3.3 Elimination experiment with 100 μm inclusions

The Al-18%Si molten alloy is poured into the ceramic tubule at 720 ℃ and cooled in atmosphere, then original sample can be got. Fig.12(a) shows the macrostructure of cross section of the solidified alloy without electromagnetic field. The primary silicon which is larger than 100 μm dispersedly distributes in the sample.

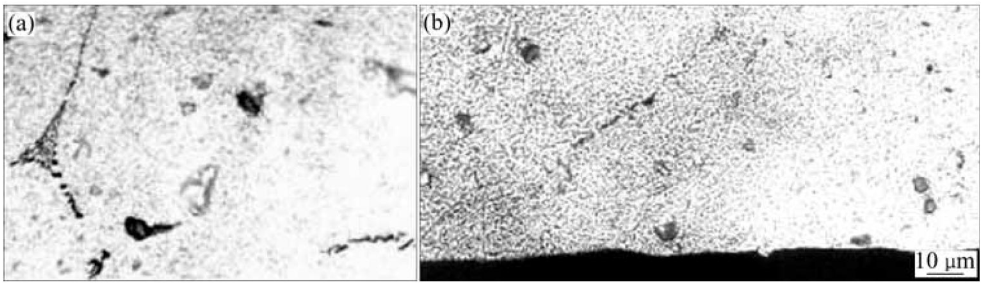

Fig.7 Microstructures of solidified sample when B=0.03 T, t=60 s: (a) Center of sample; (b) Periphery of sample

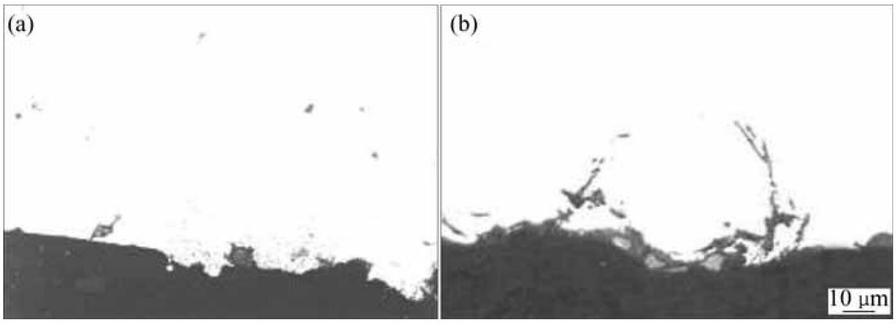

Fig.8 Microstructures of sample in periphery when B=0.06 T and t=120 s

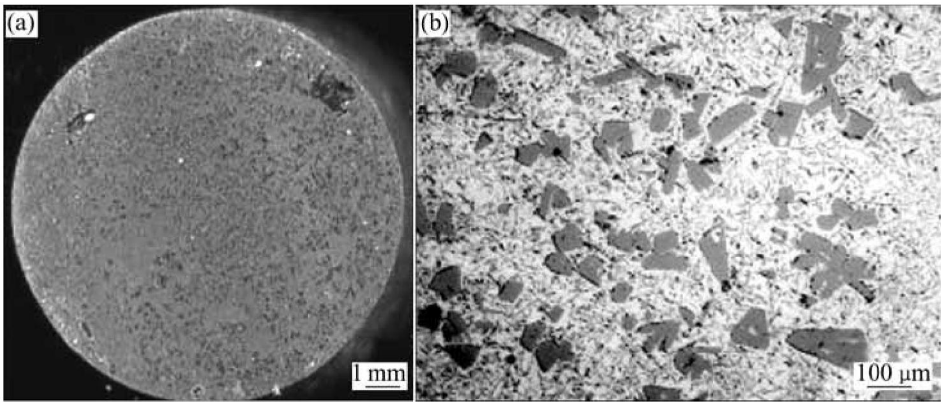

Fig.9 Solidified structures of Al-17.9%Si-0.1%P-0.62Cu alloys without electromagnetic field: (a) Macrostructure; (b) Microstructure

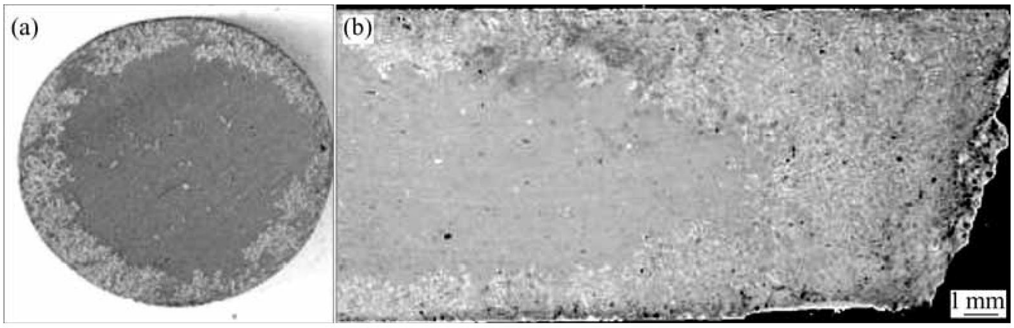

Fig.10 Solidified structures of Al-17.9%Si-0.1%P-0.62%Cu alloys with electromagnetic field and air-cooling synchronously: (a) Across section; (b) Vertical section

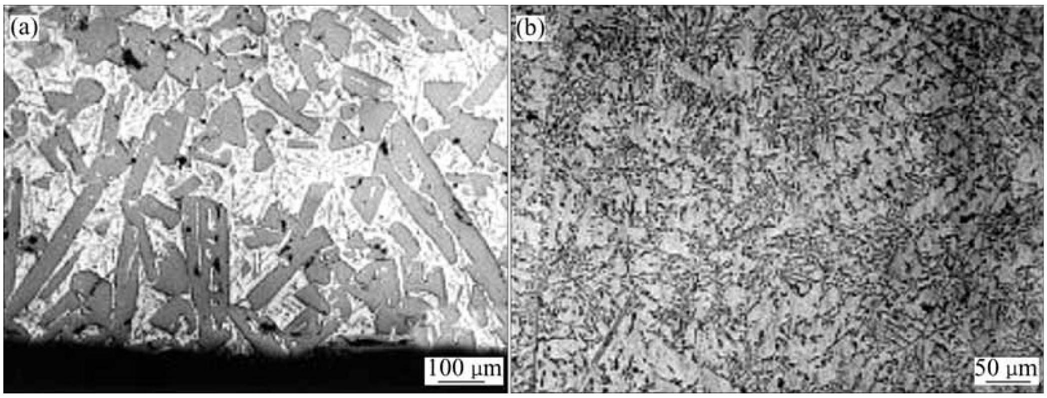

Fig.11 Microstructures of Al-17.9%Si-0.1%P-0.62%Cu alloys when B=0.03 T, t=30 s: (a) Periphery of sample; (b) Center of sample

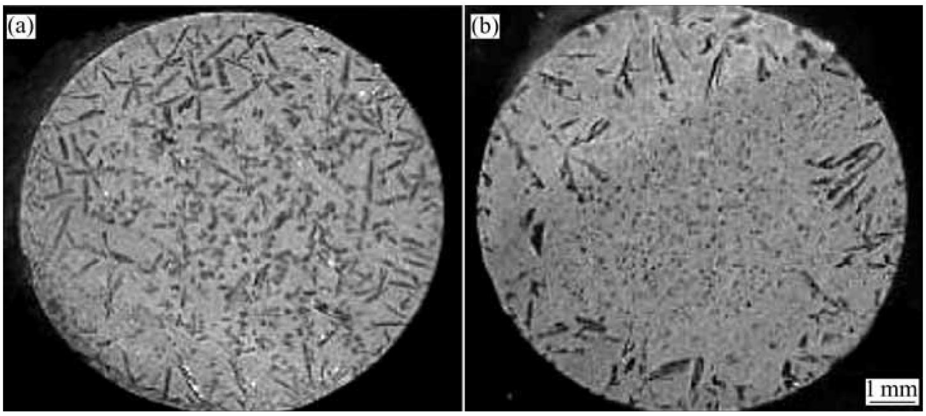

Fig.12 Macrostructures of solidified Al-18%Si alloy: (a) Without electromagnetic field; (b) With electromagnetic field

The primary silicon starts to occur when temperature is 680 ℃ in Al-18%Si alloy. In order to get the appropriate number and dimension of the primary silicon to simulate the non-metallic inclusions, as well to keep the fluidity of the melt, the simulative experiment of the electromagnetic elimination is made when the temperature of the molten alloy is 650 ℃, B is 0.03 T and elimination time is 2 s, then the sample is cooled with oil immediately. Fig.12(b) shows the macrostructure of the cross section of the sample with electromagnetic field. It can be seen that the primary silicon almost distributes in the periphery, few primary silicon particles larger than 100 μm distribute in the inner.

For further studying, the following experiment has been done. The electromagnetic elimination experiment is proceeded when the temperature of the molten alloy is 650℃. The sample solidifies with the forced air-cooling and Joule's heating. Fig.13 shows the solidified structure of Al-18%Si alloys with electromagnetic field and air-cooling synchronously when B is 0.03 T and elimination time is 30 s. It is seen from Fig.13 that the primary silicon larger than 100 μm distributes in the periphery entirely and little in the inner of the sample. Fig.14 shows the microstructure of the sample, and most primary silicon particles with 100−400 μm in length distribute in the periphery.

From the above, it can be seen that 200 μm inclusions can be wiped off in 2 s when B is 0.03 T; the non-metallic inclusions that larger than 100 μm can be eliminated entirely in 30 s in the experiment.

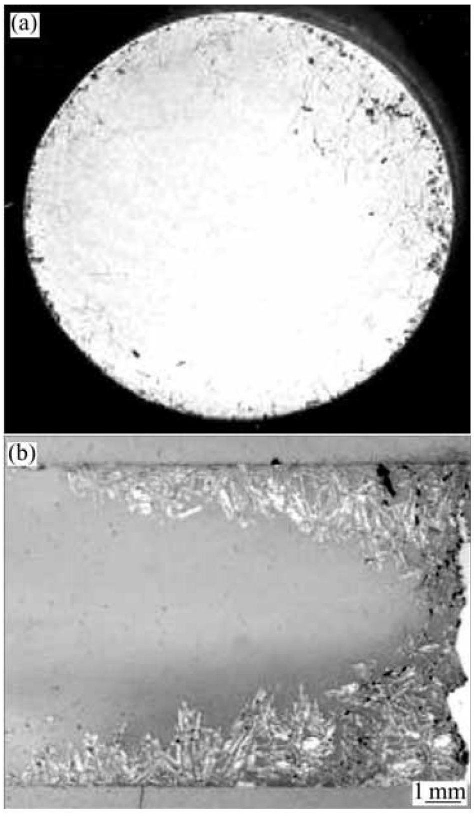

Fig.13 Macrostructures of solidified Al-18%Si alloy when B=0.03 T, t=30 s: (a) Across section; (b) Vertical section

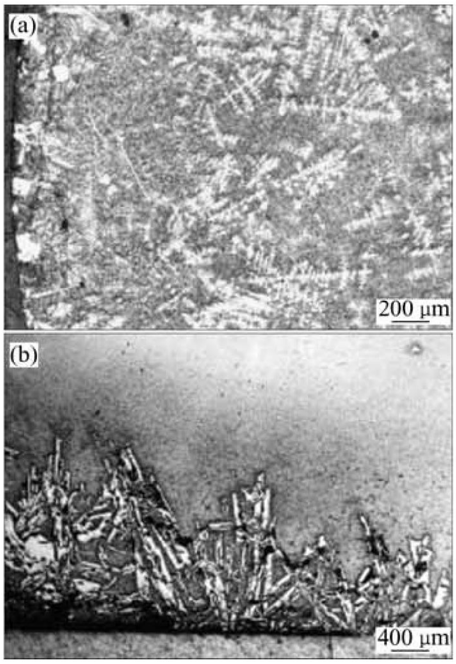

Fig.14 Microstructures of solidified Al-18%Si alloy when B=0.03 T, t=30 s: (a) Across section; (b) Vertical section

4 Discussion

4.1 Effects of electromagnetic field on elimination

With the electromagnetic body force, non-metallic inclusions can be eliminated from the inner and be restricted in the periphery of the molten metal, even some non-metallic inclusions can be squeezed out from the molten metal. The turbulent flow will be induced with the non-uniform electromagnetic body force.

4.2 Effect of flow on various dimension inclusions

It can be found from the experiment results that inclusions which are larger than 200 μm can be eliminated in a short time in the molten metal with tubule, and most primary silicon particles (30−100 μm) can be wiped off in 30 s when B is 0.03 T in the electromagnetic elimination experiments. However micron alumina inclusions (5 μm) cannot be eliminated effectively even B is 0.06 T and elimination time is 120 s in the experiment.

The experimental result of the flow shows that alumina inclusions can be found in the periphery in 2 s when B is 0.03 T and the alumina inclusions are added in position A. Then the alumina inclusions can be wiped off in 2 s or less. But the results of the electromagnetic elimination experiments with 5 μm alumina inclusions show that there are also some alumina inclusions in the inner of the samples even if the elimination time is 120 s and B is 0.03, 0.04 and 0.06 T respectively. It can be concluded that the flow in the thin tubule affects the elimination results of the 5 μm alumina inclusions.

TAKASHI et al[14] and KOICHI et al[15] have discussed the effects of the flow on the electromagnetic elimination. Larger dimension inclusions have little effect on the flow and then can be eliminated effectively; some micron size inclusions can be eliminated whereas the efficiency is too low because of the turbulent flow of the molten aluminum in the experiment. YUJI et al[16] have observed the process of collision between inclusions in the molten metal but the probability of collision is so little that will not evidently affect the electromagnetic elimination results evidently.

How to eliminate micron non-metallic inclusions is still the key problem in the electromagnetic elimination.

5 Conclusions

1) The experimental result shows that there is a turbulent flow in the molten aluminum in the thin tubule with the high frequency magnetic field and the simulation result shows the existence of the turbulent flow in the molten metal too.

2) Most primary silicon particles (30−100 μm) can be wiped off in 30 s and those larger than 200 μm can be eliminated in 2 s in tubule when B is 0.03 T.

3) Because of the turbulent flow, alumina inclusions (5 μm) cannot be eliminated effectively even if the magnetic induction intensity is 0.06 T and the elimination time is 120 s.

4) The turbulent flow is hard to avoid in the electromagnetic elimination. How to use the flow to increase the elimination efficiency should be studied further.

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