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Continuous cleaning of A356 alloy melt using high frequency electromagnetic field①

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Abstract: A set of device for electromagnetic separation (EMS) was designed and applied to process the continuous flowing melt. Tensile test was employed to compare effect of electromagnetic separation with that of the traditional processes. Compared with filtration by ceramic foam filter and process without filtration, multiple process combined with filtration and electromagnetic separation can effectively remove most of inclusions with diameter finer than 10 μm in A356 alloy casting, hence improve its tensile properties. After being processed by electromagnetic filtration, the tensile strength of A356 scrap is enhanced by 8.27%, approaching the level of fresh A356 alloy.

Key words: high frequency electromagnetic field; electromagnetic separating; melt cleaning; A356 alloy
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1 INTRODUCTION

Online treatments such as degassing, refining and filtration are very important for improving the quality of aluminum alloy parts in the practical continuous casting industries[1-3]. Simple filtration treatment does not meet the new demand of high cleanliness for aluminum melt since it can only remove nonmetallic inclusions larger than 30 μm in most cases[4]. In recent years, it was found in the new researches on electromagnetic separation that micro-sized inclusion which is smaller than 10 μm can be efficiently removed by using high-frequency alternating magnetic field and thus higher cleanliness was obtained[5-11]. However, further experiments on continuous process are needed to verify its utility in large-scale industry.

In this study a set of laboratory-scale apparatus combining filtration with electromagnetic separation was set up to conduct experiments of continuously processing A356 aluminum melt. Tensile test bars were cast after treatment in three cases, electromagnetic separation combined with filtration, with only filtration and with only degassing. Moreover, the tensile strength and rate of elongation were tested and compared to study the influences of different processes on tensile properties.

2 EXPERIMENTAL

The continuously processing apparatus was shown as Fig. 1. High-frequency alternating magnetic fields of 8.3 kHz and 15.6 kHz were obtained in an induced coil connected to an IGBT-type induction heating power supplier. The whole system was insulated in a box made with lightweight refractory to hold temperature. A gypsum-made separator with multiple 10 mm × 10 mm square channels was employed and a 20 ppi foam ceramic filter was placed before separator to trap large-sized alumina film and inclusions.

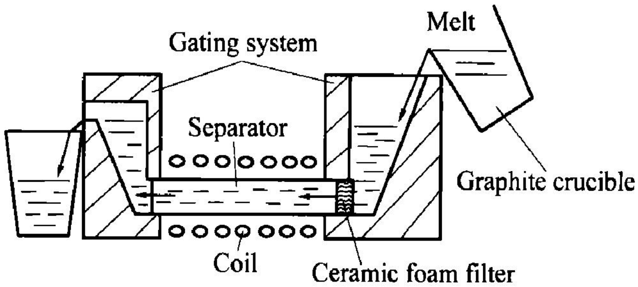

Fig. 1 Electromagnetic separation apparatus for continuous processing of aluminum alloy melt

A356 aluminum alloy was used as experimental alloy. The chemical compositions of the alloy were measured by ICP-AES analysis, as shown in Table 1.

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Table 1 Chemical compositions of A356 alloy(mass fraction, %)

Si	Mg	Ti	Fe	Mn	Cu	Al
6.840 8	0.361 5	0.012 6	0.079 5	0.037 1	0.021 6	Bal.

Obtained from ICP analysis of 3 samples

5 kg A356 fresh alloy or scrap alloy was melted in graphite crucible and kept at (740 ±5) ℃ for 30 min in a resistance furnace. The 0.5% C_2Cl_6 was put into the melt for degassing and then the melt was held for 10 - 15 min. After the temperature turned to be stable, slag on the melt was removed and continuous EMS treatment was processed on melt as shown in Table 2 in details. At the beginning of EMS process, the IGBT power supply was turned on, then the melt was poured into the pouring cup and flowed continuously through the separator channels to another crucible which was preheated to 740 ℃. The pouring rate is controlled by maintaining the head in the pouring cup. After the melt was reheated up and held stable at (725 ±5) ℃ in the furnace again, it was poured into standard mold at last. The tensile test bars were obtained under different processing conditions, as shown in Table 2. The tensile properties were tested on hydraulic pressure type testing machine. For each of the six conditions, three bars were prepared for tensile testing purpose. Samples were cut from different test bars and polished to observe the metallicgraph with optical microscope and tensile fracture with SEM.

3 RESULTS AND DISCUSSION

3.1 Tensile performance

Fig. 2 shows the tensile properties of A356 alloy treated with different processes. From Fig. 2(a), it can be easily found that the tensile strength of different sets of experiments can be sequenced as: No. 3 < No. 4 < No. 5 < No. 2 < No. 1 < No. 6. However, there is little differences for different processes (No. 1, 2, 3) on fresh A356 alloy. On another side, compared with samples without any process (No. 4), the tensile strength of A356 scraps (No. 6) after EMS treatment was increased by 8.27% which approaches that of fresh alloy. From Fig. 2(b), the rate of elongation gained in different experiments can be sequenced as: No. 3< No. 1 < No. 4< No. 2< No. 5< No. 6. It is indicated that A356 test bar experienced fragile crack failure in the tensile test since none of data in Fig. 2(b) is no more than 7%. Owing to this, the influence of processes on alloy properties can not only depend on comparing the rate of elongation.

3.2 Analysis on tensile fracture

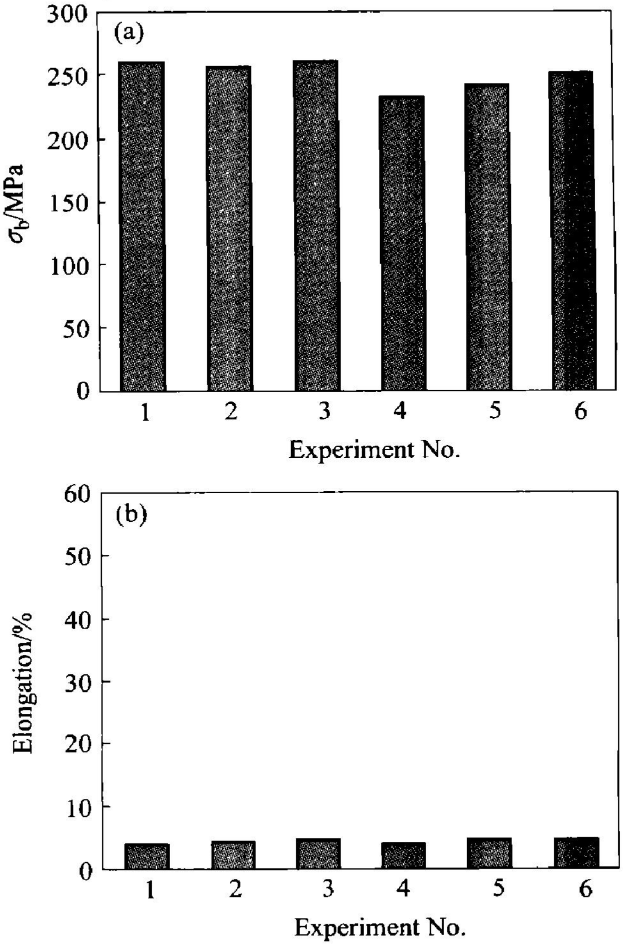

Fig. 2 Tensile properties of A356 samples after different cleaning process

Table 2 Continuous cleaning processes of A356 alloy melt

No.	Alloy	Degassing temperature/ ℃	Pouring temperature/ ℃	Mold temperature/ ℃	Filtration	EMS process
1	Fresh	740 ±5	725 ±5	250 ±5	—	—
2	Fresh	740 ±5	725 ±5	250 ±5	20ppi filter	—
3	Fresh	740 ±5	725 ±5	250 ±5	20ppi filter	15.6 kHz, 0.12 T, 8 - 10 s
4	Scrap	740 ±5	725 ±5	250 ±5	—	—
5	Scrap	740 ±5	725 ±5	250 ±5	20ppi filter	—
6	Scrap	740 ±5	725 ±5	250 ±5	20ppi filter	15.6 kHz, 0.12 T, 8 - 10 s

Processing procedures: Melting → Holding temperature → Degassing → Holding temperature → Without filtration, with filtration or EMS processing → Casting test bars → T6 heat treating

Various tensile fractures obtained on tensile samples were observed and analyzed with SEM to understand the effects of different cleaning treat-ments on properties and microstructure of A356 alloy.

3.2.1 Scrap alloy

Figs. 3(a), (b) and (c) show the typical SEM images of A356 tensile fractures obtained in experiments No. 4, 5 and 6, respectively. The tensile strength of the sample shown in Fig. 3(a), which is 213.9 MPa, is the lowest in all the A356 scrap samples without filtration. It can be found from the figure that there is an obvious deep gray area on the fracture. Apparently, blocks of alumina films existing in A356 scrap melt can not be removed without any cleaning process and thus stay in the test bar after solidification. While loading in tensile test, the alumina film was smashed into fragments and show gray part on the surface of fracture[12]. It can be avoided if the melt is treated with filtration.

The tensile sample shown in Fig. 3(b) was treated with 20ppi foam ceramic filter. Compared with Fig. 3(a), its tensile strength is improved remarkably because bulks of alumina films were removed by filter. The sample shown in Fig. 3(c) was treated with EMS process combined with filtration. It can be seen from the figure that the surface of the cup fracture is relatively even and the dimples are smaller and more homogenous than those of other two samples.

3.2.2 Fresh alloy

Fig. 4 shows the fracture surfaces of fresh A356 alloy tensile-tested samples without filtration in experiments No. 1. A cleavage fracture along the radial direction was found on the tensile fracture, as shown in Fig. 4(a), in which an arrow indicates the cleavage plane. Moreover, an amplified SEM photo (Fig. 4(b)) shows that some small fractures were formed at the deep side of the cleavage fracture plane and expanded to the transversal profile. Fig. 4(c) is the amplified picture of the square-frame area in Fig. 4(b). From the figure it can be found that the wide gap was formed around an inclusion particle of 100 − 120 μm. Liu[12] discovered in his research that the oxide inclusions in the A356 melt mainly include of alumina and $MgAl_2O_4$ particles if the melt is held at high temperature for long time. Generally, these inclusions remaining in the casting come to be the original

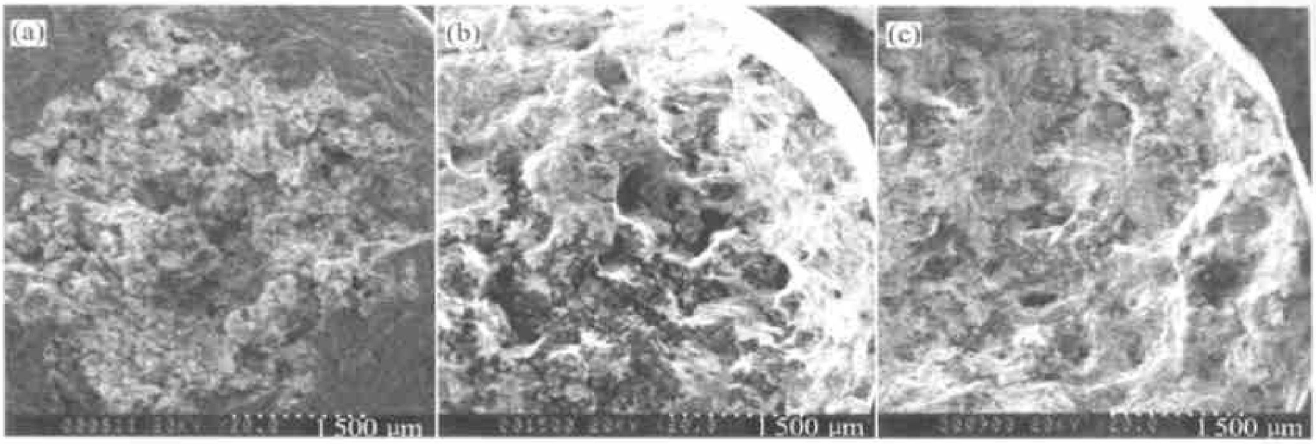

Fig. 3 Fracture surfaces of scrap A356 tensile test samples after different cleaning processes
(a) —213.9 MPa, 2.40%; (b) —244.0 MPa, 3.93%; (c) —255.0 MPa, 4.17%

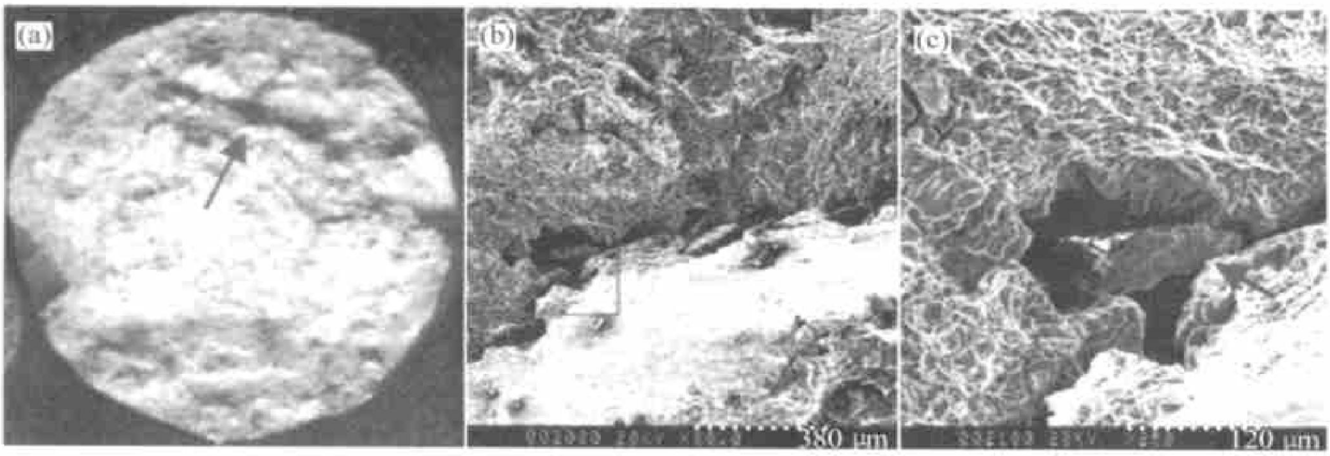

Fig. 4 Fracture surfaces of fresh A356 tensile-tested sample without filtration
(a) —Optical macrograph (arrow indicating cleavage fracture plane); (b) —Bottom site of fracture plane;
(c) —Amplified graph of local area in Fig. 4(b)

fracture-germinating place and thus decrease the mechanical strength of the matrix.

The sample shown in Fig. 5 was treated with filtration. Fig. 5(b) is the amplified graph of the indicated local area in Fig. 5(a), where large intercrystal porosity exists. In another amplified graph Fig. 5(c), a small inclusion of no more than 20 μm was found in fine dimples. This indicates that very small inclusions still exist in casting after filtration.

The test bar in Fig. 6 showing the highest tensile strength was treated with EMS combined with filtration. It is found that there is only little high-low fluctuation and very thin shear lip on the surface of cup fracture, where the regular cleavage fracture was formed at the rear, as shown in Fig. 6(a). It is also found from Fig. 6(b) that there are many fine and homogenous dimples but no expansive fracture.

In additional, the longitudinal section along the central axis of tensile fracture was cut to observe the microstructure in depth direction. The metallograph (Fig. 7(a)) of A356 fresh alloy shows local porosity in the matrix and Fig. 7(b) shows that the fracture expanding to the depth direction. It can be seen from Fig. 7(c) and (d) that there are lots of inclusions existing in the A356 scrap without any treatment. Fig. 7(c) shows that the microstructure near the fracture was smashed into fragments. And Fig. 7(d) shows that there are many porosities existing at the rear of fracture and expanding along the grain boundary. Apparently, since lots of gas were easily adsorbed to the inclusions[13], the alumina film will be easily attached to the dendritic surface and form porosities after the casting solidifying without filtration process[14]. While loading in the tensile test, these porosities become the initial place of producing fracture.

3.3 Effects of EMS process on tensile properties of A356 alloy

The inclusions in the aluminum alloy influence the breaking-down process of the casting tremendously. At first when the metal is exerted tensile force, the fractures always form at the inclusion or the interface between the inclusions and the matrix[13]. In addition, the porosities accompanying with the inclusions turn into fracture directly[15].

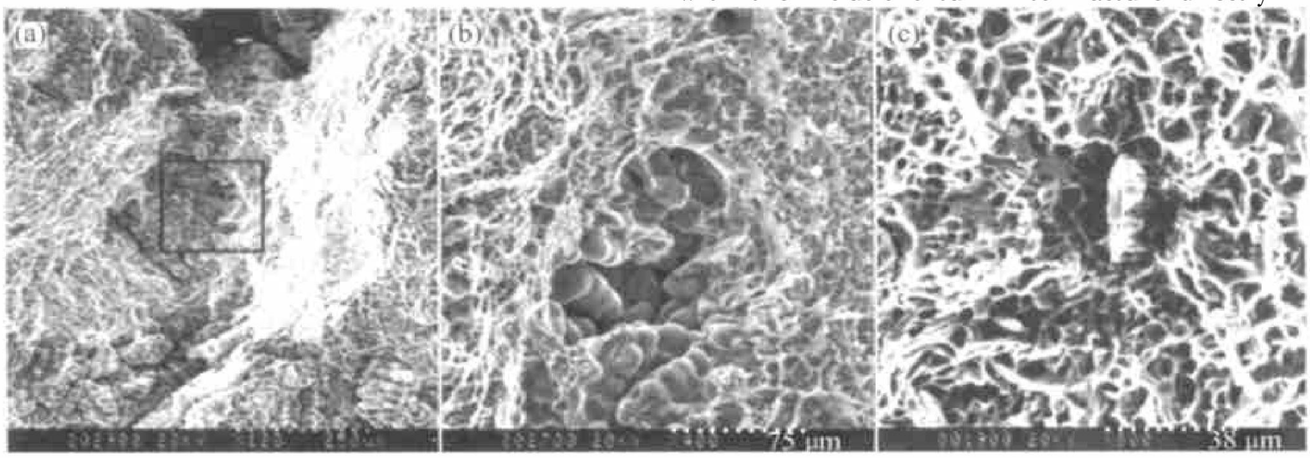

Fig. 5 Fracture surfaces of fresh A356 tensile-tested sample after filtration(256.0 MPa, 3.69%)
(a) —SEM micrograph of bottom site of fracture plane; (b) —Amplified graph of local area in Fig. 5(a);
(c) —Arrow indicating a small inclusion particle in dimple structure

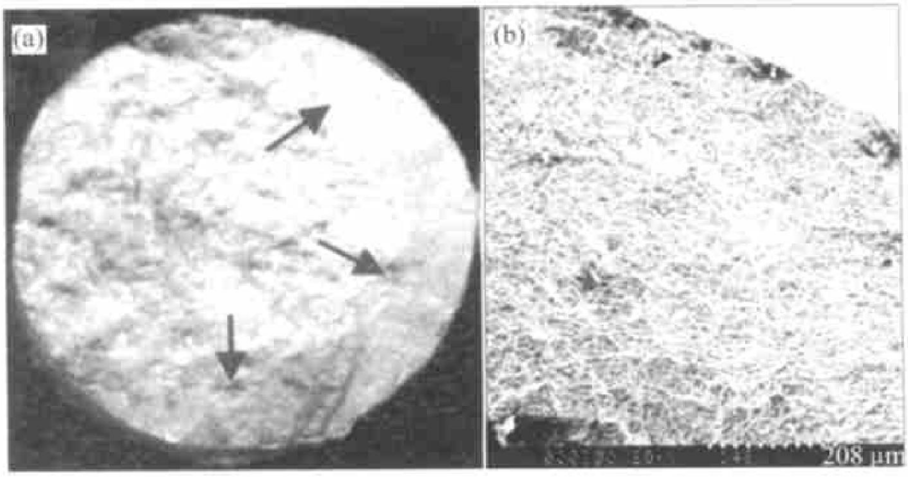

Fig. 6 Fracture surfaces of fresh A356 tensile-tested sample after filtration and EMS treatment
(a) —Optical macrograph(arrow indicating cleavage fracture plane); (b) —SEM micrograph of fracture plane

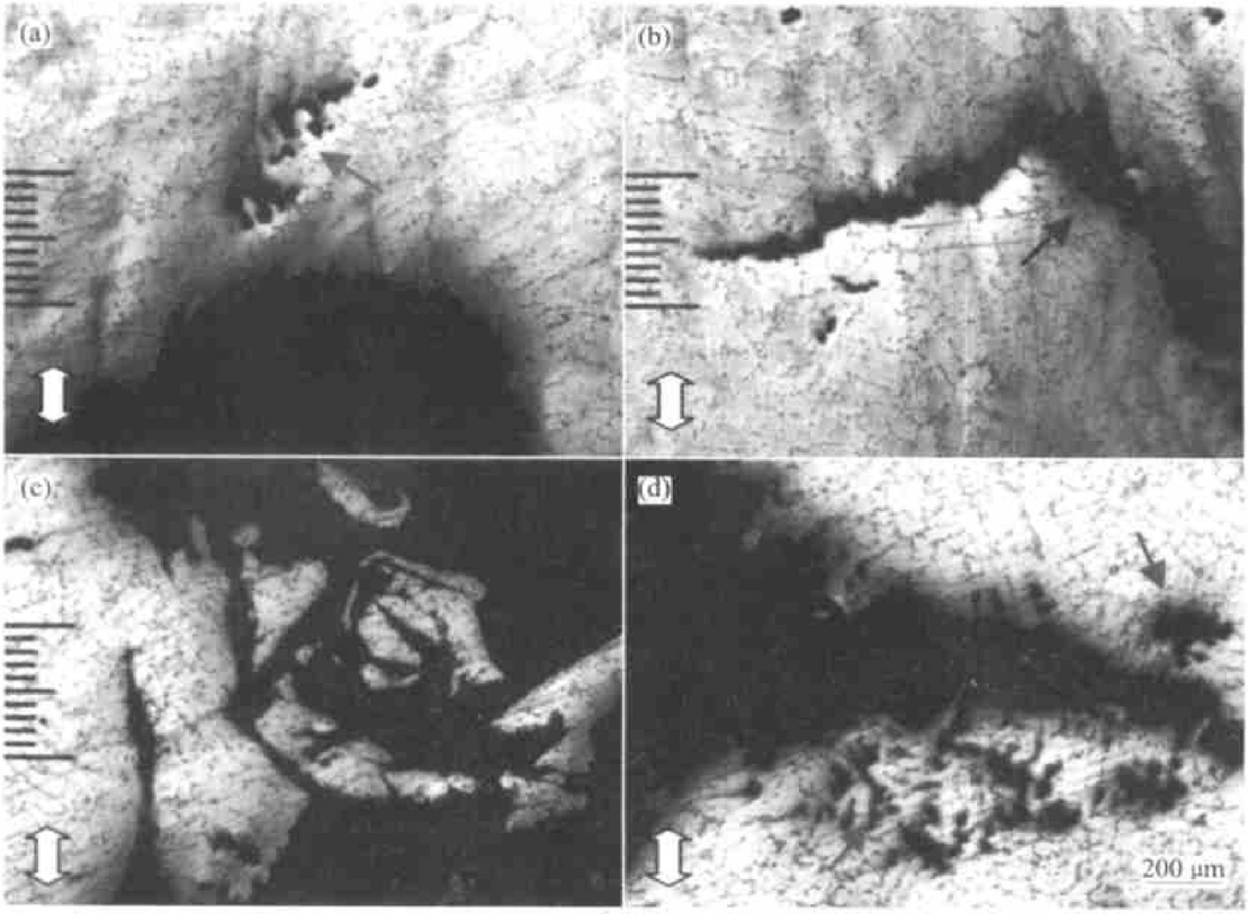

Fig. 7 Microstructures beneath fracture surface of samples
(a), (b) —256.9 MPa, 3.84%; (c), (d) —277.1 MPa, 3.75% (two-direction arrows indicating loading direction)

Moreover, the content of hydrogen increases greatly with the increasing content of the inclusions in the melt. Hydrogen in gaseous state will form large number of porosities in the casting after solidification. These porosities become the original place of fracture later and thus decrease the mechanical properties of the casting[15].

According to the data in Fig. 2, the average tensile strength of A356 scraps after filtration was improved little. It is obvious that the tensile strength of A356 alloy can be improved to some extent and stabilized by removing large-sized inclusions in the melt with 20ppi foam ceramic filter, but the tensile strength can only be enhanced to limited level because the micro-sized inclusions can not be removed with filtration. Compared with the process with only filtration, EMS process can remove micro and large-sized inclusions in the melt as well, eliminate any micro-porosity and thus enhance the tensile strength of the casting to higher level.

4 APPLICATION OF EMS PROCESS IN CONTINUOUS CASTING PROCESS OF ALUMINUM ALLOY

Aluminum foil is widely used in the packaging industry. Generally it is produced with continuous casting and tandem rolling process, in which the quality of aluminum foil mainly depends on three processes such as refining, degassing and inclusion separation. Normally online process in production includes of degassing with revolving jetting in tundish and filtrating with foam ceramic filter in launder[1]. However, simple filtration process can not efficiently remove the massive micro-sized inclusions of 1 - 30 μm existing in the aluminum melt. Thus, it is necessary to develop a new effective process with higher removal efficiency.

The imposing time of electromagnetic force on the steady flow must be long enough for EMS process. Therefore, it is suitable to use EMS process in the continuous production of nonferrous metals with low output in unit time. A set of apparatus using EMS process is sketched in Fig. 8. According to the size of the induce coil, the channel of the separator is designed as quadratic or round form which determines the flowing quantity of the equipment. Except for the type of channel, the diameter and the length of the separator, the arrangement of the channels and the absorptive capability of the inner surface must be considered. Under the condition that flowing velocity is 2 cm/s and the channel area is 60 cm^2 in total, the predictable effects will be that 9.6 t of aluminum alloy melt can be treated in 8 h on each production line.

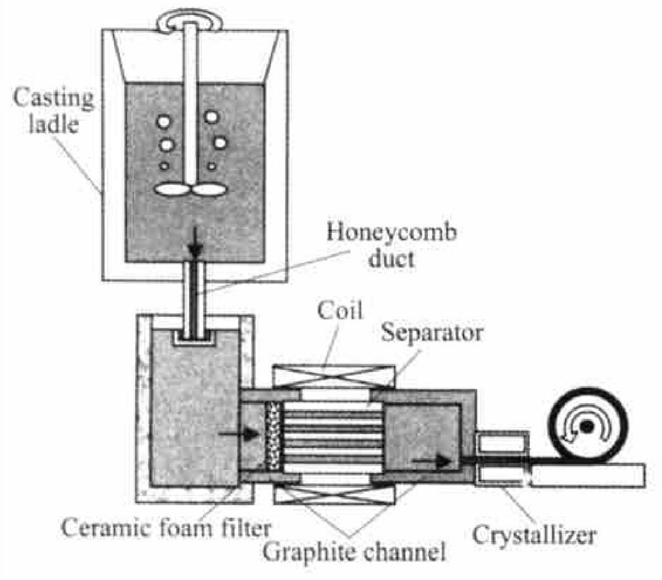

Fig. 8 Process diagram of electromagnetic separation applied in practical production

5 CONCLUSIONS

Comparing with cleaning process without or with filtration only, EMS process combined with filtration can effectively remove most of the micro-sized inclusions in A356 alloy casting and thus enhance the tensile strength. After processing with EMS, the tensile strength of A356 alloy scrap was increased by 8.27%, approaching that of fresh alloy. Since the melt must experience the electromagnetic force for enough time in the EMS process, it is mostly suitable to use it in the semi-continuous or continuous casting production which needs only low flow velocity.

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