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Materials

Casting structure of pure aluminum by electric pulse modification at different superheated temperatures

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Abstract: Electric pulse modification (EPM) is a novel technique that reduces grain size by altering the structure of a melt. It was investigated that the response of the casting structure of high pure aluminum to EPM in different superheated melts. The results indicate that the grain refining effect of a given pulse electric field holds an optimal temperature range, moreover, a lower or higher superheated temperature will both disadvantage the improvements of casting structure. It essentially lies in the cooperative action between the distorted absorption of clusters and the activated capability of atoms in the aluminum melt.

Key words: electric pulse modification; superheat; casting structure; cluster; activated ability

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1 Introduction

Many experiments indicate that the grain size of a metal has great effect on its quality. The structure with homogeneous and fine grains can enhance remarkably the strength and elongation of the material, reduce its tendency of hot tearing and improve its airtightness. Nowadays technologies of modification and inoculation are widely used to refine the grain of casting materials in industry. The laws of metal solidification under the action of electromagnetic field have been studied actively since the eighties of the 20th century [1-2], and a series of new technologies and facilities have been developed and applied to production, such as electromagnetic stirring. Electric pulse modification (EPM) [3] has been developed rapidly as a new type grain refining technology, which is carried out in liquid metal by means of exerting the pulse electric field and attains a high quality casting structure accordingly. Apart from convenience, agility and notable effect, it has an obvious advantage, *i.e.*, EPM does not contaminate melts and environment. Lots of researchers increasingly occupied themselves in it presently [4-5].

Aluminum is an indispensable metal in national economy on account of its preferable electric and heat conductivity, easy processability and alloying ability with multifarious metals. EPM of high pure aluminum can not only develop an environmental-friendship, easy-operation grain refining technology, but also enlarge the views to the melt structure and its evolution.

In this paper, the casting structural characteristic of high pure aluminum by electric pulse modification at different superheated temperatures is investigated, and it is expected to establish the foundation for industrialized application of EPM.

2 Experimental materials and methods

2.1 EPM of high pure aluminum

The right amount of high pure aluminum (99.999 wt%) in a graphite crucible was melted at a time in a well-resistance furnace, heated to 680, 730, 780 and 830°C respectively, then held at that temperature for 300 s. Degassed by nitrogen, then inserted the high pure graphite electrodes vertically into the crucible full of liquid aluminum at the corresponding superheated temperature and EPM proceeded. The electric pulse parameters were voltage, 300 V; frequency, 10 Hz; time, 20 s. It was cast into metal moulds at room temperature finally.

2.2 Macrostructure and calculation of grain size

All the aluminum ingots were put apart along their middle axis surface by means of wire cutting after cooling, the section planes of the samples were polished and eroded (with 5% HF solution), and then

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their macrostructures were observed. The grain size was defined as the grain numbers in unit area, *i.e.* squared 100 mm^2 area from the center of section planes, and calculated the ratio of grain numbers in this area to 100. Each group had 6 samples and averaged their values of the grain size.

3 Results and discussion

3.1 Macrostructure of high pure aluminum by electric pulse modification at different superheated temperatures

As for EPM, the grain refining of casting structure primarily results from the changes of melt matrix [6]. The structural variation is different from that of traditional modification of a melt; actually, it represents the evolutive dynamics of melt structure by EPM. On the other hand, currently the researches of melt structure focus mainly on the characteristics related to temperature field [7], there have been some ripe methods of analysis and identification about the microcosmic state of a melt at different superheated temperatures [8]. However, the results of this paper ought to originate from "coupling action" between different temperature fields and a given pulse electric field.

Macrostructures of high pure aluminum by EPM and corresponding changes of the grain size are shown in **figures** 1 and 2, respectively, and the macrostructure of the original sample (No EPM) is presented in figure 1(a), whose casting temperature is 730°C.

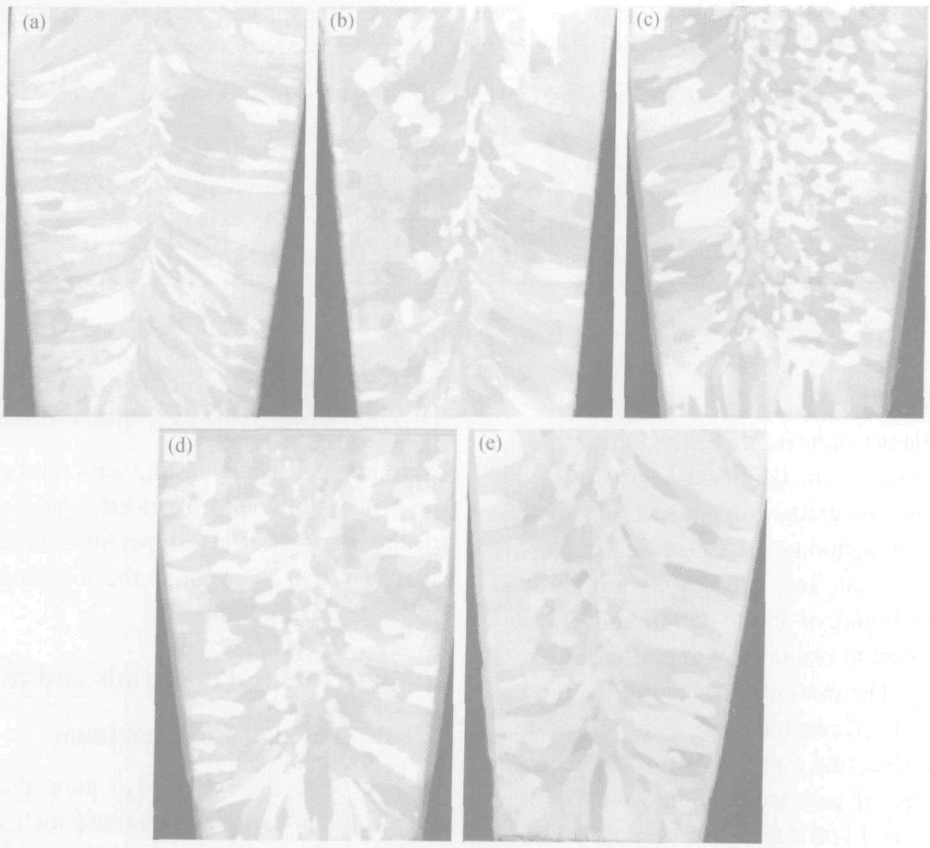

Figure 1 Macrostructures of the samples at different superheated temperatures: (a) original sample (No EPM); (b) 680°C; (c) 730°C; (d) 780°C; (e) 830°C.

It is obvious that the EPM of aluminum melt at different superheated temperatures can make its casting structure change distinctively. Generally, it is observed that the scope of an equiaxed crystal grain expands a little, the growth of column crystal is restrained and its fractal structure tends to diversification meantime. According to the views of Prigogine [9], the dissipative physical nature of the solidification system characterizes its structure as fractal, so the fractal dimension differences of the column crystal in figure 1 should stem from the cooperative action between the temperature field and pulse electric field. In addition, the observation of macrostructures denotes that the grain size of the EPM sample at 680°C (the superheated temperature is merely 20°C) is 1.10 mm^{-2}, which is two times as much as that of the original sample; the equiaxed crystal grains in the center of the casting ingot increase obviously and also the gains more refining when the temperatures of EPM are 730 and 750°C, moreover their grain sizes are 1.78 and 1.53 mm^{-2} respectively, which are three times more than that of the original sample, here the effect of EPM is remarkable comparatively. Nevertheless the grain size of the sample reduces to 1.19 mm^{-2} when the aluminum melt is superheated to 830°C, which **is** the same as that of the sample who is superheated to 680°C. Apparently, there is a superheated temperature range of the melt dependent on the given electric pulse parameters. The optimal casting structure **will** be acquired if EPM is accomplished in this temperature area, and the lower or higher temperature of aluminum liquid is disadvantageous to the effect of EPM, the coupling action of different "field" contributes little to the improvement of casting structure in the meantime.

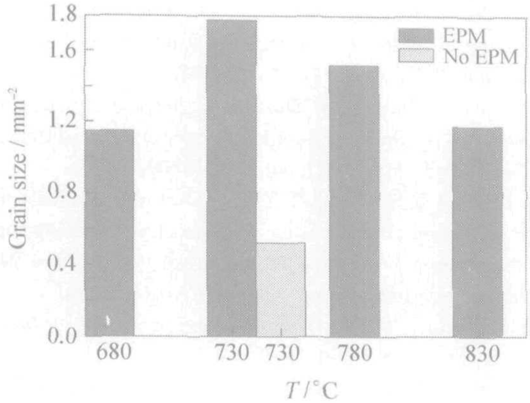

Figure 2 Grain size of the samples **at different** superheated **temperatures**

3.2 Response mechanism to the pulse electric field of aluminum melt at different superheated temperatures

The liquid metal is the matrix of solidification, however the investigations of the melt lag far behind those of solid state on account of the melt's complexity and the limitation of studying means and testing technology. Fortunately, the mechanism of EPM offers an opportunity to deep understanding of melt structure and its evolutive property. As indicated in the researches of J.Z. Wang [10], liquid metal can be considered as an aggregation of clusters (sub-crystal embryo) with discontinuous magic numbers and metal atoms, the variation of melt structure lies essentially in shell structure and the distorted growth of cluster by EPM. Additionally, the thermal relativity of cluster indicates that there are clusters with a most probable magic number corresponding to different temperatures in the melt. The dominant cluster size inclines to smaller with the increase of temperature, and the reverse process proceeds when the temperature decreases, the model description is shown by curve A in **figure 3.** According to the experimental data in reference [11], aluminum melt still holds short range order (SRO) that is an indigenous structure of fcc to crystal at its melt point nearby. The SRO parameters of the aluminum melt get a change at 800°C or so, and bcc structure is formed, the nearest distance between atoms decreases accordingly, which accords with the early cluster model of the melt approximately.

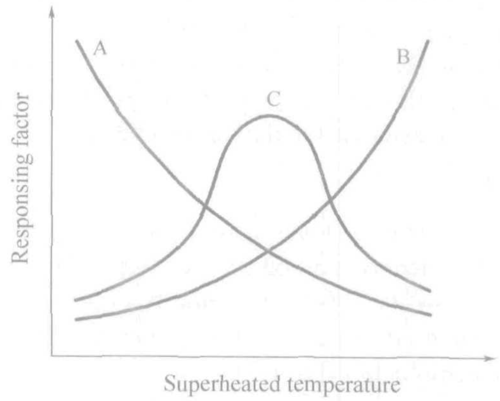

Figure 3 Response mechanism to the pulse electric field of superheated melt.

On the other hand, the heat movement of melt atoms comprises the atomic vibration of cycling the equilibrium center and the displacement (self-diffusion) of single atoms. In the light of Frenker, the self-diffusion coefficient of a melt atom is represented in the following equation [12]:

$$D=\frac{\overline{u}^2}{\tau_0 \exp(\frac{w}{k_b T})},$$

where $\overline{u}^2$ is the mean square displacement of diffused particles; τ_0 the vibrant cycle of atoms; w the activated energy of atomic transition; k_b the Boltzmann constant; T the thermodynamic temperature. For a certain mean square displacement, it is given by curve B in figure 3 that the relationship between the capability of atomic activated transition and the change of temperature.

As a result, there are two principal factors that control the response to pulse electric field of different superheated aluminum melts. On one hand, the most probable cluster size in a melt is larger at a superheated temperature, and its effect of distorted absorption is obvious under the action of pulse electric field, which is favor of the combination with the atoms around it and the following formation of critical nucleus. But here, the atoms are insensitive to combine with the distorted cluster in virtue of the lower capability of activated transition, which results in little probability of forming critical nucleus, hence the general refining effect is presented. On the other hand, the movement capability of atoms around the clusters will enhance greatly with the increase of the melt temperature, whereas the combinative capability of distorted clusters weakens. Even if the "crystal embryo" in the process of elastic collision has formed, it will easily tend to dissociate under the temperature field. Therefore, there is a best responding temperature to the superheated melt in a fixed pulse electric field as indicated by curve C in figure 3, the effect of EPM is more satisfying nearby this temperature, a lower or higher superheated temperature is not help to improve the casting structure. Namely, this responding mechanism can be expressed in the formula below.

$$C=AB,$$

where A is the responding factor controlled by electro-pulse distorted adsorption, B the responding factor controlled by the activated capability of atoms, while the coupling effect between the temperature field and pulse electric field yields C.

4 Conclusions

(1) EPM of aluminum melt at different superheated temperatures denotes that the improvement of casting structure is sensitive to melt temperature, and the optimal effect of EPM can be attained in the temperature range of 730-750°C.

(2) The micro-mechanism of coupling effect between the temperature field and pulse electric field stems from the cooperative control between the effect of distorted absorption of clusters and the activated capability of atoms in aluminum melt.

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