Influences of electric pulse on solidification structure of LM-29 Al-Si alloy

*He Lijia, Wang Jianzhong, Qi Jingang, Du Huiling and Zhao Zuofu
(College of Material Science and Engineering, Liaoning University of Technology, Jinzhou 121001, China)

Abstract: The metallographic structure of LM-29 aluminum-silicon alloy modified by electric pulse treatment has been investigated and compared with those untreated. The solidification structure of LM-29 alloy has been analyzed by means of M1AP3 Quantimet image processing and analysis system, and then the solidification process has been analyzed by means of differential scanning calorimetry (DSC). The results indicate that the primary silicon phase was refined remarkably by electric pulse while the tensile strength and elongation properties increased accordingly. Electric pulse treatment can also increase the binding power between silicon clusters and alloy melt matrix, as a result, the precipitation of primary silicon phase is suppressed to meet the demand of supercooling degree for nucleating, correspondingly. The electric pulse modification has great influence on the size of silicon atomic cluster as well as its distribution in the melt, subsequently, leads to the refinement of solidification structure.

Key words: electric pulse modification; LM-29 alloy; primary phase; cluster
CLC number: TG146.2^{+}1 Document code: A Article ID: 1672-6421(2010)02-153-04

The research on correlation of the final solidification structure with the pretreatment of the melt is one of the academic subjects at the forefront of solidification science. The effects of the overheating treatment of melt on the ingot structure have been studied by various authors in India [1], Japan [2] and China [3-6].

Applying the electric pulse to the superheated melt is a new method of pretreatment of the melt. Wang [7] puts forward the notion of electric pulse modification (EPM), based on experimental data [8-10]. The effects of the technology on microstructure of alloys include reduction of the grain size, control of columnar structure, and formation of equiaxed grains, and improvement of material homogeneity such as the uniform distribution of the second phase. Whereas, no similar literature reports the effects of EPM on LM-29 alloy applied in many industrial applications such as the engine piston for its favorable strength/weight ratio and good wearing resistance. In this paper, the effects of EPM on the microstructure and performance of LM-29 alloy, as well as its mechanism are studied.

1 Experimental procedure

The composition of the experimental alloy LM-29 is shown in Table 1. The melt was heated in the vertical resistance furnace,

Table 1: Chemical composition of LM-29 alloy

Elements	Si	Cu	Mg	Mn	Ni
wt.%	22–25	0.8–1.3	0.8–1.3	0.6	0.8–1.3
Elements	Fe	Ti	Co	Al	
wt.%	0.7	0.2	0.3–0.5	69.1–73.8	

and refined by C_2C_{16} at 800 ℃. The electrode of EPM, as shown in Fig.1, was put into the melt about 3 cm beneath the surface after holding temperature to 760 ℃. Then, the electric pulse of 800 V, 22 Hz had been applied for 2 min. After the treatment, the melt was poured into a metal mould that was preheated at 250 ℃. The primary silicon phase was analyzed by using of SEM, and the average length of primary silicon was determined with M1AP3 Quantimet image processing and analysis system. Meanwhile, the original samples were refined with C_2C_{16} at 800 ℃ and cast at 760 ℃ without EPM treatment. Then the tensile test was performed on the WDW-4200 electron universal testing machine. At last, the primary silicon crystallization process in the melt with and without EPM treatment was analyzed with the cooling curves detected by DSC device.

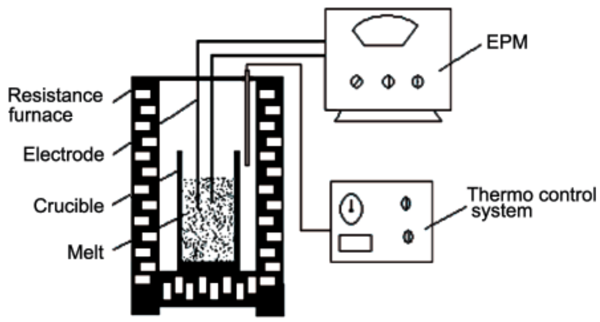

Fig 1: Schematic drawing of EPM treatment

***He Lijia**
Male, born in 1977, Ph.D, associate professor. He got his doctor's degree in 2007 from University of Science & Technology Beijing, and his research interest mainly focuses on the modification mechanism of nonferrous alloy under electric pulse. His over ten research papers have been published by now.
Email: helijia2004@sohu.com
Received: 2009-03-19; Accepted: 2010-02-15

2 Results and discussion

2.1 Microstructure and properties

The solidification microstructures of the samples, etched with 0.5%HF solution, are as shown in Fig. 2, in which the massive object is primary silicon and the needle-like is eutectic silicon. It can be seen that the silicon phase in the sample without EPM treated is coarser, with flower-like morphology, and the size of primary silicon is much larger, as compared with those from the sample after EPM treated. Meanwhile, the eutectic structure and the spacing interval tend to be smaller after EPM applied. The average sizes of the primary silicon phases at some vision fields with and without EPM were measured and calculated, according to Eq. (1) [11], which is given as:

$$L = \frac{\sum_{i=1}^{n} 2R_i + \sum_{j=1}^{n} \frac{X_j + Y_j}{2}}{2n} \tag{1}$$

Where R_i means the average of flower shape plane, and expressed as: R_i=(R_{min}+R_{max})/2, where R_{min} and R_{max} represents the largest and smallest radii of flower shape, respectively; X_j and Y_j are the largest and smallest dimension of flake shape plane respectively, n is the number of primary silicon body. The calculating results are on the three visual fields selected randomly, as shown in Fig. 3. From these results, we recognize that the average value of the primary silicon size has significantly decreased from 152.76 μm, without EPM treated, to 78.21 μm, with EPM.

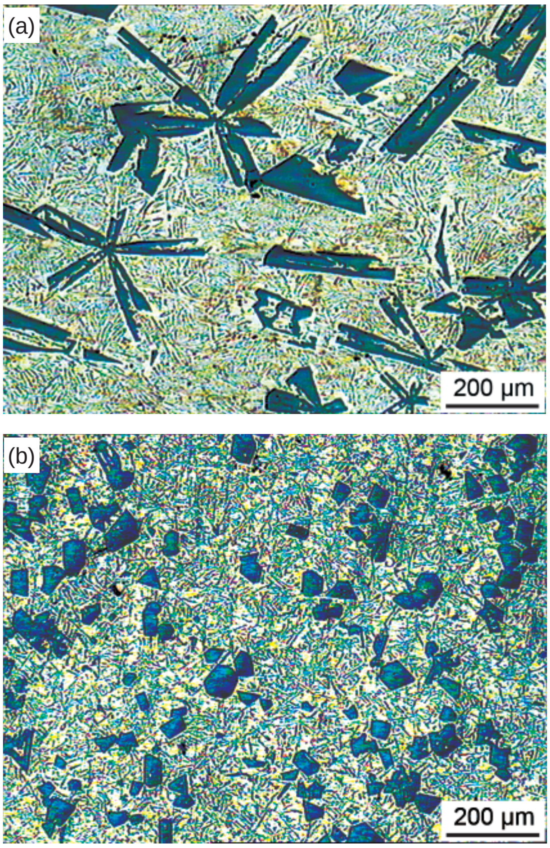

Fig 2: SEM microstructure of LM-29 alloy: untreated (a) and treated sample by EPM (b)

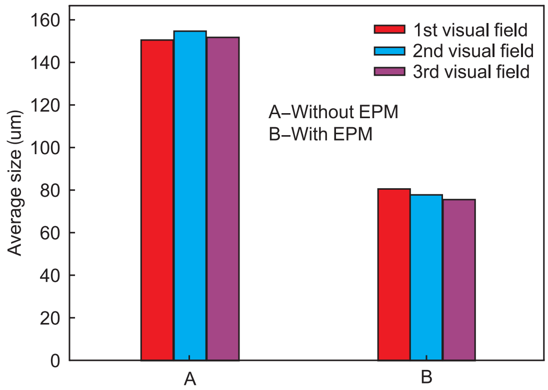

Fig 3: Average size of primary silicon of LM-29 alloy

The tensile test results of LM-29 alloy are as shown in Table 2, which illustrates that both yield strength (R_m) and elongation in percentage (A) of LM-29 alloy have increased obviously.

Table 2: Mechanical properties of LM-29 alloy

Sample No.	Untreated		Treated	
	R_m (MPa)	A (%)	R_m (MPa)	A (%)
1	164.3	1.4	189.6	1.7
2	151.6	1.3	195.4	1.8
3	161.7	1.4	168.1	1.5
4	136.4	1.2	185.2	1.6
5	142.9	1.2	205.8	1.9

Figure 4 shows freezing curves of the primary silicon phase by DSC. It illustrates that the precipitation temperature of primary silicon is 706.2 ℃ for the original sample, while it is decreased to 627.7 ℃ after EPM.

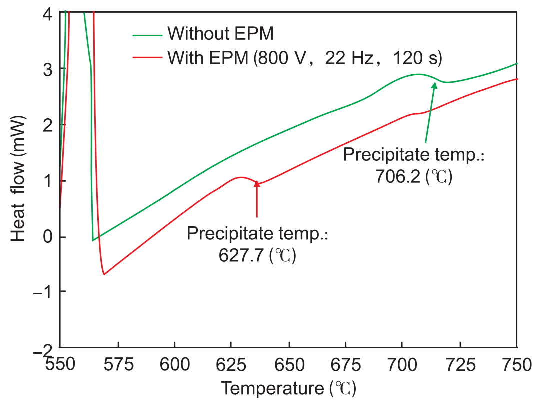

Fig 4: DSC curve showing the crystallization temperature of primary silicon

2.2 Discussion

The calculating by CompuTherm Pandat 7.0 software (DEMO Version) gives the result of the theoretical liquidus temperature of Al-Si alloy (22wt.%–25wt.%) is around 712–717 ℃, which is close to the value 706.2 ℃ of without EPM treatment. Figure 4 indicates that there exists significant difference (i.e. a supercooling degree) in the actual precipitation temperatures of primary silicon between the treatments without EPM (706.2 ℃) and with EPM (627.7 ℃). The primary phase of the sample treated by EPM was retarded 80 ℃ to precipitate than that of without EPM.

It is already known that many alloy melts slightly above liquidus such as Fe-based alloy melt can keep in a multi-phase metastable state for a long time [12-13]. As it was reported by Singh [14], lots of silicon atom clusters and refractory heterogeneous phases exist in liquid hypereutectic Al-Si alloy near the alloy liquidus, and the structure is very similar to that of the solid state. The thermodynamic analysis of silicon state in the melt was described in detail in a previous work [15]. It is a spontaneous process that the five fine tetrahedron clusters of agglomerate in a way of fivefold twinning and the polyhedron can act as a stable nucleus of primary silicon during solidification. The structure between the five petal star-shaped silicon and passive silicon is different. The former is overmatching in low overheated melt, which is also the carrier of structural heterogeneity of LM-29 alloy.

Based on atom cluster theory of liquid metal [7], the silicon clusters in liquid Al-Si alloy are described as colloid phase in the solution as in Fig.5 (a), in which the distribution of aggregative silicon clusters and cavities in the melt is heterogeneous. Under the action of electric pulse, the bonding strength of silicon atom clusters is destroyed gradually from strong to weak, as a result, the size of silicon cluster decreases. According to DLVO theory of colloid [16-17], smaller silicon clusters have much higher chemical potential than larger ones, so the solubility of smaller clusters in the alloy melt is bigger than larger ones accordingly, and the relationship between activity (effective concentration) and chemical potential is as follows:

$$\mu_i = \mu_0(T) + RT\, ln a_i \quad (2)$$

Where, μ_i is the chemical potential of element i, $\mu_0(T)$ is the standard chemical potential of element i at temperature of T, a_i is the activity of element i. Equation (2) shows that activity of element increases with chemical potential, and the chemical potential gradient is the drive force for atom diffusion [18], i.e., electric pulse makes the passivated silicon particles more active, then promotes the dissolution of refractory silicon into the aluminum melt. The sketch map of modification was shown in Fig. 5(b). At last, the heredity of raw material faded partly, thus leads to the LM-29 alloy melt more homogeneous in both structure and composition. Subsequently, it is more difficult for primary silicon particles to precipitate from the melt matrix for the well intermiscibility according to the analysis above, so there is a time delay to meet the demand of supercooling degree in DSC curve after the alloy treated by electric pulse, which is in good agreement with the DSC result.

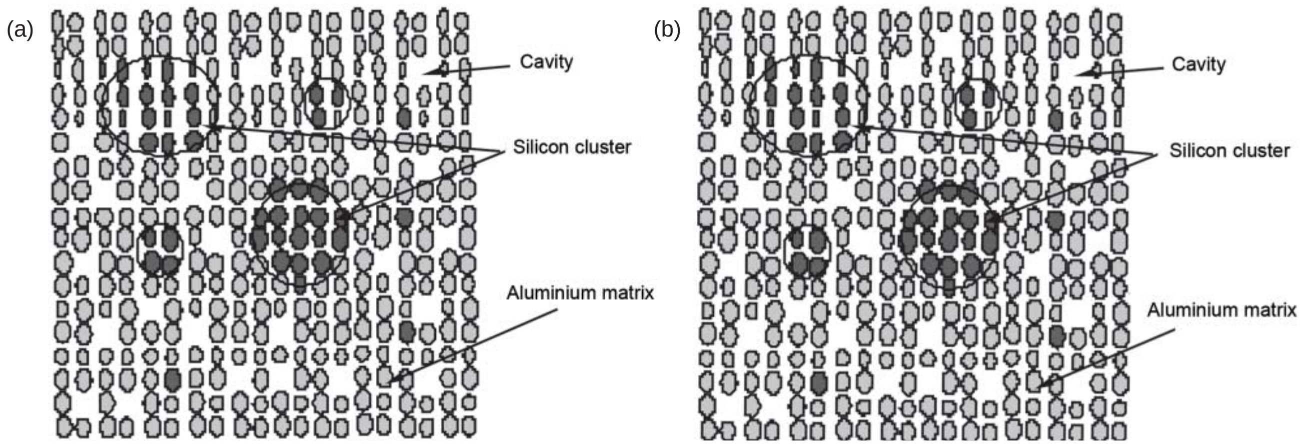

Fig 5: Sketch map showing the structure of melt untreated (a) and treated (b) by electric pulse

During solidification, freezing point of alloy reflects the acting force of components A and B in the alloy. With component B dissolves in pure A melt, the solidification supercooling can be represented as ΔT [19]:

$$\Delta T = \frac{RT_A^2}{\Delta H_A} \cdot \frac{M_A}{100} \cdot \frac{1}{M_B} \cdot C_l (1 - K_0) \quad (3)$$

Where, T_A, ΔH_A, M_A is the melting point, latent heat and atomic mass of component A, M_B is the atomic mass of component B, K_0 is the solute equilibrium partition coefficient, C_l is the solute concentration, R is the gas constant. As electric current promotes the dissolution process of silicon particle into the melt, then improves the homogeneity of the melt, so induces the combination between Si atom clusters and alloy melt stronger. It means that the effective solution concentration C_l increases, according to the Eq. (3), the supercooling degree ΔT also increases correspondingly. Therefore, during solidification process after EPM, the primary phase precipitates at a lower temperature.

3 Conclusions

(1) The primary silicon of LM-29 alloy was remarkably refined by applying EPM in the overheated melt, with its average size decreased from 152.76 μm to 78.21 μm.

(2) Electric pulse, as one of physical catalytic methods, increases dissolution of the metastable silicon clusters, and promotes the structural and compositional homogeneity of LM-29 alloy melt.

(3) By applying external electric pulse into the melt of LM-29 alloy the precipitation temperature of primary silicon was decreased around 80 ℃, which is recognized as an important role on the refinement of primary silicon.

References

[1] Misra A K. A novel solidification technique of metals and alloy under the Influence of applied potential. Metallurgical and Materials Transactions A, 1985, 16: 1354–1357.

[2] Ohmi T, Kudoh M. Formation of fine primary silicon crystals by mixing of semi-solid slurry of hypoeutectic Al-Si alloy and phosphorus-added hypereutectic Al-Si alloy melt. J. Japan Inst. Metals, 1994, 58(3): 324–329.

[3] Geng Haoran, Ma Jiaji, Bian Xiufang. Thermal rate treatment and its effect on modification of Al-Si alloy. Trans. Nonferrous Met. Soc. China, 1997, 7(1): 137–141.

[4] He Shuxian, Wang Jun, Sun Baode, et al. Effect of composition on A356 alloy processed by melt temperature treatment. The Chinese Journal of Nonferrous Metals, 2002, 12(4):769–773. (in Chinese)

[5] Wang Jianzhong, He Lijia, et al. Research of EET on the Al-22%Si alloy under the action of electric pulse. Science in China (Series E), 2008, 51(2): 1–9.

[6] Wang Jun, He Shuxian, Sun Baode, et al. Effects of melt thermal treatment on hypoeutectic Al-Si alloys. Materials Science and Engineering A, 2002, A338: 101–107.

[7] Wang Jianzhong, Qi Jingang. Heredity of aluminum melt by electric pulse modification (I). Journal of Iron and Steel Research International, 2007, 14(4): 75–78.

[8] Tang Yong, Wang Jianzhong. Effect of pulse electric discharging on solidification structure of high carbon steel. Journal of Iron and Steel Research, 1999, 11(4): 44–47. (in Chinese)

[9] Tang Yong, Wang Jianzhong. Improvement of T8 steel solidification structure by electro pulse treatment. Journal of Beijing University of Science and Technology, 2000, 22(4): 307–311.

[10] Wang Jianzhong, Chen Qingfu. Effect of electropulse modification parameters on ingot macrostructure of Cu-Al-Ni shape memory alloys. Trans. Nonferrous Met. Soc. China, 2002, 12(3): 400–403.

[11] Gui Manchang. Influences of liquid superheating treatment on the structure and mechanical properties of hypereutectic Al-Si alloys. Journal of Aeronautical Materials, 1996, 16(1): 26–31. (in Chinese)

[12] Sidorov V E. Physical properties of some iron based alloys in liquid and amorphous states. Journal of Material Science, 2000, 35: 2255–2262

[13] Dahlborg U, Calvo-Dahlborg M. Structure and properties of some glass-forming liquid alloys. The European Physical Journal B, Condensed Matter. Physics, 2000, 14(4): 639–648.

[14] Singh M, Kumar R. Structure of liquid aluminium-silicon alloys. Journal of Materials Science, 1973, 8(3): 317-323

[15] Gui Manchang. Nucleating mechanism of five petal star-shaped primary silicon. Acta Metall. Sin., 1996, 32(11): 1177–1183

[16] Derjaguin B V, Landau L D. Theory of the stability of strongly charged lyophobic sols and of the adhesion of strongly charged particles in solutions of electrolytes. Acta Physicochim., 1941, 14: 633–662.

[17] Verwey E J W, Overbeek J Th G, Van Nes K. Theory of the Stability of Lyophobic Colloids. New York: Elsevier, 1948.

[18] Israelachvili J. Intermolecular and Surface Forces. London: Academic Press, 1985.

[19] Hu Hanqi. Metal Solidification. Beijing: China Machine Press, 1985. (in Chinese)

This work is financially supported by the National Natural Science Foundation of China (No. 50674054), and the Doctorate Foundation of Science and Technology Department, Liaoning Province (20081097).