Effect of electric pulse modification on microstructure and properties of Ni-rich Al-Si piston alloy

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Abstract: In order to improve the properties of Ni-rich (2.5wt.%) Al-Si piston alloy, electric pulse modification was applied in fabricating the Ni-rich Al-Si piston alloy in this study. The effect of electric pulse modification on the mechanical properties of the Ni-rich Al-Si piston alloy was studied using optical microscope (OM), scanning electron microscope (SEM), X-ray diffraction (XRD), microhardness measurement and tensile strength testing. The results showed that the microstructures of Ni-rich Al-Si piston alloy treated by electric pulse modification were refined, the solid solubility of Cu, Ni, Si, etc. in α -Al matrix was improved, and furthermore, the microhardness and high-temperature tensile strength were increased by 9.41% and 17.5%, respectively. The distribution of second phases was also more uniform compared with that of a non-modified sample.

Key words: Al-Si; piston; phase structure; microhardness

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Piston is one of the most important components in an engine, and the choice and optimization of piston materials are key to determine overall engine quality^[1]. Recently, the Al-Si alloy piston has become the preferred choice for vehicle engines because of its low density and good wear resistance. However, the low strength of this material at high temperature restricts its further application. It is well known that grain refinement and high-temperature precipitates are important for obtaining better mechanical properties of the Al-Si piston alloy. High-temperature strengthening phases are formed by adding suitable alloying elements. Ni, as a main alloying element, has a considerable influence on room-temperature and high-temperature strengthening phases, especially on the high-temperature strength and volume stability characteristics. However, coarse bonding and skeleton Ni-rich precipitates appear with uneven distribution when an excessive Ni content is added (> 2wt.%), which is detrimental to the piston matrix^[1].

Electric pulse modification (EPM), a new type of controlling solidification technology, has drawn attention

because of its advantages such as non-pollution, flexible methods, convenient operation and lower investment. A large number of examinations have shown that EPM is a particularly effective method for the modification and refinement of Al alloys^[2-4]. In the present research, Ni-rich (2.5wt.%) Al-Si piston alloys were fabricated using EPM. The influences of EPM parameters on the microstructure and properties of the Ni-rich Al-Si piston alloy were analyzed in detail.

1 Experimental procedure

Experimental samples, containing Al-13%Si-3.7%Cu-2.5%Ni-1%Mg-0.12%Ti-0.12%Mn(wt.%), were prepared by the controlled melting of high-purity aluminum, nickel, electrolytic copper, manganese, Al-28wt.%Si and Al-10wt.%Mg master alloys in a graphite crucible using a muffle furnace. These raw materials were melted at a temperature of ~750 °C, and the liquid metal was degassed with C₂Cl₆ for 5 min, and the dreg flux was removed. Then, high-purity graphite electrodes that had been heated at 400 °C for 2 min were inserted vertically into the crucible filled with liquid metal at the corresponding superheated temperature. EPM was applied to the melt for 30 s with a fixed pulse frequency of 3 Hz and varying pulse voltage. The pulse voltage was set at 0, 300 V, 500 V and 700 V, corresponding to sample A, sample B, sample C and sample D,

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respectively. This was followed by casting the melt in a metallic mould.

All specimens were prepared by mechanical polishing for primary analysis. The microstructures of the specimens were examined using an optical microscope (Axiovert-2000MAT) and a scanning electron microscope (SEM, S-3000) equipped with an energy-dispersive X-ray spectroscopy (EDS). The microhardness tests and phase structure analysis were conducted using a microhardness tester (HV-1000) and X-ray diffraction (D/max-2500/pc), respectively. Finally, the high-temperature (350 °C) tensile strength of the specimens was tested in a universal testing set-up using three-point bending with a 120-mm span between the supports and an indenter rate of 5 mm min⁻¹.

2 Results and discussion

2.1 Grain refinement of Ni-rich Al-Si piston alloy

Figure 1 shows the microstructures of the Ni-rich Al-Si piston alloy treated at various pulse voltages. The phases in the

microstructures are marked, including α -Al, primary Si, eutectic Si, and Ni-rich phases. The solidification structure of the Al-Si piston alloy without EPM is shown in Fig. 1(a). Coarse and angular primary Si phases are unevenly distributed in the matrix and large eutectic Si phases with acute angles are randomly distributed in the matrix. The coarse floccules and Ni-rich phases grow in a divergent manner along α -Al dendrite crystals. In addition, a large number of α -Al dendrites exist in sample A without EPM. Figure 1 (b-d) display the microstructure of Al-Si piston alloy with EPM. Compared with the sample A (without EPM), these samples with EPM have a smaller primary Si size which decreases with the increasing pulse voltage. These coarse α -Al dendrite crystals disappear in the samples treated by EPM. The floccules of Ni-rich high-temperature phases well-distributed around the α -Al phases are refined in the Ni-rich Al-Si piston alloy treated by EPM. As has been reported in previous studies^[3], the grain refinement caused by the EPM is due to the repetitive high-frequency oscillation of the electric pulse that makes Si clusters change to smaller sizes with an increased number of Al clusters. That is to say, the growth of the Si clusters is restrained and α -Al nucleation rate is increased, resulting in disappearance of the α -Al dendrite crystals.

Fig. 1: Micrographs of Ni-rich Al-Si piston alloy treated at different pulse voltages (V): (a) 0; (b) 300; (c) 500; (d) 700

In order to analyze the morphology of the Ni-rich high-temperature strengthening phases, SEM images of the samples are shown in Fig. 2 for comparison. The Ni-rich high-temperature strengthening phases are present in the form of coarse fish-bone-like structures in the unmodified Al-Si alloy (Fig. 2a). Figure 2(b) is the SEM image from the Al-Si alloy sample treated with EPM. The fish-bone-like Ni-rich high-

temperature strengthening phase has cracked and the coarse strengthening phases are uniformly distributed in the matrix. This suggests that EPM causes the Ni-rich high-temperature strengthening phases to be refined and evenly distributed. It is well known that a large amount of Ni accumulates at the solid-liquid interfaces of α -Al phases during the solidification of Al-Si piston alloy. Hence, Ni-rich high-temperature strengthening

phases are usually formed at the boundaries of the α -Al dendrite crystals. In other words, the boundaries of the α -Al dendrite crystals are delineated by Ni-rich high-temperature strengthening phases, which keep nucleating at the end of the eutectic Si phase and growing along the α -Al dendrite crystal boundaries, as shown in Fig. 1. Dendrite crystals α -Al phase are refined by using EPM, leading to the refinement of the Ni-rich phases, as shown in Fig. 2.

Fig. 2: SEM images of Ni-rich high-temperature phase in non-EPM sample (a) and EPM sample at pulse voltage of 300 V (b)

2.2 Element distribution and phase structure

Table 1 shows distribution of elements in α -Al phase matrix with or without EPM. The predominant elements of Ni-rich Al-Si alloys with or without EPM are Al, Si, Mg, Ni, and Cu. The contents of these alloy elements (Si, Ni, Cu, Mg) increased in α -Al phase matrix with EPM compared with that in the Al-Si alloys without EPM. It can be deduced that the solid solubility of Cu, Ni, Si and Mg in α -Al matrix were improved after the Ni-rich Al-Si alloy were treated by EPM. The Cu and Ni distributions are shown in Fig. 3. The coarse Ni-rich phases appeared around α -Al phase. The well-distributed alloy elements were spread throughout the matrix, in contrast to the distribution in the un-modified sample.

Table 1: Elements distribution of α -Al phase matrix with or without EPM

Sample	Al (wt.%)	Si (wt.%)	Ni (wt.%)	Cu (wt.%)	Mg (wt.%)
A	87.12	10.53	1.03	0.34	0.64
B	85.64	11.29	1.45	0.56	0.77

Fig. 3: Surface scanning images of Cu and Ni in samples without EPM (a) and with EPM at pulse voltages of 300 V (b)

Figure 4 shows XRD patterns taken from Ni-rich Al-Si piston alloys treated at various pulse voltages. It is apparent that all the samples contain Al, Si, Mg_2Si , and $\text{Al}_7\text{Cu}_4\text{Ni}$ phases and no other phases are observed in XRD pattern, suggesting that the phase structure can not be affected by EPM. According to other studies^[5-7], the $\text{Al}_7\text{Cu}_4\text{Ni}$ phase as the coarse fish-bone-like phase observed in Fig. 2 is regarded as the primary high-temperature strengthening phase.

Fig. 4: XRD patterns of Ni-rich Al-Si piston alloys treated at different pulse voltages (V): (a) 0; (b) 300; (c) 500; (d) 700

2.3 High-temperature strengthening of Ni-rich Al-Si piston alloy

Figure 5 shows the microhardness of the Ni-rich Al-Si piston alloys treated at various pulse voltages. The microhardness of Ni-rich Al-Si piston alloys was improved with an increase in pulse voltage. When the pulse voltage was 700 V, the microhardness reached the maximal value at about 144.56 HV. Compared with the unmodified sample (132.12 HV), the microhardness increased by 9.41%, as shown in Fig. 5. The improvement in the microhardness of the α -Al matrix is mainly attributed to the increase in the solid solubility of alloy elements.

Fig. 5: Microhardness of Ni-rich Al-Si piston alloys treated at various pulse voltages

The results of the high-temperature tensile test conducted at 350 °C are shown in Fig. 6. It can be seen that the high-temperature tensile strength was increased significantly when the Al-Si piston alloy was treated by EPM. The high-temperature tensile strength of Al-Si piston alloy treated at pulse voltage of 700 V reached the maximal value (69.88 MPa), an increase of 17.5% over that of the Al-Si piston alloy without EPM (59.47 MPa). The high-temperature tensile strength of Al-Si piston alloy was improved due to the strengthening effect of high-temperature phases. It is well known that the second phase strengthening is the most effective high-temperature strengthening mechanism of Ni-rich Al-Si piston alloy. The intermetallic ($\text{Al}_7\text{Cu}_4\text{Ni}$) interaction with the grain boundaries makes considerable contributions to the high-temperature strength, depending on the nature, form, dimensions, and distribution of the second phases^[8,9]. The high-temperature strengthening phases in α -Al matrix were refined to more regularity without coarse and acute angles by means of EPM, and well-distributed as observed in Fig. 1. The refined and well-distributed high-temperature strengthening phases avoided

Fig. 6: High-temperature tensile strength of samples treated at different pulse voltages

the carving up of the matrixes during deformation, leading to improved high-temperature tensile strength.

3 Conclusions

Ni-rich Al-Si piston alloys were treated using EPM at different voltages. Variations of the microstructure and mechanical properties were investigated in detail. Key results can be summarized as follows:

(1) The solidification structure of the Ni-rich Al-Si piston alloy was refined and uniform distribution was obtained under various electric pulse parameters. When the pulse voltage was 700 V, the sizes of primary Si and eutectic Si were the smallest, and the $\text{Al}_7\text{Cu}_4\text{Ni}$ phase as the high-temperature strengthening phase was well distributed.

(2) The solid solubility of alloy elements including Cu, Ni, Si and Mg was improved in α -Al matrix. The microhardness and high-temperature tensile strength increased by 9.41% and 17.5%, respectively, after the Al-Si piston alloy was treated with EPM at the pulse voltage of 700 V.

References

- [1] Li Yun-guo. The study of elevated-temperature strengthening phases of Al-Si-Cu-Ni-Mg piston alloy. Ph.D. thesis, Shandong University, Shandong, China, 2011. (In Chinese)
- [2] Wang Jian-Zhong, He Li-jia, Lin Cheng, et al. EET research on the Al-22%Si alloy under the action of electric pulses. Science in China (Series E), 2008, 51(11): 1930–1938. (In Chinese)
- [3] Qi Jin-gang, Wang Jian-zhong, Du Hui-ling, et al. Heredity (II) of Aluminum Melt by Electric Pulse Modification. Journal of Iron and Steel Research International, 2007, 14(5): 76–78.
- [4] Wang Jian-zhong, Qi Jin-gang, Du Hui-ling, et al. Heredity (I) of Aluminum Melt by Electric Pulse Modification. Journal of Iron and Steel Research International, 2007, 14(4): 75–78.
- [5] Dey S K, Perry T A, Alpas A T. Micromechanics of low load wear in an Al-18.5% Si alloy. Wear, 2009, 267: 515–524.
- [6] Chen C L and Thomson R C. Study on thermal expansion of intermetallics in multicomponent AlSi alloys by high temperature X-ray diffraction. Intermetallics, 2010, 18: 1750–1757.
- [7] Chen C L and Thomson R C. The combined use of EBSD and EDX analyses for the identification of complex intermetallic phases in multicomponent Al-Si piston alloys. Journal of Alloys and Compounds, 2010, 490: 293–300.
- [8] Guo Yuan-jun, Zhang Dao, Xiao Yang, et al. Influence of Ni Element on Microstructure and Properties of Hypereutectic Al-Si Alloy. Material & Heat Treatment, 2012, 41(22): 88–93. (In Chinese)
- [9] Li Bing-chao. The study of fatigue properties of Al-Si piston alloy and its composite. Ph.D. thesis, Shandong University, Jinan, China, 2013. (In Chinese)