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High-Current Pulsed Electron Treatment of Hypoeutectic Al–10Si Alloy

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Abstract: This paper reports, for the first time, an analysis of the effect of high-current pulsed electron beam (HCPEB) on a hypoeutectic Al–10Si alloy. The Al–10Si alloy was treated by HCPEB in order to see the potential of this fairly recent technique in modifying its wear resistance. For the beam energy density of 3 J/cm^2 used in the present work, the melting mode was operative and led to the formation of a “wavy” surface and the absence of mass primary Si phase and eutectic microstructure. The surface nanocrystallization of primary and eutectic Si phases led to the increase in macro-hardness of the top surface layer, and the wear resistance was drastically improved with a factor of 4.

Keywords: high-current pulsed electron beam, hypoeutectic Al–Si alloy, wear resistance

Introduction

High-current pulsed electron beam (HCPEB) has been developed rapidly as a new high-power energetic beam used for surface modification of materials in the last 10 years owing to its simple, reliable, high efficiency and so on [1–9]. In this paper, hypoeutectic Al–10Si alloy was treated by HCPEB in order to see the effect of solid solution of massive Si phase and eutectic Si phase on its macro-hardness and wear resistance.

Hypoeutectic Al–Si alloys, acting as a kind of important as-cast alloy, are extensively applied in the automobile and aerospace fields on account of their excellent properties. But, in casting structure, few primary and coarse eutectic Si phase breaks the matrix continuity and causes poor properties that restrict application to a great extent. The refinement of coarse eutectic Si phase for hypereutectic Al–Si alloys has been researched for a long time by means of adding modifiers [10, 11]. However, there are few reports about surface modification of hypoeutectic Al–Si alloys through HCPEB treatment.

Thus, in this paper, we study the microstructure of surface layer in a hypoeutectic Al–10Si alloy using HCPEB treatment and its effect on macro-hardness and wear resistance, which indicates an important development direction of HCPEB technology in material surface modification in the future.

Experimental procedures

Sample preparation and HCPEB parameters

The hypoeutectic Al–10Si alloy used in the present research was prepared in a resistance furnace using a high-purified graphite crucible. Its chemical composition (in wt %) is as follows: Si 10 and Al balance. The samples for HCPEB treatment were cut into a number of cylinders (Φ10 mm × 9 cm height). Then the sample surfaces were ground with sandpapers and polished with diamond paste. The HCPEB treatment process was carried out in a vacuum chamber with pressure of 5×10^{-3} Pa using a Russia-made “Nadezhda-2” source. More details on its working mechanism were given in Ref. [1]. The accelerating voltage of HCPEB was 27 kV, energy density was ~3 J/cm^2, pulse duration was ~1 μs and irradiated number was 5, 15, 25 and 35.

Microstructural examination and macro-hardness and wear test

Surface observations of the initial and HCPEB-treated samples were performed on a SSX-550 scanning electron microscope (SEM). Wear tests were carried out using a MG-2000-type pin-on disc machine with intelligent control system of Vi software (Lab 6.1 version). The pin specimens were machined in the form of cylinders with 6 mm diameter and 12 mm length. The counterpart discs were made of stainless steel (1Cr18Ni9) with surface hardness of 192HV and surface roughness of Ra = 1 μm. The applied load was 10 N. Sliding speed and distance were kept constant at 0.8 m/s and 0.5 km. Macro-hardness was tested on a universal hardness tester (UH750).

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Results and discussion

Surface microstructure characteristics of hypoeutectic Al–10Si alloy before and after HCPEB

Figure 1 gives typical surface morphology micrographs of Al–10Si alloy before HCPEB treatment. It can be seen that the microstructure of initial sample is made of a small quantity of coarse primary Si phase and needle-like eutectic microstructure; the matrix is comprised of coarse α(Al) dendrite.

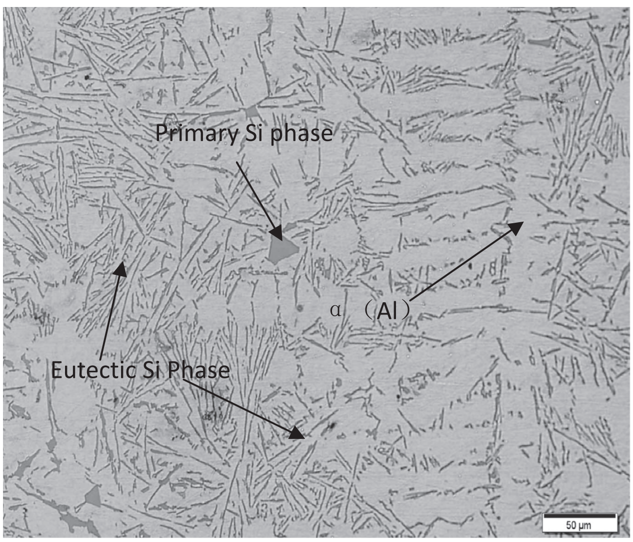

Figure 1: Optical image of initial hypoeutectic Al–10Si alloy.

Figure 2 gives the surface morphologies of HCPEB-treated samples under different number of pulses (5, 15, 25 and 35). It can be seen that the primary and eutectic Si phase completely disappears on all irradiated surfaces, and fine α(Al) dendrite and pure aluminum particle distributed on the top melted surface. Meantime, the special microstructure "crater" induced by HCPEB can be found on the 15-, 25- and 35-pulse-treated sample surface. The size of α(Al) grain is refined to about 5–10 μm. As a result, a supersaturated solid solution of Al is formed in the near-surface layer. The chemical composition distribution of treated surface becomes more homogeneous.

Cross-sectional microstructure of hypoeutectic Al–10Si alloy after HCPEB treatment

Figure 3 gives cross-sectional SEM images of Al–10Si alloy after HCPEB treatment. Compared with the matrix, the remelted layers with different microstructure characteristics can be observed obviously, as shown in Figure 3 (a, b). After HCPEB treatment, the remelted layer is formed on the top surface of modified sample, which presents single contrast due to composition homogeneity. It can be seen there is no evident distinction between Al phase and Si phase, and a supersaturated solid solution of Al is formed after HCPEB irradiation. Furthermore, the thickness of remelted layer is

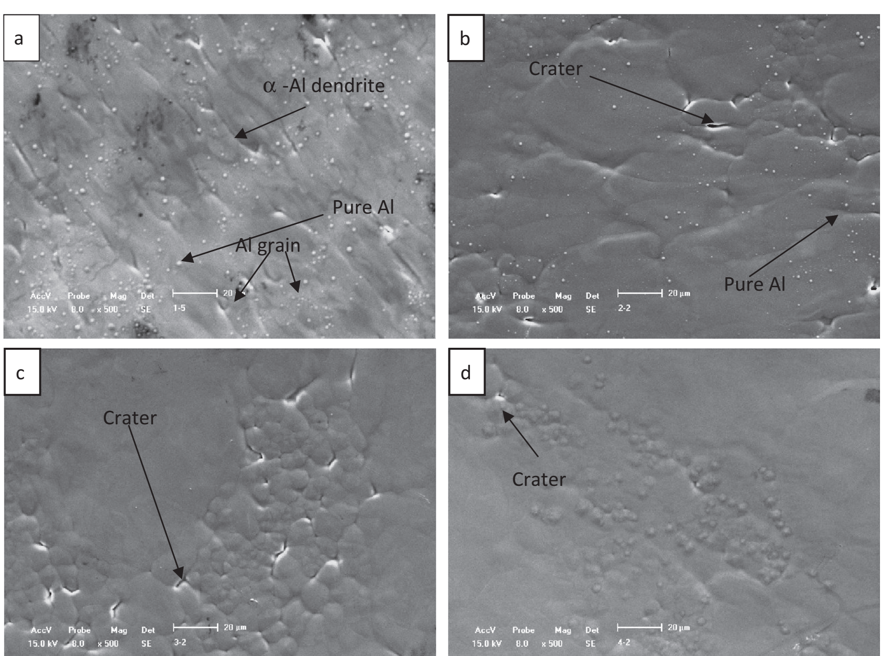

Figure 2: Surface SEM image of HCPEB-treated hypoeutectic Al–10Si alloy under different pulse numbers: (a) 5 pulses, (b) 15 pulses, (c) 25 pulses and (d) 35 pulses.

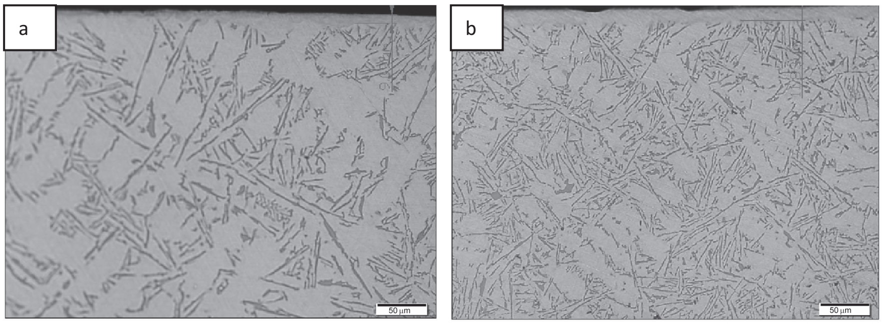

Figure 3: Cross-sectional SEM images of hypoeutectic Al–10Si alloy after HCPEB treatment: (a) 5 pulses and (b) 15 pulses.

increased slightly with increasing the number of HCPEB pulses. For five pulses, the thickness of remelted layer is about 9.09 μm, while it reaches about 11.83 μm after 15 pulses. The phenomenon that thickness of remelted layer increases with the increase of pulse number is similar with the results of HCPEB-treated DZ4 and steel samples [12, 13]. The effect of heat accumulation in the underlying substrate materials is considered as a reasonable explanation for increased thickness of the remelted layer with multiple pulses of short interval. Meantime, it can be seen that the melted layer is very compact and there are few microcracks and it is beneficial for the improvement of wear resistance of HCPEB-treated samples.

Macro-hardness of hypoeutectic Al–10Si alloy before and after HCPEB treatment

Figure 4 shows the macro-hardness changes in the hypoeutectic Al–10Si alloy before and after HCPEB treatment. The hardness of the hypoeutectic Al–10Si is improved with a factor of 20 % from 1,454 MPa of initial sample to 1,752 MPa of 35-pulse-treated sample. Meanwhile, the hardness of 5-, 15- and 35-pulse-treated samples is also improved significantly. This variation can be interpreted from fine grain strengthening effect and solution strengthening effect induced by the formation of Al supersaturated solid solution.

Wear test

The weight loss was measured before and after HCPEB treatment. Figure 5 gives the variations in weight loss of untreated and treated Al–10Si alloy with different number of pulses. It can be seen that the weight loss is reduced from 0.8×10^{-3} g for the untreated sample to 0.2×10^{-3} g for the 15- and 25-pulsed samples, showing a significant improvement of the sliding wear resistance of Al–10Si alloy after HCPEB treatment. Compared with initial sample, the weight loss of sample declines by 75 % after 15 and 25 pulses, and relative wear resistance is improved with a factor of 4. The results can be explained as follows: (i) the formation of supersaturated solid solution of Al is a main reason for enhanced wear resistance and (ii) refinement of Si phase and Al matrix in the surface layer has hardening effect on wear property.

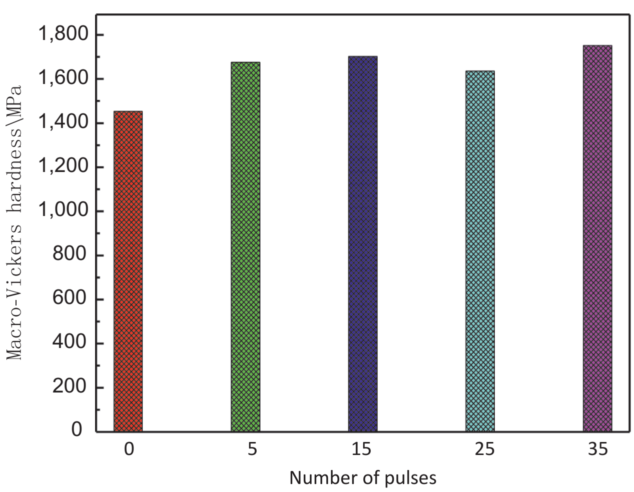

Figure 4: Evolution of macro-hardness of hypoeutectic Al–10Si alloy with number of pulses.

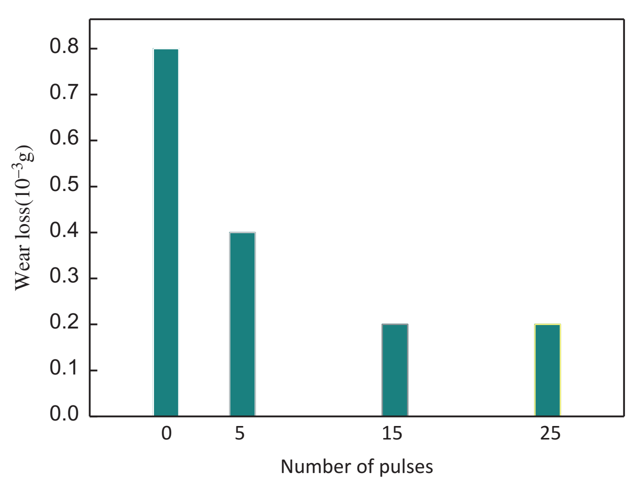

Figure 5: Evolution of wear loss of hypoeutectic Al–10Si alloy with number of pulses.

Conclusions

The work has examined the effect of HCPEB treatment on modifying a hypereutectic Al–10Si alloy surface in order to investigate wear resistance. The main conclusions are summarized as follows:

(1) After HCPEB irradiation, the primary and eutectic Si phases disappear completely due to solid solution of Si into α(Al) matrix. The chemical composition intends to be distributed uniformly.

(2) The remelted layer presents single contrast owing to composition homogeneity, and a supersaturated solid solution of Al is formed in the near-surface layer after HCPEB treatment. The thickness of remelted layer is increased slightly from 9.09 μm of 5-pulsed sample to 11.83 μm of 15-pulsed sample.

(3) After HCPEB treatment, the macro-hardness and wear resistance are improved significantly. The best wear resistance of Al–10Si alloy surface is obtained for the 15- and 25-pulsed treatment, and relative wear resistance is improved by a factor of 4.

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