Deformation twining in single-crystal aluminum induced by high-current pulsed electron beam

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Deformation twinning is a common and important mechanism for plastic deformation in hcp metals. In bcc metals, it occurs at low temperature where it becomes more favorable than dislocation-based slip processes [1]. In fcc metals deformation twinning is more rare. It normally requires low temperatures and high stresses or strain rates, although some fcc alloys twin more readily [2]. Of the fcc metals, pure aluminum and lead were traditionally cited as examples of metals that do not exhibit deformation twinning at all [3]. However, more recently, experimental work has indicated that deformation twinning does occur in aluminum under certain conditions.

In 1981, Pond and Garcia-Garcia [4] found the first evidence of deformation twinning in high purity aluminum. The twin was found at the tip of an edge crack in a transmission electron microscopy (TEM) foil. TEM investigation of the crack tip revealed a deformation twin approximately 1500 nm long oriented along the $[1\bar{1}2]$ direction with a $(1\bar{1}1)$ twin plane. The twin is thought to have formed by the emission of 1/6[121] partial dislocations on successive $(1\bar{1}1)$ planes. The tip of the twin is blunted and this is attributed to a dislocation reaction involving the leading three twinning dislocations resulting in the formation of residual and emissary dislocations. A more recent demonstration of deformation twinning in aluminum was obtained by Chen *et al*. [5] in 1999.

High-current pulsed electron beams, a new type of surface modification technique developed over the last decade [6, 7], render the treated materials with nouveau properties such as high surface hardness and high wear and corrosion resistance [7]. During the transient bombardment process a high energy (10^8–10^9 W/cm^2) is deposited only in a very thin layer (less than tens of micrometers) within a short time (a few microseconds) and causes superfast heating, melting, evaporation, and solidification. The dynamic stress fields induced in these processes cause intense deformation processes in the surface of material. Such pulsed beams deposit energy in a violent manner unattainable with conventional methods. New structure phenomena would be expected.

In this paper, we report the formation of deformation twin in the near-surface layer of single-crystal aluminum induced by the high-current pulsed electron beam (HCPEB) technique.

A schematic diagram of the HCPEB source (Nadezhda-2) is given in Fig. 1. It produces an electron beam of low energy (10–40 KeV), high peak current (10^2–10^3 A/cm^2), short pulsed duration of about 1 μs, and high efficiency (repeating pulse interval being 10 s). The electron beam is generated by an explosive emission cathode. The cathode-target distance and the energy control the beam energy density and hence the treatment effects. For more details about the HCPEB system, the readers are referred to Proskurovsky *et al.* [6, 7].

Bulk single-crystal aluminum specimens were selected as the target material. Single-crystal rod of pure 99.999% aluminum of 20 mm in diameter was provided by Metal Research Institute of Chinese Academy of Sciences. Specimens with the desired orientation (111) were cut by spark erosion with size 12 mm in length, 10 mm in width, and 10 mm in height, and one side surface was mirror polished. The polished surface of samples was irradiated using this high current pulsed electron beam source. The HCPEB bombardments were carried out under the following conditions: the electron energy 20 keV, the current pulse duration 1.5 μs, the energy density about 1 Jcm^{-2}, and the vacuum 10^{-5} Torr. The surface morphology was observed by using a JSM-5310 SEM with energy dispersive spectroscopy (EDS). The TEM observation was carried out in a H-800 TEM operating at an acceleration voltage of 175 kV.

A typical EDS result on the surface of the single-crystal aluminum specimen irradiated by various processing conditions is shown in Fig. 2, no trace of oxygen element was found. It is revealed that the specimens did

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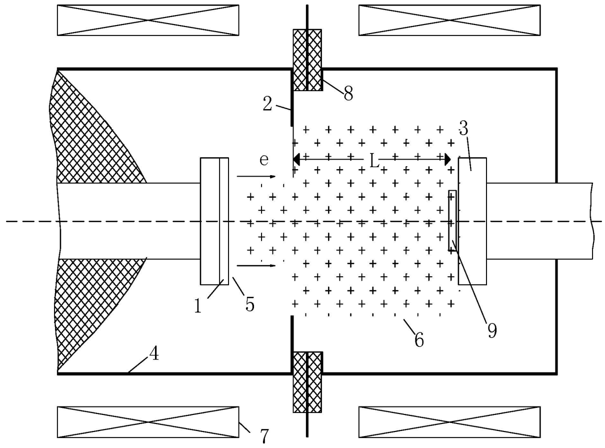

Figure 1 Schematic diagram of the HCPEB source using plasma filled systems based on vacuum spark plasma. (1) cathode, (2) anode, (3) collector, (4) vacuum-chamber, (5) cathode plasma, (6) anode plasma, (7) solenoid, (8) spark source, (9) specimen.

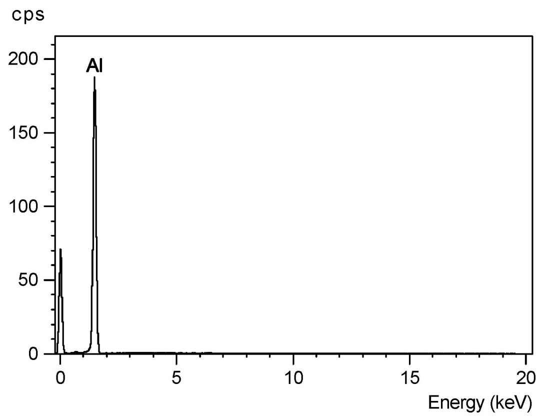

Figure 2 EDS result on the surface of the single-crystal aluminum specimen irradiated with 5 pulses.

not undergo an oxidation processing during the HCPEB irradiation.

The surface SEM morphology of the specimen irradiated with 1 pulse and 5 pulses at about 1 Jcm^{-2} energy density are shown in Fig. 3, respectively. It can be seen that no melting evidence occurs on the surface. After 1 pulse, the white intersecting strips were formed on the surface. In generally, the strips are with approximately 200–400 μm long and 2–5 μm wide, as shown in Fig. 3a and b. From Fig. 3a, one can see that there is a small displacement after two strips intersected.

After 5 pulses, the lens shape (or martensite-like) strips with approximately 200 μm length and 10 μm width were observed. Most of the strips are parallel to each other, as shown in Fig. 3c. The magnification image of the lens shape strips, as shown in Fig. 3d, reveals that the strips are regularly parallel with a median ridge in it. Fig. 3d also shows that some strips are broken (indicated by arrows), and there is evident apart space between the two sides of the arrow. It suggests that very high stress is concentrated in the strips. The lens shape of the strips is reminiscent of the typical twin lamellae feature. Fig. 4 shows the SEM morphology of cross section etched by hydrofluoric acid and ethanol solution of 1 pulse and 5 pulses, respectively. In Fig. 4a, evident changes in microstructure occurred in the depth of approximately 50–80 μm from

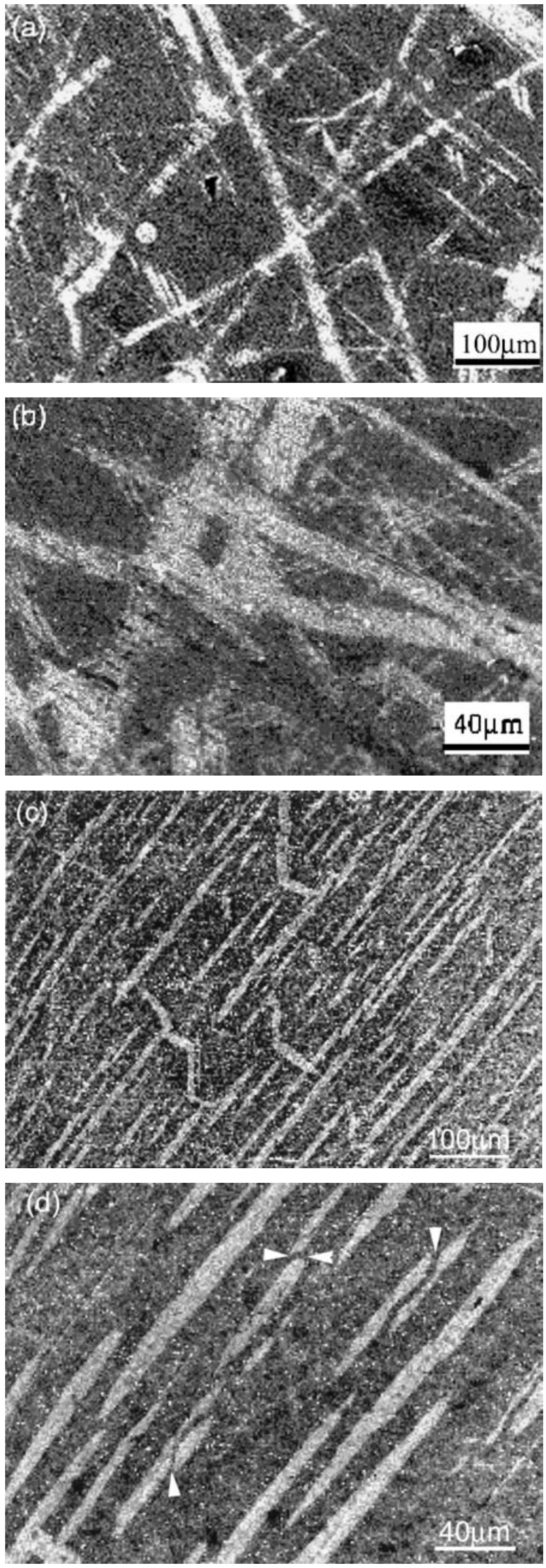

Figure 3 SEM images of the surface of the specimens irradiated with 1 and 5-pulses by HCPEB. (a) 1-Pulse, (b) higher magnification of (a), (c) 5-pulses and (d) higher magnification of (c).

the surface after 1 pulse treatment, and 250–300 μm in the case of 5 pulses (Fig. 4b). Obviously, the microstructure changes are not caused only by the thermal effects produced by HCPEB treatment, since the thermal effect of pulsed electron beams at large could reach 50 μm [6, 7]. The thermal expansion inside steep

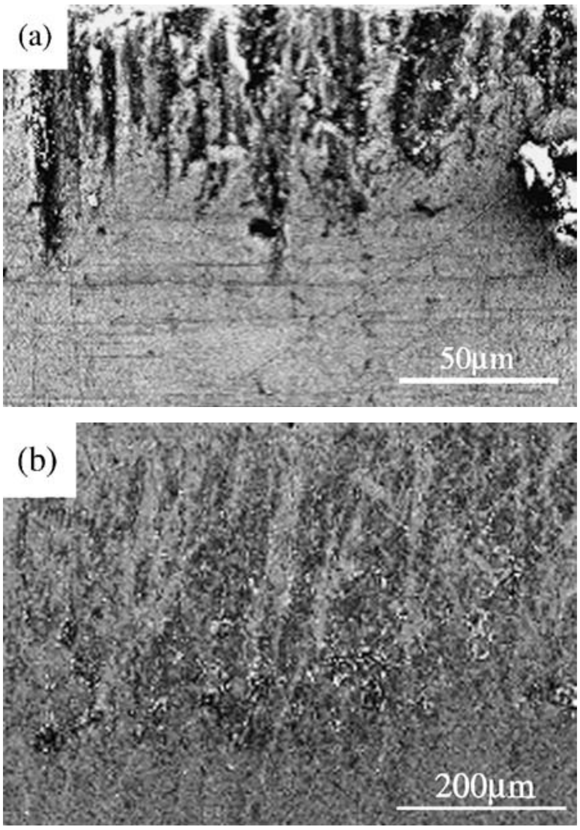

Figure 4 SEM imagess of the cross-section of the specimens irradiated with 1 and 5-pulses by HCPEB. (a) 1-Pulse, (b) 5-pulses.

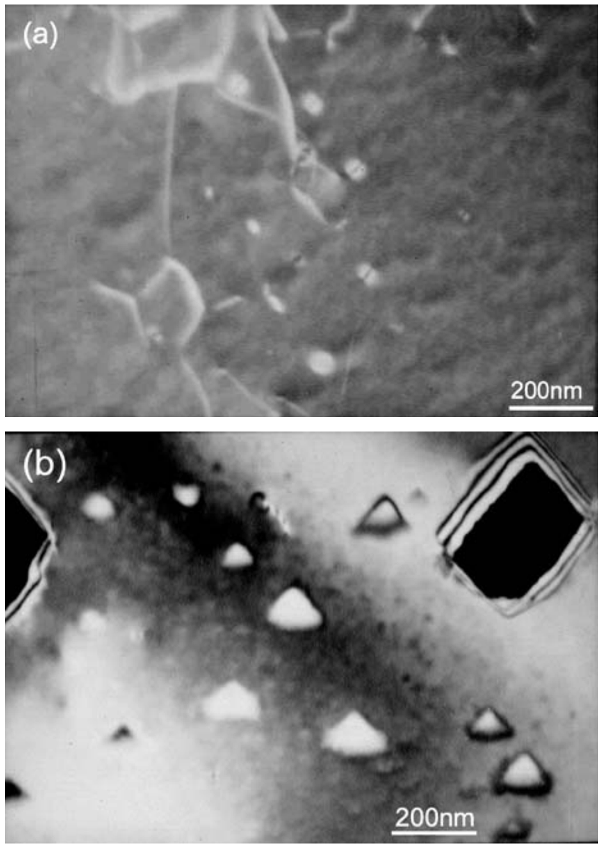

Figure 5 TEM dark-field image with vector g (220) of the specimen irradiated 1 and 5 pulses by HCPEB. (a) Showing dislocation loops induced after 1 pulse, (b) Showing SFTs and voids after 1 pulses.

temperature field in the surface layer and/or stress emission by twin lamellae appear to cause the obvious microstructure changes of cross-section morphology. In order to have a clear picture of the strips, the thin foils for the transmission electron microscopy (TEM) observation were obtained by mechanical pre-thinning, dimpling, and jet electrolytical thinning from the substrate side. Unfortunately, no twin structure was found and dislocation was seldom observed. The trace of the dislocation slipping was also completely absent in the foils. However, the vacancy cluster defects including dislocation loop, stacking fault tetrahedra (SFT) and void were observed, as shown in Figs 5a and b. The most striking result is the formation of SFT even in single-crystal aluminum. Details about the results have been discussed elsewhere [8]. According to the preparation method of the foils, it suggests that the strip zones on the surfaces are thinner than 0.5 μm. Further delicate preparations of the TEM foils are planned.

Although no direct crystallographic evidence is presented to confirm that twins formed, but the morphologies observed in SEM are typical deformation twins characteristic. It appears that high stresses and point defect populations arose during intense electron bombardment of a single crystal, leading to deformation twinning and formation of stacking-fault tetrahedra in the surface layer.

When an electron irradiated the target, due to drastic temperature change, a steep temperature gradient is generated along the incident direction of the beam. However, due to the lateral confinement along the surface, the thermal expansion in the directions vertical to the beam is strongly resisted, causing the surface thermal stress. This external force may be increased internal stress to an extraordinarily high level. However, the twin lamellae were usually absent in TEM observation since the thin foil samples are thinned to a thickness and the lateral confinement along the surface is no longer strong, which leads to the internal stress release.

As we know, there are mainly two kinds of plastic deformation for most metals, deformation twinning and dislocation slipping. In single-crystal aluminum, dislocation-based slip processes is a common and important mechanism for plastic deformation because aluminum is a kind of fcc metals with relatively high stacking faults energy. The present results, however, reveal that the deformation twins and a large number of small vacancy clusters without dislocations were formed in the near-surface of the aluminum single crystal irradiated by HCPEB. It suggests the possibility of plastic deformation of aluminum occurring without dislocations and clearly falls beyond the scope of the dislocation theory.

When the dislocation mechanism operates, internal stress is automatically relaxed and stress cannot increase, but when plastic deformation cannot proceed by dislocations, elastic deformation increases, accompanied by an increase in internal stress. When internal stress increases as high as enough, all atoms are brought to the conditions for moving to the next stable positions, while overcoming potential barriers from neighboring atoms. Here, displacement of atoms is not embodied by individual atoms, but is the shifting of atomic planes, along or close to the direction of the Burgers vectors (1/3<111>) in the glide planes of normal dislocations. Displacement of atomic planes under high stress does not operate by the propagation of localized reaction, but occurs simultaneously and result in the deformation twinning and formation of stacking-fault tetrahedra in the surface layer. This may be the real reason of the formation of deformation twins and stacking-fault tetrahedra in aluminium. Of course, further works are needed to investigate this.

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