Stacking fault tetrahedra in aluminum

Q. F. GUAN*, L. PAN, H. ZOU
State Key Laboratory of Superhard Materials and Department of Material Science and Engineering, Jilin University, Changchun, 130025, People's Republic of China; State Key Laboratory of Meterials Modification by Laser, Ion and Electron Beams, Dalian University of Technology, Dalian 116024, People's Republic of China
E-mail: guanqingfeng@jlu.edu.cn

A. M. WU, S. Z. HAO, Q. Y. ZHANG, C. DONG
State Key Laboratory of Meterials Modification by Laser, Ion and Electron Beams, Dalian University of Technology, Dalian 116024, People's Republic of China

G. T. ZOU
State Key Laboratory of Superhard Materials and Department of Material Science and Engineering, Jilin University, Changchun, 130025, People's Republic of China

It was well known that vacancy clusters exist in three types, namely voids, stacking fault tetrahedra (SFT) and vacancy-type dislocation loops. If metals are irradiated with highly energetic particles such as electrons, ions, or neutrons, some vacancy clusters are generally formed at appropriate conditions. However,it was believed that a face-center-cubic (fcc) metal which has high fault energy such as pure aluminum, which has highest fault energy, does not form the type of SFT defects. In fact, SFT was never observed in pure aluminum by irradiation methods.

SFT is a common type of structure defect originating from vacancy clustering. It is actually more frequently present than simple planar dislocation loops in the fcc metals with low-stacking fault energies [1–5]. The first observation of SFT by transmission electron microscope (TEM) dates back to about five decades [2]. This type of defect has the shape of four equilateral vacancy-type stacking faults on {111} planes intersecting along ⟨110⟩ edges to form a perfect tetrahedron [3, 4]. Experimentally, SFT is often present in quenched metals or in irradiated low-stacking fault energy metals where supply of vacancies is abundant [3, 4, 6].

High-current pulsed electron beams (HCPEB), a new type of surface modification technique developed over the last decade [7], renders the treated materials with new properties such as high surface hardness and high wear and corrosion resistance. 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 letter, we report the observation of a new structure phenomenon by using TEM, formation of SFT in a single-crystal aluminum sample irradiated with a HCPEB resource.

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.* [7, 8].

Bulk single-crystal aluminum specimens were irradiated with 1, 5 and 10 pulses at a relatively low energy density of 1 Jcm^{-2} approximatively. The duration of the pulse is about 1.5 μs. The foils used for TEM observation were thinned by jet electropolishing from the substrate side. The TEM observation was carried out in a H-800 TEM operating at an acceleration voltage of 175 kV.

The TEM dark-field images taken with vector **g** (220) shown defect structure of the specimen irradiated with 1 pulse is illustrated in Fig. 2a. A lot of dislocation loops are observed in the near-surface. In general, the sizes of the visible dislocation loops were found to be in the range of a few nanometers to about tens of nanometers. Owing to the superfast heating and cooling, non-equilibrum thermal vacancies are quenched in the heat-affected zone. These vacancies would tend to aggregate into vacancy clusters and even form specific defect structures such as prismatic dislocation loops, which are energetically more favorable than SFT in high stacking fault energy metals [9]. Another type of defect structure with a truncated tetrahedra shape was also observed in the local regions of this foil, as shown in Fig. 2b. It is worth noting that both dislocation loops and truncated tetrahedra were coexistent. Dislocations are completely absent in this local region.

*Author to whom all correspondence should be addressed.

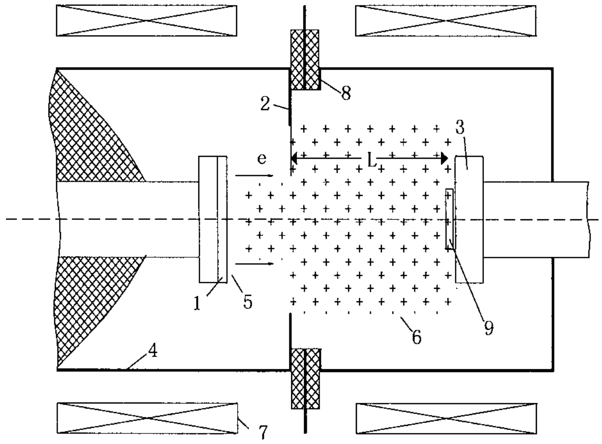

Figure 1 Schematic diagram of the HCPEB source using plasma filled systems based on vacuum spark plasma. (1) cathode, (2) anode, (3) collector, (4) vacuum-chamber, (5) cathode plasma, (6) anode plasma, (7) solenoid, (8) spark source, (9) specimen.

Fig. 3 shows the defect structure of the specimen irradiated with 5 pulses. In a TEM dark-field images taken with vector **g** (220) (Fig. 3a), one sees a lot of triangular shapes of the defects about 100 nm in size. The triangular shape of the defects is reminiscent of the typical SFT morphology. Fig. 3b shows the TEM bright-field images along [111] zone axis. The typical perfect pyramidal sturctures are clearly observed. The TEM dark-field images with systematic changes to the cited reflections indicate that they are found to be SFT surrounded by {111} planes. It is noted that the vacancy clusters of SFT and the square viods synchronously form in the regions with no dislocations, as shown in 3(c). Dislocation loops are completely absent in this specimen. It suggests that there is a close relation between dislocation loop and SFT and between SFT and void. From Fig. 3c we also see that besides the larger SFT, very dense tiny defect clusters are also observed.

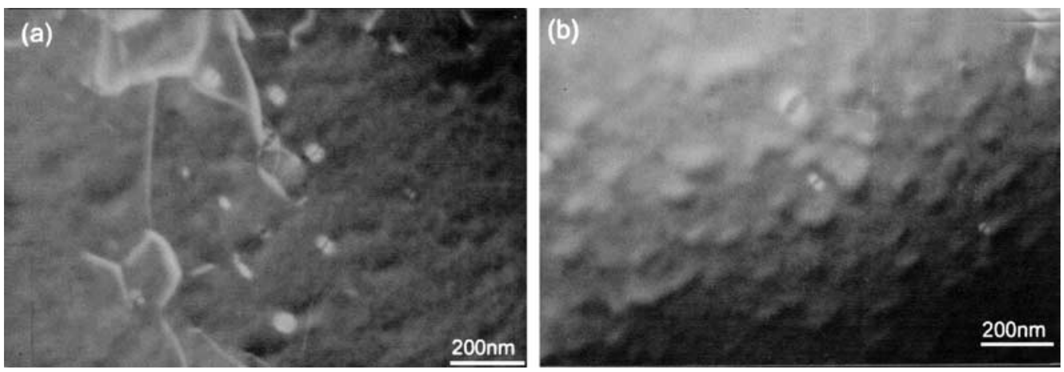

Figure 2 TEM images showing a variety of vacancy clusters in the specimen irradiated one pulse: (a) TEM dark-field image with Vector **g** (220) showing the defect structure of dislocation loops and (b) [111] zone axis TEM bright-field image showing a defect structure with truncated tetrahedral shape.

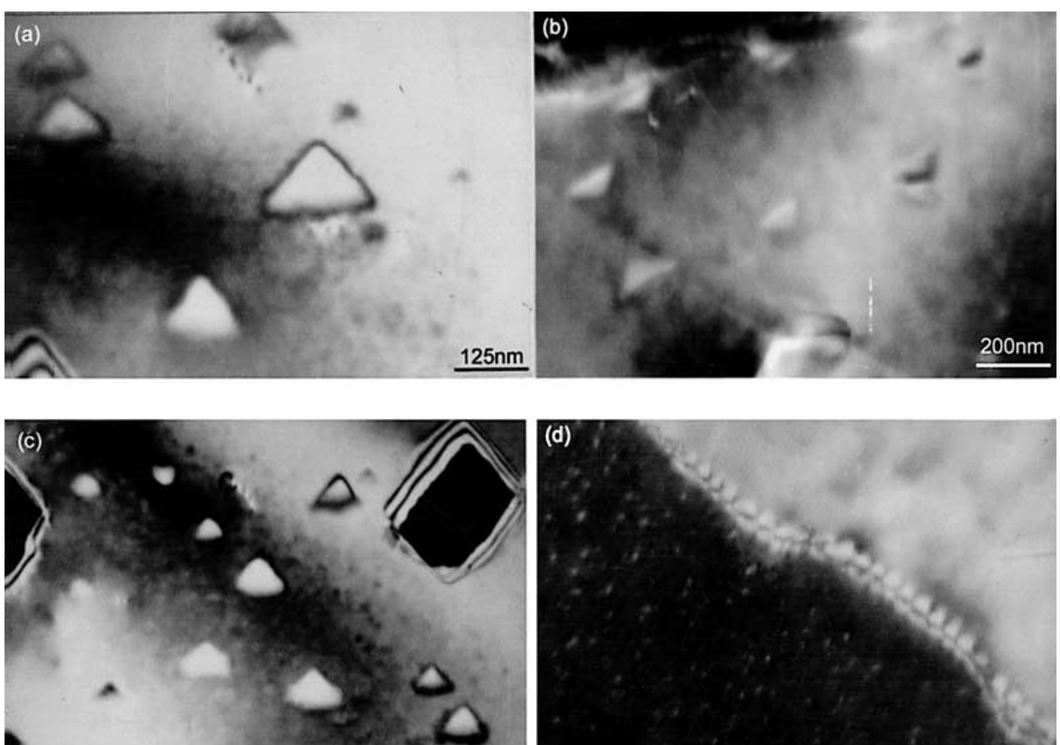

Figure 3 TEM images showing a variety of vacancy clusters in the specimen irradiated five pulses: (a) TEM dark-field image with vector **g** (220) showing the SFT structure, (b) [111] zone axis TEM bright-field image showing SFT with perfect pyramidal structures, (c) TEM dark-field image with vector **g** (220) showing SFT and voids, and (d) TEM dark-field image with vector **g** (220) showing SFT walls.

They are too small to determine their morphology, but probably inferred to be small SFT from their contrasts. These small SFT are much more abundant than larger ones but the size distribution, generally a few nm, does not exhibit specific patterns. Another interesting phenomena is shown in Fig. 3d. Two rows of SFT wall are formed in a local region of the sample.

It is well known that is single-crystal fcc materials, especially single-crystal aluminum, dislocation based slip processes is a common and important mechanism for plastic deformation. However, the present work indicates that dislocation-free plastic deformation takes place under HCPEM irradiation. Although the detailed mechanism of the new dislocation-free plastic deformation remains unclear, the observed phenomena clearly fall beyond the scope of the dislocation theory. It appears to indicate that the defects of vacancy clusters such as SFT and voids play an important role in dislocation-free deformation of single-crystal aluminum induced by HCPEM irradiation. Of course,work is needed to investigate this.

SFT can grow by absorbing vacancies [1]. The present results reveal that very dense vacancies must be produced in the near-surface of the irradiated material. Prgrebnjak *et al*. demonstrated that a high density of non-equilibrium vacancy (up to 10^{-3}) was formed in the near-surface of pure iron irradiated by HCPEB [10]. This was detected by a positron annihilation method. This density of non-equilibrium vacancy is 10 orders higher than that of the situation at room temperature. In such a system with huge numbers of non-equilibrium vacancies, the conventional mechanism of SFT formation may not be suited to interpret the present results. It means that new mechanisms about SFT formation and dislocation-free plastic deformation need to be established.

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References
1. M. KIRITANI, *Mater. Chem. Phys.* **50** (1997) 133.
2. J. SILCOX and P. B. HIRSCH, *Philos. Mag.* **4** (1959) 1356.
3. *Idem.*, *ibid.* **4** (1959) 72.
4. S. KOJIMA, Y. SATO, H. TAOTA, I. ISHIDA, T. YOSHIIE and M. KIRITANI, *Philos. Mag.* A **95** (1989) 519.
5. J. P. HIRTH and J. LOTHE, "Theory of Dislocations," 2nd ed. (Krieger, Malabar, FL, 1992).
6. T. L. DAULTON, M. A. KIRK and L. E. REHN, in "Microstructure Evolution During Irradiation," Vol. 438 of MRS Symposium Proceedings, edited by B. P. Dale, E. Alexander, N. W. Cheung and W. Skorupa (Materials Research Society, Pittsburgh, PA, 1996) p. 318.
7. D. I. PROSKUROVSKY, V. P. ROTSHTEIN, G. E. OZUR, *et al*., *J. Vac. Sci. Technol.* A **16** (1998) 2480.
8. *Idem.*, *Surf. Coat. Technol. 125*, **49** (2000) 6.
9. D. FENG, "Metal Physics," Vol. Ist ed. (Chinese Science Press, 1998) p. 343 (in Chinese).
10. A. D. POGREBNJAK, *et al*., *Physics Letter* A **241** (1998) 357.

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