Note

Microstructures of High-speed Deformation in 0.20% C Carbon Steel Induced by High-current Pulsed Electron Beams Irradiation

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1. Introduction

High-speed deformation of metals which may be different from conventional deformation has attracted much attention in recent years.^{1–5)} Materials scientists have emphasized the role of high-speed deformation in engineering applications, mainly the relationship between deformation-induced microstructures and residual mechanical properties. The complex interrelationships between stress, stress state, strain, strain rate and temperature, have been used for pursuing a better design of materials with the objective of postponing a period of use.

High-current pulsed electron beam (HCPEB) was usually used as a tool for material surface processing.^{6,7)} It is characterized by a high power density of 10^8 – 10^9 W/cm² at the target surface. During the interaction of incident pulsed electron beam with the surface of materials, such a high energy is deposited only in a very thin layer within a short time and causes superfast processes such as heating, melting and evaporation. After the beam turned off, the heated region is immediately cooled down by thermal conduction at a fast cooling rate typical of 10^5 – 10^8 K/s. Such a rapid cooling of the heated region can produce high-speed deformation on the target surface. Our previous works indicated that HCPEB provides an effective technique to investigate the microstructures and mechanism of high-speed deformation. It is known that the characterization of deformation microstructures is a very important tool in the development of our understanding of the thermo-mechanical evolution during high-speed deformation.

In our previous works the microstructures of typical fcc metals (*i.e.* aluminum, nickel and AISI 304L stainless steel) have been examined in various manners during HCPEB irradiation.^{8–11)} However, little effort has been applied to determining different types of crystal structures, such as in bcc metals. In the present study, we investigated deformation structure of low-carbon steel under HCPEB irradiation, since steels are the most commonly used engineering materials. The present note was focused on the identification of deformation microstructural features induced by HCPEB irradiation.

Fig. 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 and (9) specimen.

2. Experimental Procedures

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/cm²), short pulse duration (approx. 1 μ s) and high efficiency. The electron pulse is generated by an explosive emission graphite cathode. The accelerating voltage, magnetic field intensity, and anode-collector distance control the beam energy density. More details on the principle of the HCPEB system are given in references.^{6,7)}

An annealed low carbon steel with composition (wt%) 0.20 C, 0.25 Si, 0.38 Mn, 0.016 P, 0.012 S and remains Fe, was selected as the target material. Specimens were machined to size 10 mm in length, 10 mm in width, and 6 mm in height, and one side surface was mirror polished. The bombardments of samples were carried out using HCPEB under the following conditions: the electron energy was 28 KeV, the current pulsed duration was 3.5 μ s, the energy density was 4 J cm⁻² and the pressure of residual gas in the vacuum chamber was about 10^{-5} Torr. The specimens were bombarded with 10 pulses. Microstructural examinations were performed with an optical microscope and a transmission electron microscope (TEM) of type H-800. The foils used to TEM observations were obtained by preparing one-sided mechanically prethinned, dimpled and, in the last step, electrolytical thinning of the thin plates until the electron transparency occurred.

3. Results and Discussion

Figure 2 shows the typical surface morphologies of the irradiated samples treated with 10 pulses. For the treated samples, microstructure on the irradiated surface could be observed directly and the chemical etching process was not needed. It can be seen clearly that the irradiated regions became rougher and some craters were formed. The craters shown in Fig. 2 ranged from a few μ m to 100 μ m approximately in diameter and appeared to distribute uniformly on the surface. Based on our previous studies,^{11,12)} such a typical morphology is the result of the local sublayer melting and eruption through the solid outer surface. Additionally, dense slipping bands existed in many grains. The grain boundaries split the deformed grain into many small domains. These phenomena indicate the existence of severe

Fig. 2. Showing the top view of 0.20% C steel produced by a HCPEB irradiated specimen.

deformation in the surface layer within a short time.

Another very interesting features of two types of banded structures observed are also presented in Fig. 2. One is the deformed shear band, and the other is the white shear band, as noted by the arrows in Fig. 2. It is worth to note that these shear bands involves several grains, whereas the slip bands are limited into one grain with defined crystallographic direction. These phenomena are the typical characteristics of shear localization.¹³⁾

On closer inspection of the deformed shear bands, it was discovered that the boundaries of the shear band changed their shape to curve and very fine grains were formed within the shear band. For the white shear band, many small craters stand in a line in it, suggesting the rise in temperature within the band.

In order to have a clear picture of the microstructures induced by HCPEB irradiation, the thin foils for TEM observation were obtained by mechanical pre-thinning, dimpling, and jet electrolytical thinning from the substrate side. **Fig. 3(a)** shows the typical pearlite microstructure of untreated sample consisting of laminated cementite and α -ferrite. After HCPEB treatment, the width of cementite phase became narrower in the most regions of the TEM sample, as shown in **Fig. 3(b)**. No evident signatures of severe deformation were observed in these regions. However, the traces caused by severe deformation induced by HCPEB irradiation were obtained in some observed regions. **Figs. 4(a)** and **4(b)** show that a prominent feature found after HCPEB irradiation is the formation of elongated dislocation cells and tangled structure (dislocation cell) in α -Fe and the formation of small dislocation loops in the dislocation cells was also observed. It is worth noting that very low dislocation density was measured within the dislocation cells, suggesting that the vacancy clusters are not formed directly from the interaction of dislocations, but by the aggregation of vacancies. Yasunaga *et al.*⁴⁾ investigated the different mode of plastic deformation at high strain rates and found that the formation of small dislocation loops was observed in bcc metals (V and Nb) at higher strain rates exceeding 10^3 s^{-1} . They also demonstrated that the dislocation loops were identified as vacancy type. Based on Yasunaga's viewpoint, the mode of high-speed deformation indeed occurs within the sublayer of irradiated samples during HCPEB irradiation and the high-speed deformation accompanied by production of vacancies also occurs in the shear bands of α -Fe. Another interesting deformation fea-

Fig. 3. (a) TEM images of the original sample, (b) the near surface zone of the 0.20% carbon steel after HCPEB irradiation.

Fig. 4. Showing the TEM images within the shear bands of α -Fe induced by HCPEB irradiation: (a) elongated dislocation cells and dislocation loops in it, (b) dislocation cell and dislocation loops in it, (c) dislocations array to form straight lines, (d) rounded cementites particles.

tures observed near this region is shown in **Fig. 4(c)**, indicating that dislocations array to form straight lines. Furthermore, **Fig. 4(d)** reveals that rounded cementite particles in the α -ferrite matrix were formed near those severe deformation regions.

The surprising feature observed was a glassy region separated from the nanocrystalline region by an interface. **Fig. 5** shows the two regions and the interface, with the glassy region at the center and the crystalline one in the periphery. The respective diffraction patterns are also included. Whereas the interface region shows both the ring pattern characteristic of the nanocrystalline phase and spots characteristic of α -Fe, the glassy region shows only the characteristic halo pattern of the amorphous phase. There are few observations of a crystalline-to-amorphous transition in carbon steel as far as we know. Mayers¹³⁾ were able to produce the amorphous phase within the shear band of 304 SS by high-speed deformation in a Hopkinson bar at strain rates of 10^4 s^{-1} . Their result is very similar to **Fig. 5** in this report. They believed that the amorphous phase is formed by a solid-state amorphization process. Both the heating and cooling times within the shear band are extremely short and propitiate the retention of non-equilibrium structures. For more details the readers are referred to Mayers.¹³⁾

Recently, Kiritani *et al.*^{1,2)} reported that a large number of vacancies were produced during high-speed heavy plastic deformation of thin foils of fcc metals. They observed a large density of vacancy defect clusters but very low dislocation densities in the foils after deformation. As a possible explanation, they proposed a dislocation-free deformation mechanism. Based on this mechanism, we can interpret ex-

Fig. 5. Amorphous and nanocrystalline regions inside shear band and respective diffraction patterns.

perimental results as follows. When an electron irradiated the target, due to the change of drastic temperature, a steep temperature gradient was generated along the incident direction of the beam.¹⁴⁾ However, the thermal expansion in the direction vertical to the beam was strongly resisted, causing the surface thermal stress. When material was subjected to a HCPEB irradiation, dislocations were first induced in the near-surface of the target. Based on our previous works of AISI 304L austenite stainless steel irradiated by HCPEB,¹⁴⁾ initial pulses irradiation induced stress with lower value, which just results in the formation of dislocation tangle microstructures and increase the dislocation density and intensity of the target. The stress induced by subsequent irradiations is coupled with these structure defects formed before to harden the target. Therefore, the thermal expansion due to the lateral confinement along the surface becomes even stronger with increasing the pulse number. Thus, much higher values of the stress are achieved in the case of multiple pulses. This external force may be increased internal stress to an extraordinarily high level, which can lead to the formation of a mass of vacancy defect clusters. The numerical simulation of the thermal-mechanical process of HCPEB treatment by Zou *et al.*¹⁵⁾ suggests that the quasistatic stress is coupled with the temperature field and the maximum compressive stress in the near surface layer reaches several hundreds of MPa after HCPEB irradiation, which can produce very violent deformation in the surface layer of the irradiated material. Under such high stress and strain, all atoms of the irradiated surface layer rather than only atoms near the core of dislocations are brought to the condition to displace during the deformation. The natural expectation is the formation of large zones containing disordered atoms in it, just like the atom near the core of dislocation and/or grain boundary. The amorphous phase in this report may be an implication.

It is worth to note that very low dislocation densities in the foils were observed after high-speed deformation in Kiritani's works, whereas some complicated dislocation structures were presented in this report, just like Figs. 4(b) and 4(c). For our work, bulk specimens were employed. Therefore, except vacancy–vacancy interaction is very important to form vacancy clusters in the shear bands, interstitial–interstitial interaction is also important to form an interstitial cluster in the area of shear bands. Based on Shimomura's computer simulation¹⁶⁾ on the void formation in neutron-irradiated Cu and Ni, interstitial clusters move by the combination of one dimensional $\langle 111 \rangle$ crowdion motion and switching to another $\langle 111 \rangle$ movement direction in

α -Fe at higher temperature. Finally, interstitial clusters arrive to a group of interstitial clusters. After removing of interstitial clusters, only vacancy clusters are left. Interstitial clusters in the grouping coalesce to change to joggy dislocation loops. These dislocations will evolve to complicated structure by further absorbing of interstitial clusters. At higher temperature, dislocations will evolve to straight lines, just like Fig. 4(b). Vacancy clusters relax to a collapsed structure such as dislocation loops (Figs. 4(a) and 4(b)). Based this viewpoint, we can not ensure the dislocation structures in Figs. 4(b) and 4(c) were directly resulted from dislocation sliding. Thus, our experimental results seem still to support the dislocation-free deformation mechanism proposed by Kiritani *et al.* Of course, further works are needed to investigate this.

4. Conclusions

Annealed 0.20% C carbon steel was irradiated with HCPEB irradiation. The deformation microstructures induced by HCPEB irradiation has been investigated. The results indicate that the shear localization occurred on the irradiated surface of the steels. TEM results reveal that the formation of small dislocation loops was observed in the shear bands of α -Fe. These vacancy clusters are not formed directly from the interaction of dislocations, but by the aggregation of vacancies. Characterization by TEM also reveals the region within the shear bands consisting of a region having a glassy structure. Two formation mechanism of the amorphous structure are discussed. The dislocation-free deformation mechanism proposed by Kiritani is the more probable mechanism of the formation of amorphous structure.

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