Physical Model of Stress and Deformation Microstructures in AISI 304L Austenitic Stainless Steel Induced by High-current Pulsed Electron Beam Surface Irradiation

Qingfeng GUAN,1) Qingyu ZHANG2) and Chuang DONG2)

1) College of Materials Science and Engineering, Jiangsu University, Zhenjiang, 212013, P. R. China.
E-mail: guanqf@ujs.edu.cn 2) State Key Laboratory of Materials Modification by Laser, Ion and Electron Beams, Dalian University of Technology, Dalian 116024, P. R. China.

(Received on October 18, 2007; accepted on December 4, 2007)

AISI 304L austenite stainless steel was irradiated by a high-current pulsed electron beam (HCPEB) source in different process. The deformation microstructures were investigated by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The relationship between stress characteristic and the microstructures has been established. The current numerical simulations of the thermal-mechanical process of HCPEB treatment were also reviewed comparing with the present experimental results. Our experimental results suggest that the value of the stress induced by HCPEB is between 10²–10³ MPa or even larger. This stress results in the change of microstructure of the irradiated material in deeper region beneath the surface. According to the experimental results, a new physical model of the thermal-stress process and related modification mechanism as a result of HCPEB irradiation has been developed.

KEY WORDS: AISI 304L austenite stainless steel; HCPEB; deformation microstructures; stress; twin lamellae.

1. Introduction

High-current pulsed electron beam (HCPEB), a new type of surface modification technique developed over the last decade has been studied extensively.1–7) During the transient bombardment process a high energy (10⁸–10⁹ W/cm²) is deposited only in a very thin layer (less than tens of micrometers) within a short time (a few microseconds) and causes superfast heating and cooling, even melting, evaporation, and solidification on the treated surface of material. The dynamic stress fields induced in these processes can cause intense deformation processes in the surface of material. The energy of such pulsed beams depositing in a violent manner is unattainable with conventional methods. A significant enhancement of mechanical and tribological properties has been investigated, not only on the treated surface and subsurface layer but also at depths of millimeter scale, which is far beyond the depths of the heat-affected zone (HAZ).8) Several physical models and numerical simulations have been developed to show the mechanism of significant structure and property varieties.¹,9–10) However, their simulation results only partly agree with the experimental results near surface region, but display a great diversity beyond the depths of HAZ. In addition, the research on the microstructures has received less attention compared to numerical simulations. Therefore, more efforts should be done for better understanding of HCPEB modification physical models.

In the present paper, we applied HCPEB technique to 304L austenite stainless steel which has lower stacking fault energy and can be produced readily abundant deformation structures by the external applied stress. We focus on the microstructures induced by thermal-stress effect produced by HCPEB irradiation. The physical model of the thermal-stress process and related modification mechanism as a result of HCPEB irradiation was also presented.

2. Experimental

A schematic diagram of the HCPEB source (Nadezhda-2) is given in Fig. 1. It can produce a pulsed electron beam of low energy (10–40 keV), high peak current (10⁶–10⁷ A/cm²), short pulse duration (0.5–5 μs), and high efficiency (repeating pulse interval being 10 s). The electron beam is generated by an explosive emission graphite cathode. Spark plasma sources are placed evenly in a circle behind the anode, providing an anode plasma that conducts the electron beam to the collector (target). An external magnetic field is applied to confine the beam. The accelerating voltage, magnetic field intensity, and anode-collector distance all control the beam energy density. For more details about the HCPEB system, the readers are referred to Refs. 1) and 2).

AISI 304L austenitic stainless steel with composition of (wt%): 18.2Cr, 9.4Ni, 1.5Mn, 0.4Si, 0.2Mo, 0.2Cu, 0.1Co, 0.003Ti, 0.027P, 0.003S, and 0.044C (balance Fe) was selected as the target material. Specimens were machined...
with a size of 14 mm in length, 10 mm in width, and 6 mm in height, and one side surface was mirror polished. The polished surfaces of samples were irradiated at room temperature with one, five and ten pulses respectively using this HCPEB source. The HCPEB irradiation was carried out under the following conditions: the electron energy 28 keV, the current pulse duration 3.5 μs, the energy density about 4 J/cm², and the vacuum 10⁻⁵ Torr. The thin foils for the TEM observation were obtained by mechanical pre-thinning, dimpling, and electrolytical thinning from the substrate side. The TEM microstructures observed were at about 20–50 μm depths from the irradiated surface. Microstructures were examined with a scanning electron microscopy (SEM) of type JSM-5310 and a transmission electron microscopy (TEM) at an acceleration voltage of 175 kV.

3. Results

Figure 2 represents the depth distribution of microhardness on the cross-section of the 304L stainless steel samples, which were given 1, 5 and 10 pulses HCPEB irradiation each at an average energy density per shot of 4 J/cm². No significant hardening was achieved in the sample of 1 pulse irradiation. However, multiple-pulses HCPEB irradiation produced significant hardening. The average microhardness of 5 pulses sample is higher than that of 10 pulses sample. The peak values of the microhardness appear at a depth of about 80 μm beneath the irradiated surface, which is far beyond the HAZ (about 10 μm). It suggests that the hardening of the irradiated samples result from the stress effect induced by HCPEB treatment rather than the heat effect.

Figure 3(a) shows the typical SEM morphologies of the surface of the irradiated samples treated with 5 pulses.
Other treatments with different pulses yielded approximately uniform surface microstructures. It can be seen clearly that the irradiated regions of the sample surface became rougher and some craters were formed on it. The craters shown in Fig. 3(a) ranged from a few \( \mu m \) to 20 \( \mu m \) approximately in diameter and appear to be distributed uniformly on the surface. The details about the craters will be discussed elsewhere. In the cross-section SEM morphologies shown in Figs. 3(b)–3(d), the micro-cracks parallel to the irradiated surface were formed in range of deeper depth beneath the irradiated surface (about 2 mm depth). One can see that the more is pulsed numbers of HCPEB irradiation, the wider and longer micro-cracks are produced. The space between adjacent micro-cracks, which are periodic approximately along the vertical, can be estimated from Figs. 3(b)–3(d), are \( \sim 100 \mu m \) at 1 pulse, \( \sim 50 \mu m \) at 5 pulses and \( \sim 30 \mu m \) at 10 pulses, respectively. It is suggested that the micro-cracks were introduced by stress which has considerable high value during HCPEB irradiation. Based on above experimental results, significant hardening and reduction of ductility can occur in the AISI 304L austenitic stainless steel as a result of HCPEB irradiation.

The TEM microstructures of deformation of reference samples are revealed in Fig. 4. In original sample, small stacking faults are the dominating structures as shown in Fig. 4(a). After 1 pulse, small stacking faults (about 20 nm) and the structure of dislocation tangles have been well established as shown in Fig. 4(b). After 5 pulses bombardment, the sizes of stacking faults become larger (about 0.2 \( \mu m \)) and the dense dislocation networks are achieved as shown in Fig. 4(c). Moreover, large numbers of twin lamellae have been observed as shown in Fig. 4(d). In the case of 10 pulses sample, wider stacking faults and more numbers of twin lamellae can be observed, as shown in Figs. 4(e) and 4(f). The size of stacking faults and twin lamellae become even larger, and the intersecting between twin lamellae and stacking faults are more frequently presented comparing to the sample of 5 pulses HCPEB irradiation.

In the case of 5 and 10 pulses, an evident displacement of the stacking faults can be observed clearly, resulting in zigzag-shaped stacking faults after twin lamellae and stacking faults intersected (indicated by arrows in Figs. 4(d) and 4(f)). Larger displacements were observed in the sample of 10 pulses. Obviously, the displacements (from a few nanometers to ten nanometers) were induced by the twin lamellae. Therefore, stacking faults presumably formed first and were then intersected by twin lamellae since the later are straight and the former are zigzag like. It also indicates that deformation is concentrated in twin lamellae. This can be further seen clearly in Fig. 5, which demonstrates the situation at the intersection of twin lamellae on two different \{111\} planes. Figure 5(a) presents a picture of a
broaden twin lamellae at 10 pulses HCPEB irradiation. The diffraction pattern taken from the area is given at the upper-right corner, which indicates clearly that the twin planes belong to \{111\} type. In the dark-field image picture shown in Fig. 5(b), due to the imaging condition, the twin lamellae indicated by arrows has no contrast, while the other twin lamellae on intersecting \{111\} plane have strong bright images. From the displacement between the left and right pasts of twin lamellae, one can see larger strain is located in the indicated twin lamellae. Comparing to 10 pulses irradiation, few intersecting between twin lamellae are presented at 5 pulses irradiation, as illuminated in Fig. 6.

4. Discussions

Proskurovsky et al. believed that thermal stress wave induced by HCPEB treatment is the dominant factor for the structure and property varieties beyond the HAZ. They described the thermal stress wave in Fe induced by the HCPEB treatment using numerical simulations. The amplitude of the simulated thermal stress wave is as weak as 0.1 MPa, too low to manifest significant structure and property modifications. Zou et al. described the nonstationary thermal stress fields induced by temperature grads, which consist mainly of quasistatic stress and thermal stress waves. The thermal stress wave is a typical nonlinear wave with small amplitudes of about 0.1 MPa, which manifests, however, a strong impact on materials structure and properties far beyond the heat-affected zone. The quasistatic stress is coupled with the temperature field and the maximum compressive stress in the near surface layer reaches several hundreds of MPa, which is sufficiently high for metallic materials to deform. Nevertheless, this model still did not explore in detail the thermal stress wave beyond the HAZ. It suggests that a comprehensive understanding and detailed description of the coupled temperature and stress behaviors induced by pulsed beam treatments, very complex, nonequilibrium, and transient, are still missing. New physical mechanism of the thermal-stress process and related modification mechanism as a result of HCPEB irradiation needs to be developed.

Due to the 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 thermal stress (\(\sigma_\text{t}\)), as shown in Fig. 7(a). The thermoelastic stress wave (\(\sigma_\text{x}\)) is also shown in this figure. As the temperature rises, a local melting starts in a subsurface layer. Therefore, the locally melted droplets are formed beneath the surface as shown in Fig. 7(b). Due to the liquid pressure, a resultant force \(P\) from the quasi-static thermal stress and the liquid volume expanding exerts on the droplets and is transmitted by the droplets in all directions. The force \(P\) along the beam direction constitutes the source of the shock thermal stress wave (Fig. 7(b)). It is then enhanced by the temperature increasing, as schematically represented as a wave oscillation in Fig. 7(b). If the thin outer surface solid layer cannot withstand this pressure, a volcano-like eruption occurs as shown in Fig. 7(c), just like the craters in Fig. 3(a). The shock stress is then released (Fig. 7(c)). After the eruption, the compressive stress is then released, as described in Fig. 7(c). The maximum compressive quasi-static stress \(P\) in the surface layer, according to numerical simulation developed by Zou et al., can reach \(10^2\)–\(10^3\) of MPa, which easily induces violent deformation in metallic materials.

In order to have a clear picture of above physical model, the stress range induced by HCPEB irradiation should be
evaluated from our experimental results. Based on a variety of deformation microstructures produced for austenitic stainless steels by changing material condition. Byun categorized the deformation microstructures in terms of the equivalent stress range.11) (1) Dislocation tangles were dominant at low equivalent stresses \( \leq 400 \text{ MPa} \). (2) Small, isolated stacking faults were formed in the stress range from about 400–600 MPa. (3) Large stacking faults/twin bands became dominant at stresses \( \geq 600 \text{ MPa} \). A key conclusion was that the austenitic stainless steels will deform by forming a determinate microstructure when the stress exceeds a critical equivalent stress level by any of the following possible strengthening measures: irradiation, increasing strain level, and decreasing test temperature. Comparing Byun’s conclusions to the presented experiment results, we can deduce reasonable that the microstructure of 1 pulse HCPEB irradiation correspond to a stress level of 400–600 MPa, and the multi-pulses more than 600 MPa. Based on above analysis, our physical model can perfectly explain varieties of mechanical property in deep region induced by high stress produced by HCPEB irradiation.

5. Conclusion

A HCPEB source of Nadezhda-2 type was employed to irradiate the surface of the AISI 304L austenitic stainless steel. The relationship between stress characteristic and the microstructures has been investigated. A new physical model has been built to describe the intricate nonequilibrium process and associated thermal mechanical effects induced by the HCPEB bombardment. HCPEB irradiation causes significant hardening at a depth of about 80 \( \mu \text{m} \) beneath the irradiated surface, which result from the stress effect induced by HCPEB treatment. The shock stress is resulted from the quasi-static thermal stress and the liquid volume expanding exerted on the droplets, 400–600 MPa at 1 pulse HCPEB and more than 600 MPa at 5 and 10 pulses. It is the dominant factor for inducing violent deformation in metallic materials.

Acknowledgement

This work was supported by the Chinese Nature Science Foundation (Grant No. 50671042) and Jiangsu University Science Foundation (Grant No. 07JDG032). To whom we are very grateful.

REFERENCES

1) D. I. Proskurovsky, V. P. Rosentein, G. E. Ozur, Y. F. Iyanov and A. B. Markov: Surf. Coat. Technol., 125 (2000), No. 1–3, 49.
2) Q. F. Guan, S. Q. Wang, X. H. Cui, Q. Y. Zhang and C. Dong: ISIJ Int., 47 (2007), 1375.
3) A. D. Pogrebnjak, V. S. Ladysev, N. A. Pogrebnjak, A. D. Michaliov, V. T. Shavlya, A. N. Valyaev, A. A. Valyaev and V. B. Loboda:Vacuum, 58 (2000), 45.
4) A. D. Pogrebnjak, S. Bratushka and V. I. Boyko: Nucl. Instrum. Methods B, 145 (1998), 373.
5) A. D. Pogrebnjak et al.: Phys. Lett. A, 241 (1998), 357.
6) C. Dong, A. M. Wu, S. Z. Hao, J. X. Zou, Z. Liu Z, P. Zhong, A. Zhang, T. Xu, J. Chen, J. Xu, Q. Liu and Z. Zhou: Surf. Coat. Technol., 163–164 (2003), 620.
7) Q. F. Guan, L. Pan, H. Zou, A. M. Wu, S. Z. Hao, Q. Y. Zhang, C. Dong and G. T. Zou: J Mater. Sci., 39 (2004), 6349.
8) Q. F. Guan, P. L. Yang, H. Zou and G. T. Zou: J Mater. Sci., 41 (2006), 479.
9) A. B. Markov and V. P. Rosentein: Nucl. Instrum. Methods B, 132 (1997), 79.
10) J. X. Zou, Y. Qin, C. Dong, X. G. Wang, A. M. Wu and S. Z. Hao: J Vac. Sci. Technol. A, 22 (2004), 545.
11) T. S. Byun: Acta Mater, 51 (2003), 3063.