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Surface nanocrystallization, austenization and hardening of medium carbon steel by an explosive impact technique

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ABSTRACT

An explosive impact technique was used to harden a medium carbon steel plate with a thickness of 6 mm. The explosive impact produced relatively uniform microstructure and mechanical properties in the impact surface layer. The austenite equiaxed nanocrystallines were formed in this layer; the grain size and the depth respectively are 10 nm and 5 μm approximately. The microhardness of the impact surface was increased to 475 HV from 130 HV and the wear resistance was doubled. Moreover, the impact surface has a greater hardness than the explosive surface, and the hardness gradually decreased with the depth increases from both sides. The plastic deformation penetrated through the entire plate depth, the depth of highly hardening layers was arrived at 500 μm and a sandwich structure was produced. By the server plastic deformation, the cementite flakes appeared slip, segmentation and the fracture. Comparing with the surface severe plastic deformation (SPD) processes, the explosion impact has a stronger ability for hardening the entire plate depth and a little weaker surface strengthening effect. The nanocrystallization, austenization and hardening mechanisms were discussed.

1. Introduction

Surface strengthening techniques have been adopted to improve the hardness, strength, wear resistance and fatigue life for metal and alloy products. Recently years, the surface severe plastic deformation (SPD) processes, such as surface mechanical attrition treatment (SMAT), high-energy shot peening (HESP), supersonic fine particle bombarding (SFPB) and ultrasonic rolling (USR), provided novel routes to enhance the surface mechanical properties by introducing the nanostructures into surface layers; the mechanism of the nanocrystallization was recognized to associate with dislocation behaviors during plastic deformation [1–4], that is, the dense dislocation walls (DDWs) and dislocation tangles (DTs) formed in the original grains and refined cells; the transformation of DDWs and DTs into subboundaries with small misorientations separated the individual cells or subgrains, and the subboundaries further evolved into the highly misoriented grain boundaries. However, the high strain and high strain rate are necessary for the formation of nanocrystallites. Moreover, a martensitic transformation was found in the treated surface of stainless steels [5,6].

Explosive forming is a unique processing technique for hardening metal plates; its economical and successful applications began in the early 1970s with the manufacture of a large area of high-strength aluminum alloy and steel parts [7]. By a high-energy explosive impact, a highly plastic deformation hardening can be introduced into surface, subsurface and even the entire body. Balasubramaniam et al. [8] choose the explosive forming to form a low carbon steel sheet for the capsules; the forming parameters were predicted from theoretical considerations by equating the disk shape with an equivalent dome. Krishtal et al. [9] reported that the substantial hardening by the explosion load depends on the original structure; the explosive forming often induces an increase of microtwins and dislocation density. Van Wely [10] noticed that in the explosive forming, even when the gross deformation is zero, the shock wave causes changes in the material structure, such as increased twinning, concentration of point defects, fracture of inclusions and a different dislocation structure. Due to these phenomena the mechanical behavior was changed. Murr [11] indicated that a non-equilibrium vacancy concentration existed in 304 stainless steel by an explosive shock loading and the vacancy supersaturation in 304 stainless steel is strain-rate dependent. Otto et al. [12] compared the effects of explosive forming and static deformation on the mechanical properties of A285 and A515 pressure vessel steels. It was found that after the explosive forming and standard stress relief anneal, both steels meet well the ASEM specification, however, the static deformation reduced the impact strength of A285 steel; the explosively formed A285 steel has an impact strength as the received stock. At 35% strain level, the cold roiling A515 steel has greater impact resistance and low ductile-brittle transformation temperature than the explosive forming. Li et al. [13] studied the explosive hardening of high Mn steel by using a light gas gun under a selected impact load from 10 to 20 GPa and pulse duration time from 0.04 to 1.6 μs. The experimental results show that a lot of twins formed in the shocked area and caused the surface hardening. Maranda et al. [14] investigated the microstructure change and hardness distribution of the strengthened surface layers of pearlite–ferrite

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St72P rail steel by varying the thickness layer of explosive and the number of loadings. They found that the grain size reduced and the hardness increased with increasing the explosive dosage and the loading number. Bataev et al. [15,16] studied the surface structure evolution of an explosively impacted steel plate with a typical ferrite–pearlite structure; that is, formation of numerous deformation twins in both ferrite grains and pearlite colonies; formation of extended bands of localized deformation, which are not crystallographically connected with the original ferrite–pearlite structure; fine grains formation in the severe plastic flow zones. The size of the ferrite grains was reduced by an order of magnitude than the original grain size.

Comparing with the above SPD techniques, the explosive impact technique has many outstanding advantages, such as instant formation, large-surface processing and the formation of highly hardening layer, However, it can be found from the above reports that the structure and mechanical properties of the impacted surface layer, as well as the surface strengthening mechanism have not been paid great attentions. Therefore, the aim of the present work is to introduce the explosive impact technique to treat a medium carbon steel and to investigate the microstructure and properties of the surface layer as well as the hardening mechanism.

2. Experimental procedures

2.1. Preparation of samples

A sketch of the explosive device is shown in Fig. 1. The rigid anvilblock (45# steel, smooth surface, 10 cm thick) was coated with a high-temperature lubricant, on which 4 support nails (45# steel, φ2 × 3 mm) were placed. The annealed 45# steel plate (0.42 wt.% C, 0.65 wt.% Mn, 0.27 wt.% Si) with a size of 500 × 150 × 6 mm was installed on top of the nails. Both of the surfaces were mechanically machined. The emulsion explosive powders (specific gravity of 0.9 g/cm^3, detonation velocity of 4600 m/s, explosive load of 1.97 g/cm^2) were uniformly paved on the annealed steel plate and a detonator was inserted. By igniting the detonator, the explosion was triggered. The upper surface (explosive surface) experienced an impact of explosive airflow, and the lower surface (impact surface) experienced a strong impact with the rigid anvilblock. To analyze the typical microstructure and mechanical properties of the treated plate, the samples were selected at positions *A*, *B* and *C* as indicated in Fig. 1.

According to the Ritchter's two-dimensional model [17], the initial impact speed of a plate at the explosive moment can be expressed by

$$\frac{V}{D} = 2\sin\frac{1}{2}\left\langle\frac{1}{B + C/R}\right\rangle \tag{1}$$

$$B = \frac{\sqrt{3}}{4}\frac{1}{\sqrt{1-\frac{1}{r}\sqrt{r^2-1}}} \tag{2}$$

$$C = \frac{\sqrt{3(r^2-1)}}{2r\sqrt{1-\sqrt{r^2-1}/r}} \tag{3}$$

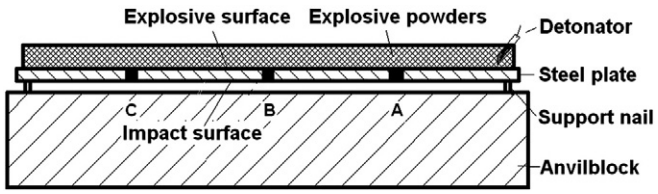

Fig. 1. Sketch of explosive device.

where *V* is the initial impact speed of the plate at the explosive moment, *D* is the detonation velocity of 4600 m/s, *r* is the polytropic exponent of detonation products, and *R* (= 0.3287) is the mass ratio of the emulsion explosive and steel plate.

The initial impact speed of the steel plate can be calculated as approximately 460 m/s, which is much larger than those of the SPD processes.

2.2. Characterization

The microstructure of annealed and treated samples was observed by a scanning electron microscope (SEM) (S-3400, HITACHI). The surfaces of the samples were mechanically polished and etched by a 4 wt.% nitric acid–96 wt.% alcohol solution. The surface layer of the treated samples was investigated by a high resolution transmission electron microscopy (HRTEM) (JEM-2010, NEC) and an accessory selected area electron diffraction (SAED). The microhardness of the surfaces and at different depths on the transverse sections was inspected by a durometer (HXD-1000TM) with an applied load of 0.25 N and a loading time of 10 s. The average value was tested against five points that are located on the same straight lines parallel to the impact surface. A wear test against the surfaces of annealed and treaded samples was conducted on a pin-disk type of abrasion tester (MM-W1; wearing area of 10 × 10 mm, applied pressure of 50 N, disk rotation speed of 100 rad/min). The abrasive paper was coated with SiC powders with a granularity range of approximately 38–44 μm. After wearing for 5 min, the paper was replaced and the weight of the samples was scaled with an electronic balance (MS304S, Mettler-Toledo, accuracy of 0.1 mg). Three samples were used to determine the average weight-loss.

3. Results

3.1. SEM analysis

The annealed 45# steel possesses a biphase structure of ferrite and pearlite as shown in Fig. 2a. After the explosive impact, the impact surface is roughly flat and the impact wave streaks from right to left were produced. A complete plastic deformation penetrated the transverse section of the steel plate. Moreover, the explosive surface was remelted and the impact surface kept its original morphology (no). Because the deformation morphology is very similar at positions *A*, *B* and *C*, only the SEM morphology at position *B* was presented. A sandwich structure formed and the soft ferrite phases were flattened along the direction perpendicular to the impact (Fig. 2b, c and d). The cementite flakes appeared severe slide each other (Fig. 2e); this indicates that a large shear deformation happened inside except the compression deformation. As a result, the thickness of the plate was reduced to approximately 3.9 mm (35% of compression deformation) in the present conditions.

Below the impact surface layer, the microstructure still maintains ferrite and pearlite phases, while the pearlite phases appeared fracture and segmentation during the plastic deformation as indicated at *A* and *B* respectively in Fig. 3a. On the contrary, the microstructure in the impact surface layer was greatly changed. The surface layer presented vortex (Fig. 3b), cementite flake slide (Fig. 3c) and the broken cementite bulks (Fig. 3d), which indicates existence of the complex dynamic stresses (shear and compression) in the impact layer. This phenomenon was not observed in the SPD processes [1–4] because of their very limited momentary plastic strains.

3.2. TEM/HRTEM analysis of the impacted surface layer

Nanocrystallines with approximately 10 nm in diameter uniformly distributed in the deformed grains (Fig. 4a). The equiaxed nanocrystallines at positions *A*, *B* and *C* are shown in Fig. 4b, c and d. The size of the nanocrystallines at position *B* is less than those at