Recovery and Recrystallization of Surface Deformation Layer of 18CrNiMo7-6 Steel after Shot Peening during Isothermal Annealing

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Abstract:
Variations of micro-structure, residual stress of 18CrNiMo7-6 steel after triple shot peening (TSP) against annealing time and temperature were studied. X-ray diffraction line profile analysis (XRDLPA) was used to identify changes of the micro-structure and residual stress relaxation behaviors of top surface of 18CrNiMo7-6 steel after TSP with intensity of 0.50 + 0.30 + 0.15 mmA during isothermal annealing. Results show that micro-strain and compressive residual stress (CRS) on top surface of 18CrNiMo7-6 steel after TSP decreases with the increases of annealing time while domain size increases with increasing annealing time at four fixed different temperatures. At the fixed time, changing rate of micro-structure and residual stress is bigger at higher annealing temperatures.

Keywords: Shot peening; Residual stresses relaxation; Micro-structure; Recovery; Recrystallization

Introduction

18CrNiMo7-6 steel has excellent mechanical properties, and it is widely used in many industrial components such as heavy-duty arbors, bushings, bearings, gears, shafts, sprockets, wear pins etc. [1, 2]. SP is one of the most commonly used mechanical surface treatment in order to obtain the hard surface layer and improve surface quality [3, 4]. In the process of SP, a localised elastic-plastic deformation in near-surface regions leads to a formation of compressive residual stresses (CRS) and severe microstructural alterations [5-7]. The CRS, microstructure refinement and work hardening produced in the shot peened layer can prevent fatigue crack initiation and propagation, so improve the fatigue life of the material [8-11]. The previous work [12] has reported that TSP with the intensity of 0.50 + 0.30 + 0.15 mmA is optimized, and can more efficiently refine micro-structure, generate a higher CRS and improve micro-hardness of 18CrNiMo7-6 steel. In this work, 18CrNiMo7-6 steel after TSP with intensity of 0.50 + 0.30 + 0.15 mmA is used as research object.

In recent years, the researches about 18CrNiMo7-6 steel have almost focused on the mechanical property and micro-structure characterization at room temperature [3, 4, 12, 13]. But little investigation was made on the characterization about the recovery, recrystallization behavior and thermo-stability of 18CrNiMo7-6 steel after SP at increased temperatures, and this study focuses on the stability of CRS and nanocrystalline microstructure produced by SP during isothermal annealing. Meanwhile, XRDLPA is a well-known reliable and non-destructive technique. It is widely used to characterize residual stress and micro-structure of materials [14-19]. In this study XRDLPA was used to identify the change of micro-structure and relaxation behavior of residual stress on the top surface of 18CrNiMo7-6 steel after triple SP during isothermal annealing. And residual stress relaxation mechanism was also discussed.

Experimentals

Materials

The studied samples are manufactured from case-hardened steel 18CrNiMo7-6 (EN 10084). The chemical composition of 18CrNiMo7-6 steel is: 0.170 C, 0.190 Si, 0.560 Mn, 1.520 Ni, 1.650 Cr, 0.320 Mo, 0.006 P, 0.003 S, 0.028 Al, 0.020 Cu, 0.002 Sn and the balance Fe (weight%). All specimens were austenitized at 950 °C for 50 h, subsequently heated at 860 °C for 2 h and quenched in oil, followed by tempering at 180 °C for 3 h and cooling in air.

Shot peening treatment

SP treatments with the intensity of 0.50 + 0.30 + 0.15 mmA were performed by using air blast machines (Carthing Machinery Company, Shanghai). The intensities of SP were measured by the arc height of Almen specimen (A type). The diameter of peening nozzle was 15 mm and the distance between the nozzle and the sample was 100 mm. TSP is to go through 100% peening at 0.52 mmA followed by 100% at 0.25 mmA followed by 100% at 0.16 mmA. The TSP treatments can not only strengthen the sample surface but also make the surface smoother after dual SP, so lower SP intensities or smaller shots were selected to carry out on the third SP treatments. Cast steel balls with diameter of 0.6 mm and hardness of 610 HV or Al_2O_3 ceramic balls with diameter of 0.3 mm and hardness of 700 HV were selected as shot media in SP technologies. The coverage of SP was 100% at all depth.

Measurements and calculations

XRD patterns were measured by Rigaku Ultima IV diffractometer (Cu-Kα radiation) with a D/tex1D high-speed detector. The voltage, current, scanning velocity and step were 40 kV, 30 mA, 2°/min and 0.02°, respectively. The residual stresses of samples were measured by X-ray stress analyzer (LXRD, Proto, Canada) with Ni filter (Cr Kα radiation). The voltage and current was 30 kV and 25 mA, respectively. The shifts of BCC $(211)_\alpha$ peaks were detected in the measurements and then the residual stress was determined by the $\sin^2\psi$ method [20, 21]. The peaks of $(211)_\alpha$ lattice plane were measured at a high 2θ value of 156.4°.

In order to study microstructures, the Cauchy and Gaussian integral breadths of the measured XRD line profiles can be obtained according to the Voigt method [22-24]:

$$b_C^h = b_C^f + b_C^g ; b_G^{h^2} = b_G^{f^2} + b_G^{g^2} \quad (1)$$

Where subscript C and G denote the Cauchy and Gaussian components, and superscripts *h*, *f*, *g* denote measured line profile, structural broadened profile and instrumental profile, respectively. It is assumed that the Cauchy component of the f profile is solely due to crystallite size while the Gaussian component arises from micro-strain. In Voigt method [22, 23], according to integral breaths of single diffraction peaks obtained by Eq. [1], the domain sizes (D) and micro-strain (ε) can be calculated by formula (3):

$$\mathrm{D} = \frac{l}{b_C^f \cos q} ; e = \frac{b_G^f}{4 \tan q} \quad (2)$$

Where λ, β, θ represent the wavelength of Cu-K_α, integral breath and Bragg angle, respectively.

Results and discussions

XRD patterns of the top surface of 18CrNiMo7-6 steel before and after TSP treatments are shown in Fig. 1. From Fig. 1, it can be found that both austenite and martensite phases are found on the top surface of 18CrNiMo7-6 steel before TSP treatment, and only martensite state is detected after TSP treatments, implying that the retained austenite has transformed to martensite after TSP treatments; this result has been discussed in Refs. [12].

In order to further quantify the integral breadths of normalized $k\alpha_1$ diffraction profiles of (110) peak for the top surfaces of 18CrNiMo7-6 steels after TSP, the $K\alpha_2$ components of diffraction peaks were eliminated and the backgrounds were corrected. Voigt method was used to calculate the integral breathes of $k\alpha_1$ diffraction lines of the top surface of TSP treated samples during annealing at different temperatures and times, and the results are shown in Figs. 2 and 3. Then, domain size and micro-strain of the top surface of SP treated samples at different annealing temperature and time can be calculated according to formulas (1) and (2), and the results were shown in Figs. 4 and 5, respectively. It can be found from Figs. 2 and 3that both Cauchy and Gaussian breadth decrease with increase of annealing time at each temperature which indicates that the domain sizes increase and micro-strains decrease with increase of annealing time at each fixed temperature, as illustrated in Figs. 4 and 5, respectively. Moreover, the change rates of domain size and micro-strain are far bigger at higher temperature. After TSP, the elastic-plastic deformation is introduced in the surface layer of samples. During isothermal annealing, the micro-strain relaxation occurs and domain size increases in the process of recovery and recrystallization, which both are driven by the stored energy of deformed state [20].

Fig. 6 shows the variations of residual stress on the top surface of 18CrNiMo7-6 steel before and after SP with annealing time at different temperatures. It can be seen from Fig. 6 that the top surface of 18CrNiMo7-6 steel after TSP has an obvious CRS, which is beneficial to the improvement of mechanical properties [8-11]. At each fixed temperature, with increasing annealing time, the CRS decreases gradually owing to the recovery and dynamic recrystallization of deformation surface. And the CRS has been closed to a stable value when annealing time increase to 120 min. Meanwhile, the plot clearly shows significant dependency of stress relaxation behavior on the exposure temperature and time. Overall, higher temperature and longer exposure time resulted in a larger relaxation.

Conclusions

After TSP treatment with intensity of 0.50 + 0.30 + 0.15 mmA, only martensite phase and a large CRS exist on the top surface of 18CrNiMo7-6 steel. After isothermal annealing for different aging time at the four different temperatures, the Gaussian and Cauchy breadths of (110) diffraction peak for the sample are reduced gradually with increase of annealing time at each fixed temperature; the micro-strain of top surface of 18CrNiMo7-6 steel after TSP decreases with increase of aging time while domain size increases with increasing aging time at these four temperatures. The residual stress decreases with aging time at these four temperatures. The change rates of micro-structure and the residual stress are bigger at higher annealing temperatures.

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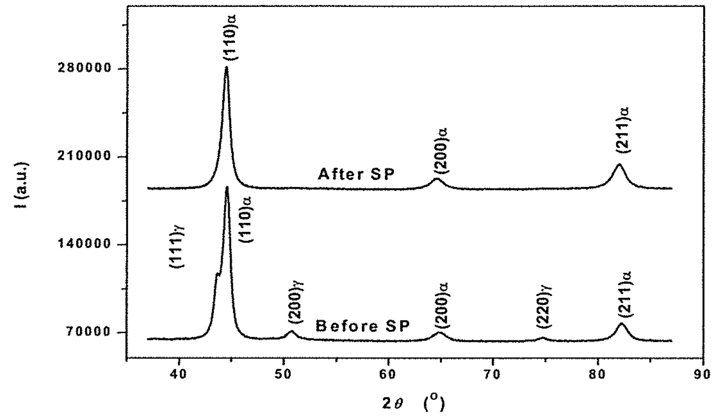

Fig. 1 The surface XRD patterns of 18CrNiMo7-6 steels before and after TSP

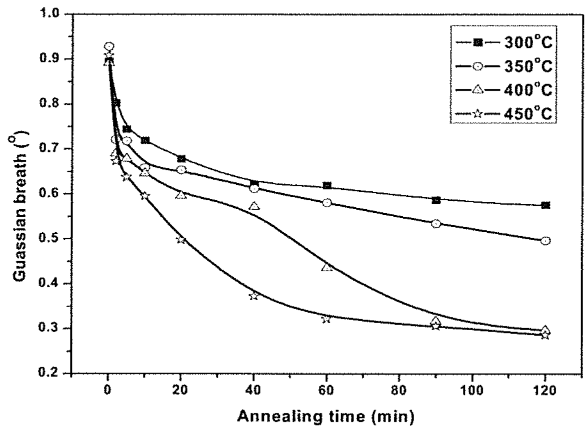

Fig. 2 Variations of Gaussian breadths of (110) peak with annealing time at the four different temperatures

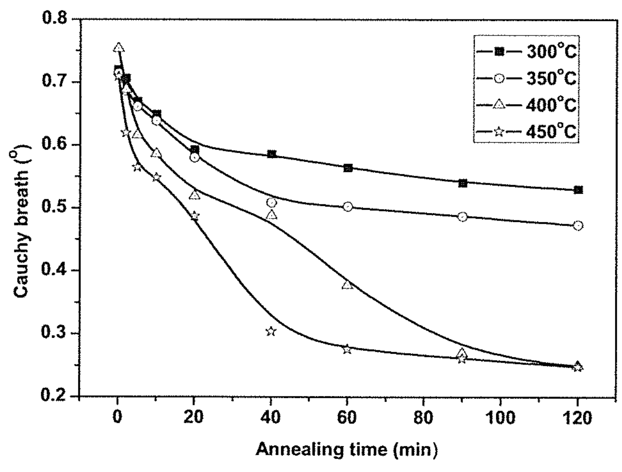

Fig. 3 Variations of Cauchy breadths of (110) peak with annealing time at the four different temperatures

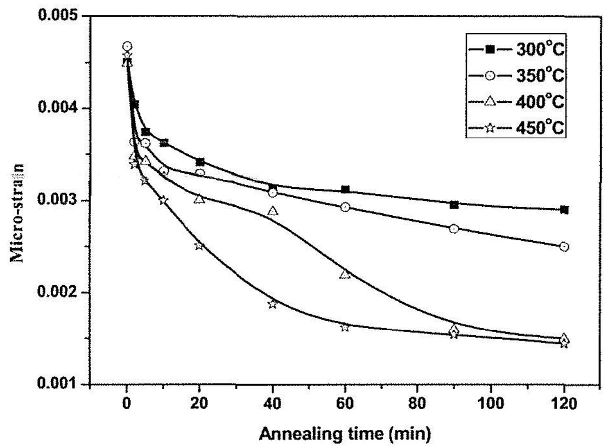

Fig. 4 Variations of micro-strain with annealing time at the four different temperatures

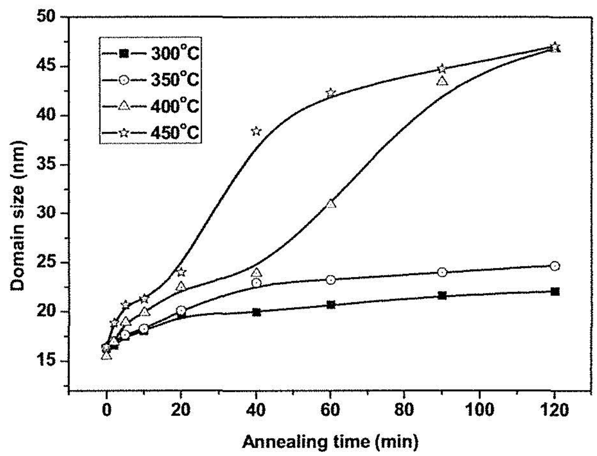

Fig. 5 Variations of domain sizes with annealing time at the four different temperatures

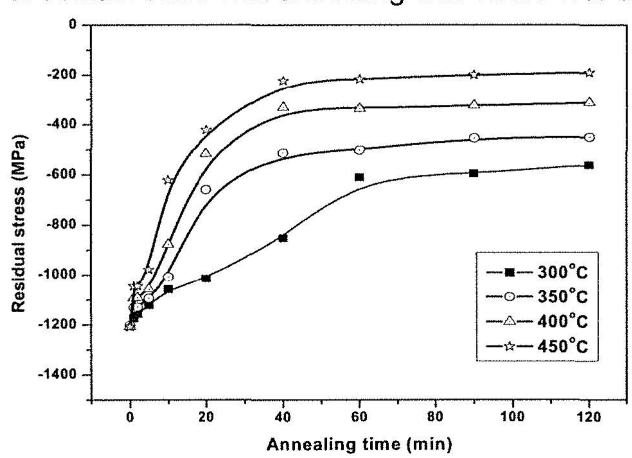

Fig. 6 Residual stresses (martensite) relaxation behaviors of the shot peened sample during isothermal annealing at different time, annealing temperatures are 300 °C, 350 °C, 400 °C and 450 °C, respectively.