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A nanocrystalline-amorphous mixed layer obtained by ultrasonic shot peening on pure titanium at room temperature

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ABSTRACT

A nanocrystalline-amorphous (NC-A) mixed layer was obtained by ultrasonic shot peening (USP) on pure titanium at room temperature and observed by X-ray diffraction pattern (XRD), scanning electron microscope (SEM) and high-resolution transmission electron microscope (HRTEM). The results showed that the amorphization percentage in the NC-A mixed layer increased continuously with the increase of the peening duration, shot diameter and sonotrode amplitude or the decrease of the peening distance. The maximum amorphization percentage achieved in this study was 44.09%. Moreover, with the amorphization percentage in the NC-A mixed layer increasing, the surface hardness increased constantly. Base on the experimental results, the amorphization mechanism during USP treatment was also analyzed.

1. Introduction

Ultrasonic Shot Peening (USP) is a mechanical surface treatment that uses the ultrasonic vibration as energy source to drive shots to impact specimens repeatedly for surface modification or strengthening [1]. It can be applied to rapidly realize surface nanocrystallization (SNC) [2] and has advantages of low energy consumption, short process time, non-pollution, strong controllability and so on [3]. Lu et al. firstly put forward the idea that realizing SNC by USP in 1999 [4]. Tao et al. [2] then successfully obtained nanocrystalline (NC) layer on pure iron. After that, scholars generated NC layers respectively on 316L stainless steel [5], low carbon steel [6], low alloy steel [7], aluminum alloy [8] and pure copper [9], and reported that surface hardness, corrosion resistance, tensile strength, fatigue life and other properties of these USP-treated metals were greatly improved [10–14].

Owing to good mechanical properties, chemical stability, and biocompatibility [15,16], titanium alloys are widely used in many various fields like aerospace, military, marine, medical and so on. Therefore, many scholars focused on the application of USP on titanium alloys. Mordyuk et al. [17] obtained NC layer on pure titanium by rotating pin ultrasonic peening technique and found that the high-cycle fatigue life and surface hardness were improved greatly. Suh et al. [18] reported similar results that the fatigue life of the USP-treated titanium alloy was increased. The NC layer was also observed by Zhang et al. [19] on USP-treated TC4. Besides, Deng et al. [20] and Jindal et al. [21] concluded that the NC layer generated by USP could enhance the corrosion resistance and bioactivity of pure titanium.

Overall, SNC was always considered as the most important microstructure evolution that induced the improvement of material properties after the USP treatment. However, it was reported recently that amorphization or partial amorphization could be obtained by severe plastic deformation (SPD), like shot peening [22], cold rolling [23], surface mechanical attrition treatment [24], cryogenic laser shock peening [25], high pressure torsion [26], severe cold drawing [27] and ultrasonic impact treatment (UIT) [28,29] etc., which also had an important and unique impact on the materials performance. As a new method of SPD, USP should also induce the amorphization or partial amorphization. However, the studies about surface amorphization of titanium alloys treated by USP were scarce.

Thus, to test and verify this novel idea, pure titanium was selected and subjected to USP with different process parameters. Surface nanocrystallization and partial amorphization of pure titanium after USP was investigated by XRD and HRTEM. The influence rules and mechanism of different process parameters on the amorphization were studied and discussed. The influence of partial amorphization on surface hardness of pure titanium was also analyzed.

2. Experimental details

Pure titanium with a composition of $Fe_{0.03}C_{0.08}N_{0.03}H_{0.014}O_{0.015}Ti_{bal}$ and a size of 30 mm × 30 mm × 3mm was used in this work. The USP treatments were carried out at room

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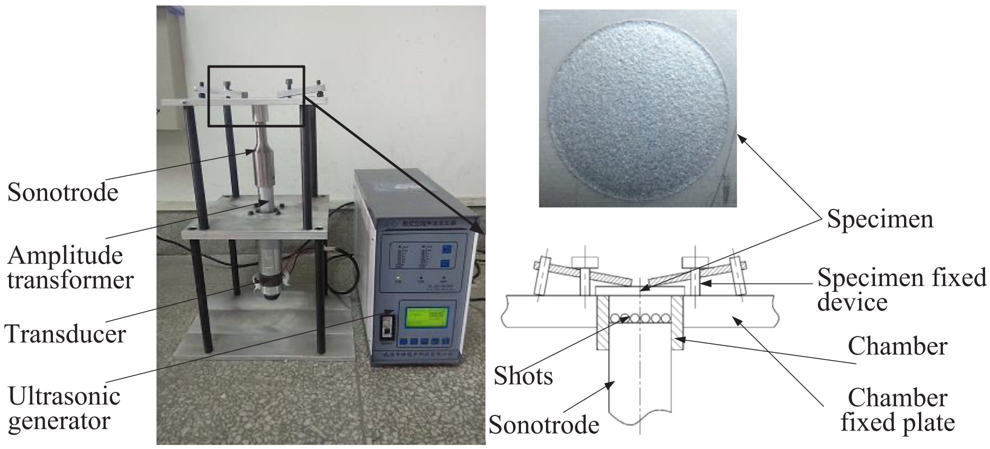

Fig. 1. Ultrasonic shot peening equipment and treated specimen.

Table 1
Process parameters of different USP treatments.

Specimen	Peening duration (s)	Shot diameter (mm)	Sonotrode amplitude (μm)	Peening distance (mm)
1	5	2	32	7.5
2	10	2	32	7.5
3	20	2	32	7.5
4	50	2	32	7.5
5	100	2	32	7.5
6	200	2	32	7.5
7	400	2	32	7.5
8	800	2	32	7.5
9	100	1.4	32	7.5
10	100	3	32	7.5
11	100	3	40	7.5
12	100	3	40	10
13	100	3	40	12.5

temperature in the air by the USP equipment designed and manufactured independently, as shown in Fig. 1. The process parameters of USP treatments are shown in Table 1, which were designed to respectively study the influence of peening duration, shot diameter, sonotrode amplitude and peening distance. The peening distance represents the distance between the top surface of the sonotrode and the bottom surface of specimens. Microstructural evolution and phase analysis were conducted on X-ray diffraction pattern (XRD), Scanning electron microscope (SEM) and high-resolution transmission electron microscope (HRTEM). To prepare the HRTEM foil, the USP-treated specimen was firstly ground to the thickness of 80 μm from the untreated side and then continued to be thinned by ion thinning. Finally, the foil with the diameter of 3 mm was punched for the observation. The original grains were mainly uniform equiaxed grains with an average size of about 37 μm, as illustrated in Fig. 2(a).

3. Results

As shown in Fig. 2, the microstructures of the surface layer on pure titanium after USP treatment could be divided into three parts: NC layer, transition layer and the original grain layer from top surface to the bottom surface. The thickness of the NC layer increases with the increase of the peening duration, sonotrode amplitude and the shot diameter or the decrease of the peening distance. Specimen 11 owns the thickest NC layer with a thickness of about 100 μm [30].

As indicated in Fig. 3(a) and (c), the peak (0 0 0 2) of original specimen was much higher than the other peaks because of the existence of a strong rolling texture [23,31]. After USP treatment of 100 s (II), the peak (0 0 0 2) intensity had an obvious decline, which means the rolling texture was no longer strong though the peak (0 0 0 2) was still the highest. When the peening duration reached 800 s (III), the peak (0 0 0 2) intensity decreased greatly and was even lower than the peak $(2\bar{1}\bar{1}3)$, though the peak $(2\bar{1}\bar{1}3)$ also decreased continuously with the

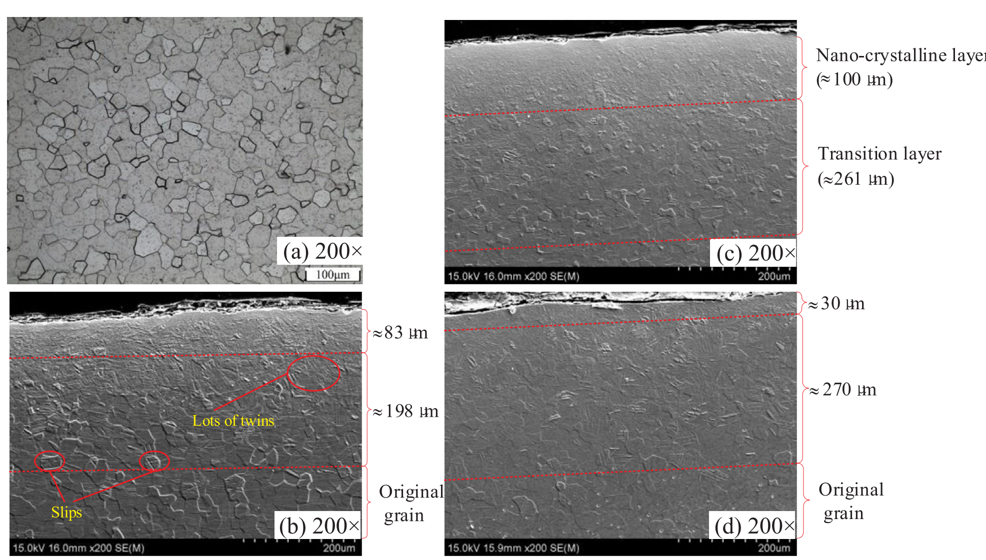

Fig. 2. The microstructures of the cross sections along the thickness direction of (a) The original, (b) Specimen 8, (c) Specimen 11, (d) Specimen 12.