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Microstructure characteristics and formation mechanism of TC17 titanium alloy induced by laser shock processing

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ABSTRACT

As one of the surface strengthening technologies, laser shock processing (LSP) can form a gradient refined surface layer in metallic materials. The gradient microstructural characteristics of TC17 titanium alloy induced by ultrahigh strain rate deformation in LSP were systemically examined by transmission electron microscope (TEM). The microstructure near substrate consisted of dislocations and deformation twins with high density; The microstructures featured of dislocation tangles, dislocation cells and subgrains closer to the surface, and the deformation twins became less prevalent due to higher strains and strain rates where there were insufficient time for atoms to reposition to the twinned orientation to accomplish the twinning deformation; The original coarse grains with size of tens of micrometers (average grain size 43 μm) were refined instantly to hundreds of nanometers (average grain size 396 nm) in the top surface of TC17 titanium alloy after LSP, which was the result of rotation dynamic recrystallization (RDR) proved with quantitative calculation of recrystallization kinetics. There was a gradient distribution of hardness values of the LSPed surface layer.

1. Introduction

Titanium alloys are widely used in aerospace, chemical and other fields due to their high specific strength, corrosion resistance and other superior performances [1]. TC17 titanium alloy (nominal composition of Ti-5Al-4Mo-4Cr-2Sn-2Zr) accounts a large proportion of the total usage of titanium alloys due to the excellent toughening and high temperature property [2–5]. Failures, such as fatigue, usually initiate from surface during practical application [6,7], so it is of great value for enhancing the surface properties of metallic materials.

Surface treatment technologies, such as shot peening (SP) [8,9] and surface mechanical attrition treatment (SMAT) [10], can effectively refine the original coarse grains to submicron or even nanometer scale and induce enhanced gradient microstructures in surface layer without changing the chemical composition. As a new kind of surface treatment method, laser shock processing (LSP) [11] has found an increasing wide utilization in metallic materials for surface strengthening in recent years, and even have been used in technical grade ceramics [12].

The influence of LSP on microstructure evolution of metallic materials has been extensively investigated. Wang [13] investigated the microstructural characterizations of LSPed K403 nickel-alloy with high-level dislocation energy and found that the surface nanocrystallization was accomplished by evolution of dislocations; Mordyuk [14] studied the differences of microstructure characteristics of austenitic stainless steel AISI 321 treated by ultrasonic impact peening (UIP) and LSP, and found a refined nano-crystalline surface layer with depth of about 30 μm in the UIPed sample, while there were dense highly tangled dislocation arrangements and dislocation-cell structures in LSPed one. Ge [15] investigated the nanocrystallization mechanism of surface layer of AZ31B alloy treated by LSP and found that the evolution of dislocation configurations was the main reason of grain refinement; Lu [16] focused on the microstructural characteristics of LY2 alloy after multiple LSP impacts and proposed that subgrain boundaries, which transformed from dislocation tangles and dense dislocation walls, converted to the refined equiaxed grains with highly disoriented grain boundaries by means of continuous dynamic recrystallization. There are limited investigations of microstructural characteristics

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of titanium alloys treated by LSP. Lainé [17] compared the different dislocation structures in Ti-6Al-4V titanium alloy treated by metallic SP and LSP, and explained the reason for few deformation twins appeared in LSP was the ultrahigh strain rate which limited the deformation time that was too short for the formation of deformation twins; Ren [18] investigated the evolution of microstructure in Ti-6Al-4V titanium alloy treated by LSP and concluded that the multidirectional twin intersections and division of subgrain boundaries led to the grain refinement; Zhou [19] found nanocrystalline grains with size of 30–60 nm in the surface of TC17 titanium alloy after LSP with 3 impacts, and the dislocation activities were the main reason of the grain refinement; Qiao [20] got refined grains which was half of the original in surface of Ti17 titanium alloy after 3 impacts LSP and the grains could be further refined with more impact times. Most of the investigations of microstructural characteristics of titanium alloys treated by LSP were limited to the treated top surface, while there are few studies on the evolution of microstructures at different depths, and the grain refinement mechanisms with no evidence of quantitative analysis of recrystallization kinetics in top surface were inconsistent with each other.

It was the first time that the gradient microstructural characteristics of TC17 titanium alloy induced by LSP were systematically investigated by means of TEM and the surface grains instant refinement was quantitatively explained based on recrystallization kinetics of rotation dynamic recrystallization (RDR) mechanism in which the dynamic recrystallization was completed by rotating of low-angle subgrain boundaries to form high-angle boundaries in this paper.

2. Material and methods

The chemical composition of TC17 titanium alloy for LSP was shown in Table 1. The equiaxed coarse grains before LSP possessed an average grain size of about 43 μm. A rectangular specimen with size of 30 mm × 15 mm × 5 mm was used for LSP experiment.

In LSP experiment, aluminum foil with thickness of 100 μm was taken as the thermo-protective layer, and flowing water with thickness of 1 mm was taken as the confining layer. Other processing parameters used in LSP were listed in Table 2.

LSP treated cross-sectioned sample for optical microscope (OM) was prepared using 600–2000# abrasive paper with flowing water during mechanical grinding process and the 3.5 μm diamond abrasion paste was used during mechanical polishing process. Then the cross-section was etched by Keller reagent (92 ml H_2O, 4 ml HNO_3 ml, 2 ml HF, 2 ml HCl) for final optical observation. Microstructures of TC17 titanium alloy at different depths after LSP were observed by TEM. The TEM specimens were prepared as follows: cutting two strips perpendicular to the treated surface with dimensions of 10 mm × 1.1 mm × 1.1 mm (length × width × thickness) and adhered the treated surface face to face and then inserted into a copper tube with a diameter of 3 mm and bonded them together with Gatan G1 glue. Slices cutting down perpendicular to the tube's axis were thinned by mechanical grinding to about 30 μm thick and finally prepared by the method of ion-beam thinning with ion energy of 5 KV and incident angle of 7° for perforation and 3 KV and 2° for 30min to enlarge the thin zone.

Table 1
Chemical composition of TC17 titanium alloy (wt %).

Al	Mo	Cr	Sn	Zr	Fe	Ti
4.5–5.5	3.5–4.5	3.5–4.5	1.6–2.4	1.6–2.4	0.30	Bal

Table 2
Processing parameters used in LSP.

Type	Value
Beam divergence of output/mrad	≤2
Spot diameter/mm	2.5
Pulse energy/J	7
Pulse width/ns	15
Laser wavelength/nm	1064
Energy stability/%	<1.5
Overlapping ratio/%	8

The mechanical property of TC17 titanium alloy after LSP was characterized by Vickers hardness test. Ten measurements along depth direction were taken at intervals of 0.2 mm with load of 1 Kg and holding time of 10s, while the hardness value of top surface was measured separately for supplement.

3. Analysis

3.1. Peak pressure of laser-induced shock wave P (GPa)

The peak pressure of laser-induced shock wave was calculated based on Fabbro's results [21]:

$$P = 0.01\sqrt{\frac{\alpha}{2\alpha+3}} \times \sqrt{Z} \times \sqrt{I_0} \tag{1}$$

where constant fraction α of the internal energy represents the thermal energy [21], and the best value is 0.2 in water confined mode [22]. Z $(\mathrm{g \cdot cm^{-2} \cdot s^{-1}})$ is the reduced shock impedance in confined LSP which is defined as follows:

$$\frac{2}{Z} = \frac{1}{Z_1} + \frac{1}{Z_2} \tag{2}$$

where Z_1 is the shock impedance of target, and Z_2 is the shock impedance of confining layer. $Z_1 = 2.75 \times 10^6 \mathrm{g \cdot cm^{-2} \cdot s^{-1}}$ [23] for TC17 titanium alloy, and$Z_2 = 0.165 \times 10^6 \mathrm{g \cdot cm^{-2} \cdot s^{-1}}$ [22] for water confinement. The reduced shock impedance Z was calculated to be $0.311 \times 10^6 \mathrm{g \cdot cm^{-2} \cdot s^{-1}}$ by formula (2).

I_0 is laser power intensity which calculated as follows [15]:

$$I_0 = \frac{4E}{\tau \cdot \pi d^2} \tag{3}$$

where E(J) is the pulse energy, τ(ns) is the laser pulse duration time, d(cm) is the laser pulse spot size. The E, $\tau$and d in LSP experiment were set to 7 J, 15ns and 0.25 cm, respectively. I_0 was calculated to be 9.5 $\mathrm{GW/cm^2}$.

Took α, Z and I_0 into formula (1) and the peak pressure of laser-induced shock wave was calculated to be 4.2 GPa.

3.2. Adiabatic temperature increase $\Delta T(K)$

The strain rates of treated metals in LSP generally reach $10^7 s^{-1}$ [16]. The laser pulse duration time was 15ns here, while the duration time of laser-induced shock wave in LSP with confining layer is about 2–3 times longer than direct ablation [22], which was approximately 45ns in this experiment. The strain was estimated to be$\varepsilon = \dot{\varepsilon}t = 10^7 \times 45 \times 10^{-9} = 0.45$.

The plastic deformation with ultrahigh strain rate during LSP could be treated as an adiabatic process and there was a temperature increase caused by the converting of plastic deformation to