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Effects of Laser Shock Processing on Fatigue Performance of Ti-17 Titanium Alloy

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Abstract: Ti-17 titanium alloy was treated by laser shock processing (LSP) and the high-frequency fatigue properties were evaluated. The fatigue fracture and the microstructures were observed by scanning electron microscope (SEM) and transmission electron microscope (TEM). The result shows that the average fatigue life of the LSP sample increases 2.62 times at maximum stress 300 MPa under stress ratio is 0.1. The micro-hardness of the samples subjected to LSP increases 20 % compared with the basic material. The proliferation and tangles of dislocations of Ti-17 occurs and the density of dislocation increases after LSP treatment. The high dislocation density of LSP impacts changes the initiation of crack from corner to subsurface, and hinders the crack extension, thus increases the fatigue performance of the Ti-17.

Keywords: laser shock processing, Ti-17 titanium alloy, fatigue performance, micro-hardness

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Introduction

Titanium alloys exhibit high strength-to-weight ratio and excellent corrosion resistance, and it has been used widely in aerospace, automotive, chemical and medical industries. In aircraft industry, the titanium alloys are used for landing gears, large springs and structural parts in wings. For example, the proportion of titanium alloy amounts to about 9 % by weight in the Airbus A380 [1]. As a typical "beta-rich" α + β titanium alloy, Ti-17 (Ti-5Al-2Sn-2Zr-4Mo-4Cr) exhibits outstanding characteristics, such as excellent corrosion resistance, superior fracture toughness and high harden ability. Thus it has been widely used to fabricate jet engine and compressor components [2]. However, as much higher life of aero-engine is needed urgently, to extend the fatigue life of titanium alloy has become a very important subject.

Laser shock processing (LSP) is a novel approach to improve fatigue property, hardness and other mechanical properties of metals, during which a deeper compressive residual stress is generated on the irradiated surface [3, 4]. When the high-power (GW/cm^2), short-pulse (ns) laser passes through the transparent confining layer and hits the surface of the absorbing material, the absorbing material vaporizes and forms the plasma with high temperature and high pressure in an ultra-short time (Figure 1) [5, 6]. The rapidly expanding plasma is trapped by the confining layer, which creates a shock wave propagating into the material [7, 8]. The plastic deformation occurs and the compressive residual stress is generated on the deformed region [9, 10]. The uniform compressive residual stress improves the fatigue performance characteristics and strength of the material [11, 12]. Some researchers have done much work on TC4 titanium alloy with LSP treatment. Qiao Hongchao found that the surface hardness of TC4 with LSP treatment increased 33.5 % and the compressive residual stress on the surface of laser irradiated area reached −323 MPa [13]. Lu Jinzhong have studied the surface micro-hardness and residual compressive stress of EBW (electron beam welding) joint, the result showed that the micro-hardness increased and much high residual compressive stress was created [14, 15], and the high cycle fatigue endurance increased 15.8 % after LSP treatment [16]. In addition, the hardness of Ti-17 titanium alloy has been improved by 10 % in 1 mm depth affected layer [17]. However, the studies about the fatigue property of Ti-17 titanium alloy subjected to LSP treatment has seldom reported.

In this work, the micro-hardness and fatigue performance of Ti-17 titanium alloy with LSP treatment were tested. Moreover, fracture morphology and microstructure of the alloy were observed and analyzed.

Experiments

Experiment material and dimension

The substrate was of a Ti-17 titanium alloy having 5 mm thick. The chemical composition of this material was

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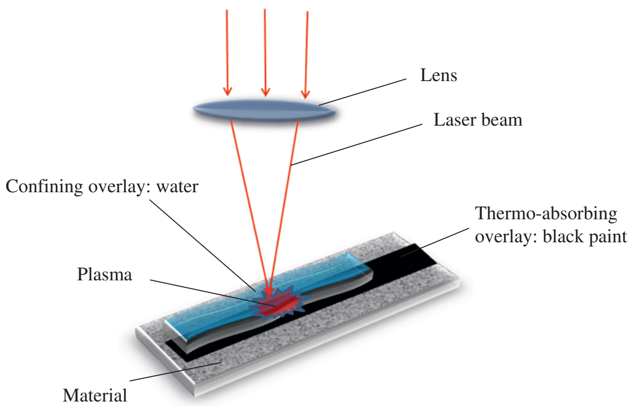

Figure 1: The sketch map of confined treatment with laser shocks.

Table 1: Chemical composition of Ti-17 titanium alloy (wt.%).

Al	Sn	Zr	Mo	Cr	Fe	C	N	Ti
4.5	1.8	1.8	3.5	3.5	0.3	0.05	0.05	Balance

given in Table 1. The sketch map of the fatigue sample is shown in Figure 2.

Laser shock processing

The LSP experiments were performed using a Q switched Nd: YAG laser operating at 2 Hz with a wave length of 1,064 energy was around 5 J. The footprint of laser spot with a diameter of 3 mm was top-hat and the FWHM of the pulses was 10 ns, shown in Figure 3. Specimen treated area was 60 mm × 15 mm on both sides. The specimen was treated two times on both sides. In order to improve the absorption from the laser energy and prevent the sample surface from the laser ablation, 0.1 mm black tape was used as an absorbing layer. In addition, the water layer with a thickness of 1–2 mm was applied on the black tape as the transparent confining layer to increase the peak pressure of the laser shock waves, impulse in the samples and the action time.

Micro-hardness test

The micro-harnesses of the original sample and the LSP sample were measured by the micro-hardness tester (DHV-1000) with 50 g load and 10 s holding time. The micro-harnesses of 7 points were tested at the interval of 1 mm along a straight line on the original sample and LSP sample, respectively.

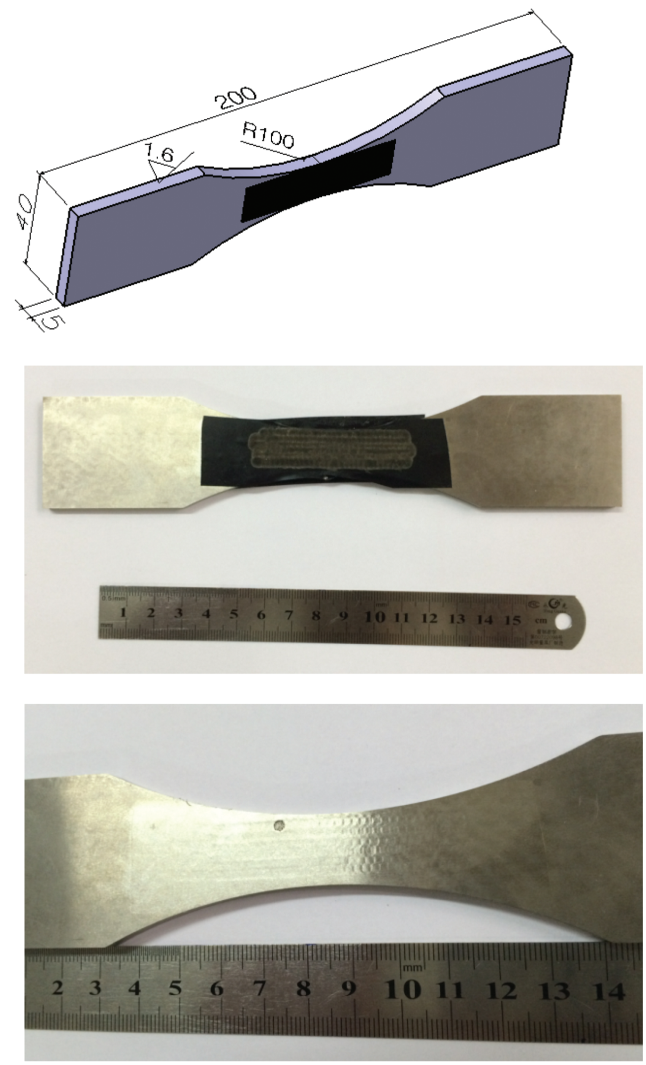

Figure 2: The sketch map of the fatigue samples.

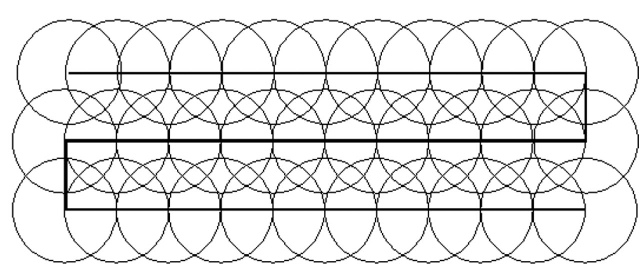

Figure 3: Geometry of treatment with laser shocks.

Fatigue test

The fatigue experiments were performed on a high frequency (87–88 Hz) testing machine (QBG-100) at room temperature. All fatigue samples were tested to failure at maximum stress 300 MPa, and a stress ratio (minimum to maximum stress ratio) of $R = 0.1$ under constant-amplitude load control with precision. Then the fatigue life of the fatigue samples with and without LSP treatment were gained.

Fracture morphology and microstructure

The fracture morphologies of the fatigue samples with and without LSP treatment were examined via a scanning electron microscope (SEM) (JSM-6010LA, JEOL). The microstructure of the samples with and without LSP treatment was examined by a transmission electron microscope (TEM) (JEM-2100, JEOL).

Results and discussion

Effects of LSP treatment on the microscopic structure of Ti-17 titanium alloy

The microstructure of Ti-17 titanium alloy before LSP treatment is shown in Figure 4(a), and that after LSP treatment is depicted in Figure 4(b). The density of dislocation after LSP treatment increases greatly compared with that before LSP treatment. The plastic deformation was carried out on the irradiated region of the alloy under the shock wave generated by LSP. The dislocation was formed in the first place, and then plastic deformation was produced by dislocation slip. The shock waves affect the grain in various directions through the reflection and refraction of the shock wave on the grain boundary [18]. Thus a new grain boundary was formed by complicated slip and agglomeration of the dislocation.

Effects of LSP treatment on the micro-hardness

Figure 5 shows the micro-hardness of Ti-17 titanium alloy with and without LSP treatment. From the result, the average micro-hardness of original Ti-17 titanium alloy is 345 Hv. After LSP treatment, the average micro-hardness of Ti-

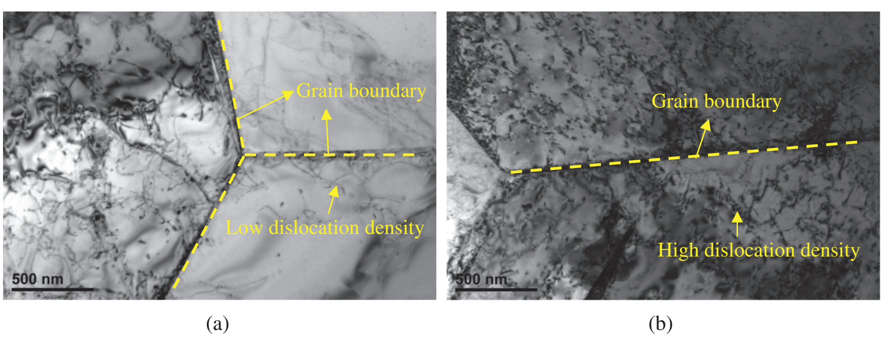

Figure 4: The density of dislocation of sample without LSP (a) and with LSP (b).

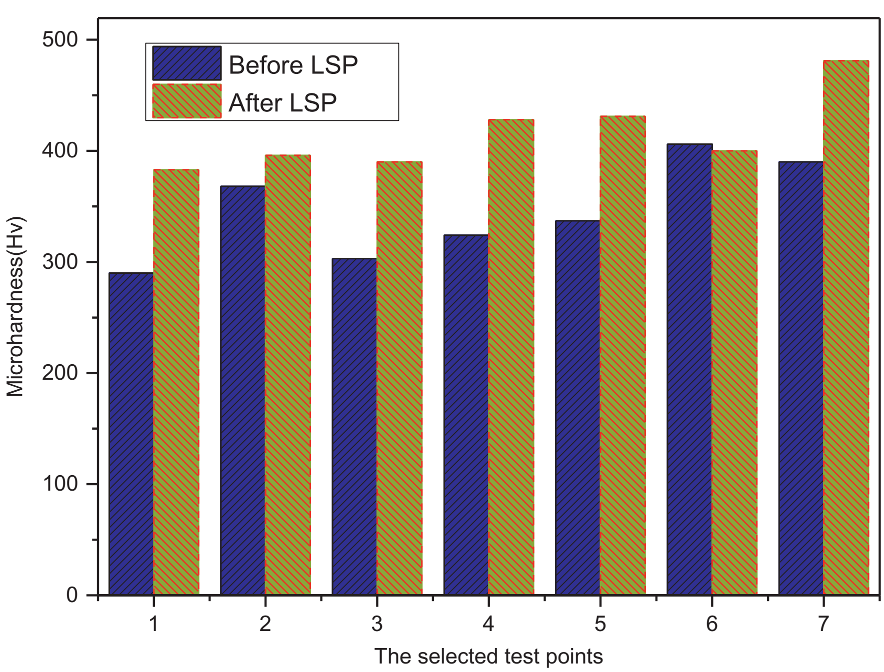

Figure 5: The micro-hardness of sample with and without LSP.

17 titanium alloy is 415 Hv. Thus the average micro-hardness of Ti-17 titanium alloy increases about 20 %.

Note that higher density of dislocation hinders plastic flow of metal, and also improves the micro-hardness of materials. The relationship between micro-hardness and the density of dislocation can be expressed by the following formula [19]:

$$Hv = Hv_0 + aGb\rho^{\frac{1}{2}} \tag{1}$$

Hv, The micro-hardness of materials; Hv_0, The micro-hardness of the matrix; a, Constant related to the material; G, Shear modulus; b, Burgers vector; ρ, Density of dislocation.

From formula (1), it can be seen that Hv is proportional to $\rho^{1/2}$. Furthermore, increase of dislocation density ρ is helpful to improve the micro-hardness of material.

Effects of LSP treatment on the fatigue life

Figure 6 shows the fatigue life results of Ti-17 titanium alloy with and without LSP treatment at 300 MPa. The average fatigue lives of Ti-17 titanium alloy before and after LSP treatment are 133 kilo-cycle and 349 kilo-cycle, respectively. Thus, the average fatigue life of LSP samples improves 2.62 times at 300 MPa.

Effects of LSP treatment on the fracture morphology

The fatigue fracture is the direct result of material progressive smash and it is a real reflection of the fracture process. There are three regions in the fatigue fracture: crack initiation, fatigue crack growth area and transient fault zone. The total lives of test samples under cycle loading could be determined by the initiation and growth of the cracks.

Figures 7(a) and 7(b) show the crack initiation site and early crack growth of fatigue samples before and after LSP treatment. The white arrows point the crack initiation, the yellow arrows display the trend of crack growth, and the full lines are the boundaries of fatigue crack growth area and transient fault zone. It could be found that the fatigue crack initiation formed at the tip of un-LSP rectangular sample. The fatigue crack originates from the corner, and then expands into the internal of the sample. The lack of surface stress concentration of the un-LSPed specimen leads to a single crack nucleus and a semi-circular shape surface crack, shown in Figure 7(a). On the other hand, the rough surface of the LSPed sample promotes multiple crack initiation sites and the crack adopts an elongated semi-elliptical shape (Figure 7(b)), and the crack initiation is at the depth of about 100 μm from the top surface. Compared with Figures 7(a) and 7(b), it can be seen that the crack initiation changed from corner to sub-surface of the sample after LSP. This is because that the compressive stress generates in surface layer after LSP, it counters the tensile stress, and transforms the tensile stress state into compressive state, which results in an increase in resistance to fatigue crack initiation in the surface layer. Thus, the crack initiation after LSP is changed from surface to subsurface [20]. If there are no defects in material, crack initiation generally formed on the surface of material [21], just as Figure 7(a). Note that high density of dislocation generates in the surface layer after LSP (Figure 4), which will hinder the formation of crack initiation on the surface, then the crack initiation

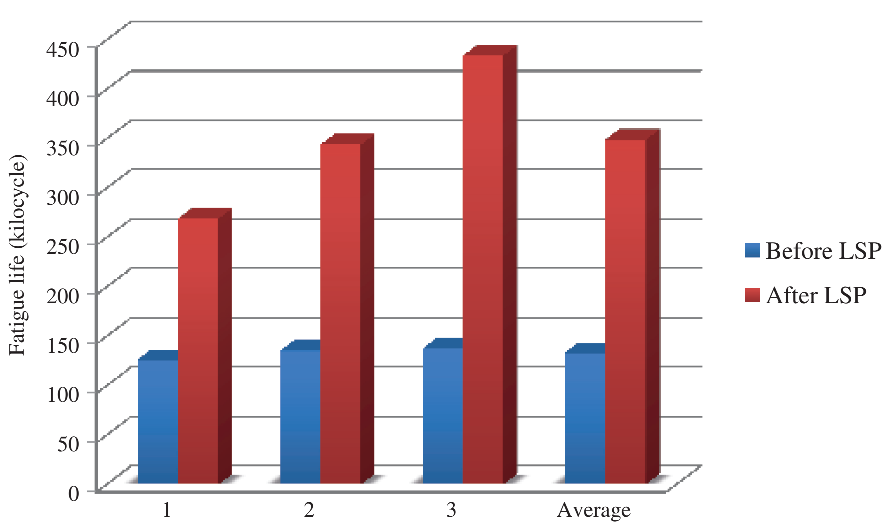

Figure 6: The fatigue life of sample with and without LSP.

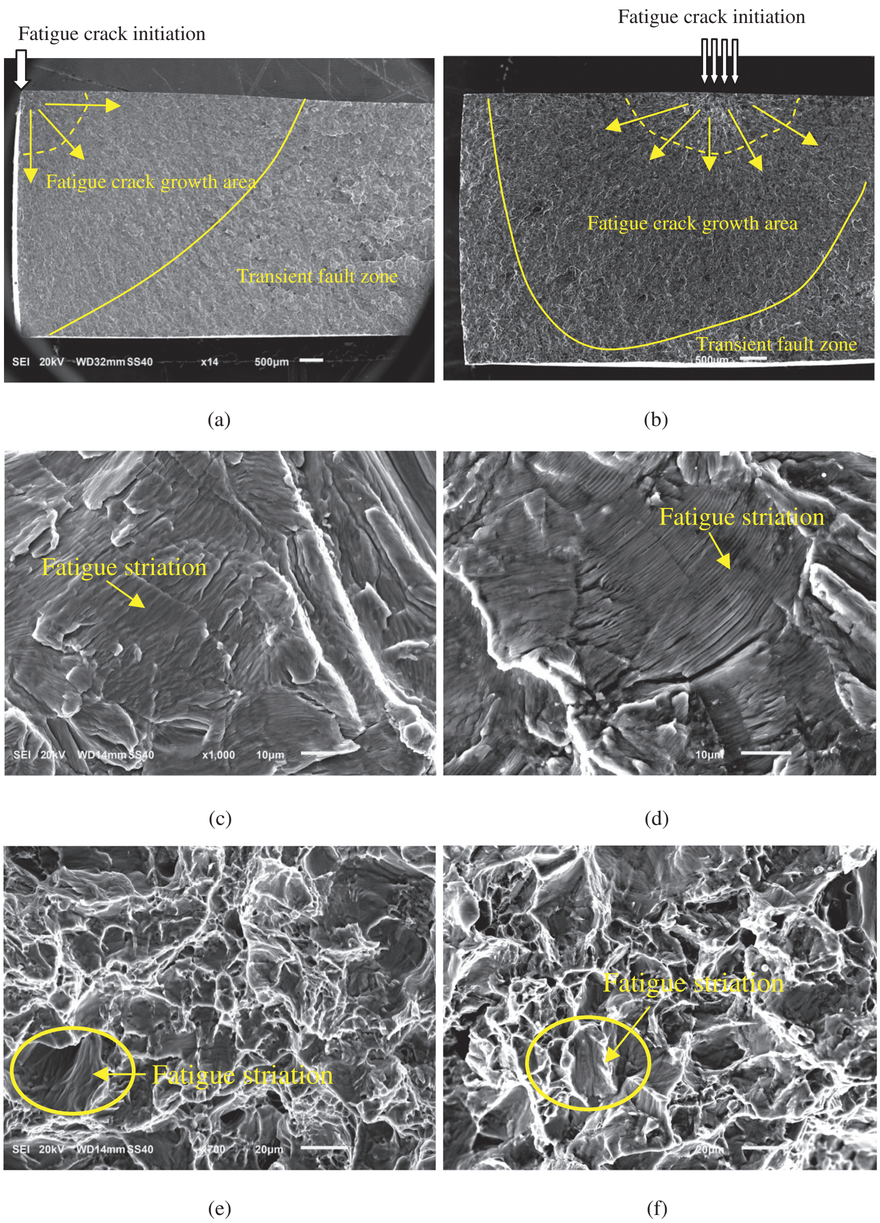

Figure 7: The fracture morphologies of sample without LSP (a) and with LSP (b), the fatigue striation of sample without LSP (c) and with LSP (d), the transient fault zone of sample without LSP (e) and with LSP (f).

formed on material subsurface, which is helpful to the life extension [22, 23].

The existence of fatigue striation is the most important feature of fatigue crack growth. Under the cycle loading, most metals experience the stable crack growth period. The fatigue striation and its specific form are the direct fatigue fracture microscopic data of the fatigue fracture [24]. It can be seen fatigue striation is vertical to the crack extending direction, and each fatigue striation represents a fatigue loading cycle. Fatigue striation is straight and parallel on the small fault block, but adjacent striation on the discontinuous minor fault blocks is not parallel, accompanied by the presence of fatigue steps. Figures 7(c) and 7(d) show the SEM of the fatigue fracture with and without LSP treatment under higher power lens. Compared to the non-LSP sample fracture, characters of the Ti-17 titanium alloy fatigue fracture after LSP are very typical. The fatigue striation width of original sample is at the level of 2–3 μm, while the fatigue striation width of LSPed sample is at the level of 0.6–0.8 μm. The distance between fatigue striations is narrower and the number of striations is very larger in the LSP zone, which indicates that the crack expansion distance is small under each loading cycle. This reduction in striation spacing indicates a slower fatigue crack growth rate and is partially attributed to the deeper compressive residual stresses induced by LSP, which means LSP has an inhibitory effect on fatigue crack growth, and this pattern agrees well with the result reported by Liu [25].

Figures 7(e) and 7(f) display the images of the transient fault zone of the samples with and without LSP treatment. Transient fault zone is the extension area after fatigue crack grows instability to the critical size. There are no obvious differences between specimens with and without LSP treatment in transient fault zones. Note that lots of dimples are discovered in the transient fault zone of both specimens. Moreover, some fatigue striations exist in the dimple (the diagram of circular area).

Conclusions

In summary, the following conclusions can be drawn:

(1) Under the condition of maximum stress 300 MPa and 0.1 stress ratio, the average fatigue life of sample without LSP treatment is 133 kilocycle, and the average fatigue life of sample with LSP treatment is 349 kilocycle. The average fatigue life of the sample increases 2.62 times.

(2) After the laser shock processing, the micro-hardness of the LSP sample increase 20 %. The proliferation and tangles of dislocation in the surface layer occurs, and the density of dislocation increases. The high dislocation density changes the crack initiation, and hinders the crack extension, thus increases the fatigue performance of the Ti-17 after LSP impacts.

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