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Laser shock peening induced fatigue crack retardation in Ti-17 titanium alloy

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ABSTRACT

Laser shock peening is an advanced surface treatment technique of great interest introducing beneficial compressive residual stress and further enhancing fatigue crack propagation resistance of metallic components. In this study, fatigue crack propagation and subsequent retardation of Ti-17 titanium alloy under laser shock peening are presented. Varying degrees of fatigue crack retardation were observed after peening with pulse energy of 20 J and 30 J. The fatigue life was increased up to 2.4 times that of the unpeened counterpart. The fatigue arrests were observed in the deceleration zone after peening, showing different angles with the fatigue crack path as the peening energy varied. The fatigue crack retardation mechanism based on the plastic zone size and crack propagation energy density drop at the crack tip was further discussed, and a crack tip energy density criterion was proposed to quantitatively understand the fatigue crack retardation.

1. Introduction

Titanium alloys have been extensively used in aero engines, for example in fan blades, blisks and low temperature section components of pressure compressors, due to their high specific strength, excellent mechanical properties and outstanding resistance to fatigue, high temperature and corrosion [1–5]. However, these titanium components are frequently subjected to extreme working conditions, such as foreign object damage [6,7], thermal stress [8,9] and cyclic vibration [10,11], which are likely to cause deformation and even fracture of the structural components. These failures greatly reduce the service life and seriously affect the use reliability of aero engines [12–14]. Thus, several processes are available for modifying the surface related properties and enhance the fatigue performance of components [15–19]. Among these processes, laser shock peening (LSP), as an advanced surface treatment technique, applying high power nanosecond pulse laser onto the surface of metallic components to induce high amplitude and large depth compressive residual stress [20,21] is receiving increasing attention [22–25]. This compressive residual stress has been found to be effective in improving fatigue properties in aluminum alloys, steels and titanium alloys [26–28] by delaying the crack initiation and by decelerating the crack propagation rate.

It has been found that the fatigue striation spacing in LSP treated specimen is narrower than unpeened ones [29]. Research shows that a higher laser peening energy or coverage area could lower the fatigue crack propagation (FCP) rate of 6061-T6 aluminum alloy, especially in the initial fatigue crack growth stage [29,30]. Compared with shot peening, laser peening induced a relatively flat crack front because of a deeper penetration of compressive residual stress, which leads to a better FCP life. Although the crack closure and enhanced FCP life could be observed in both the shot peened and laser peened specimens with different degrees [31], the FCP rate still showed continuous increasing during the propagation. Interestingly, deceleration in the FCP rate during the propagation was observed in AA2024-T351 aluminum alloy after LSP by Kashaev et al. [32]. They suggested that LSP induced compressive residual stress caused the crack closure effect and consequently increased the level of crack opening load and thus reduced the effective load range, which could decelerate the crack propagation. To the best of our knowledge, this is the very few published works with the observation of such a deceleration zone using LSP. To date, the generation mechanism of such a deceleration zone and its micro-features on the fracture surface remains unclear. Therefore, it is of great importance and necessity to thoroughly understand this phenomenon to expand its applications in scientific and engineering fields.

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

Al	Sn	Zr	Mo	Cr	Fe	Ti
5.00	2.12	2.09	4.13	4.08	0.3	Bal.

This study seeks to observe the deceleration zone during FCP, analyze the fatigue morphologies of different regions on the fracture surfaces and further reveal its deceleration and retardation mechanism in laser shock peened Ti-17 titanium alloy.

2. Experimental procedures

2.1. Material

The material employed in this study was a Ti-17 titanium alloy with a thickness of 5 mm, and its chemical compositions are given in Table 1. The microstructure of the alloy consists of alpha phase and beta phase with precipitation of lamellar secondary alpha phase. The mechanical properties are presented as follows: ultimate tensile strength of 1185 MPa, yield strength of 1137 MPa, elongation of 11.7%, elastic modulus of 110 GPa and Poisson's ratio of 0.33.

2.2. Laser shock peening

The LSP experiments on the alloy were carried out using a Q switched Nd: YAG high power pulse laser with a wavelength of 1064 nm, a pulse duration of 15 ns, a circular spot size of 4 mm and an overlapping rate of 50%. The pulse energies employed in this study were 20 J and 30 J, respectively; thus, the peak power densities equal to 10.61 GW/cm^2 and 15.92 GW/cm^2. A running water layer with a thickness of about 2 mm was applied as the transparent layer to increase the peak pressure of the laser shock wave. To avoid possible damage or roughening of the specimen surface by laser irradiation and to reduce the reflection loss of incident laser light, a protective coating, aluminum foil with a thickness of 100 μm (3 M, USA), is typically attached to the peening surface. Specimens were double-side peened with a zigzag laser path covering an area of approximately 20 × 20 mm^2, as shown by the blue patterns in Fig. 1a.

2.3. Fatigue crack propagation (FCP) tests

FCP tests were performed on a 50 kN fatigue machine (Instron-8801, USA) using the compact tension (CT) specimens, according to the test standard of GBT 6398–2000, China. Dimensions of the specimen employed are presented in Fig. 1a. Prior to FCP tests, nine CT specimens were pre-cracked to 13.5 mm (1 mm from the notch tip) under mode - I (tensile opening) with a constant external load of 2 kN, and were divided into three categories: BM (base metal), LSP - 20 J × 3 (20 J with three impacts) and LSP - 30 J × 3 (30 J with three impacts). The specimen with typical fatigue fracture characteristics among the three specimens in each group was taken to analysis. Shortly after the pre-cracking, a sinusoidal load (1.5 kN) was applied at a frequency of 20 Hz and a stress ratio of 0.1 on BM at the ambient temperature (20 °C) in air, as shown in Fig. 1b. While the LSP - 20 J × 3 and LSP - 30 J × 3 specimens were tested after a typical LSP process, with specimen showing in the up right corner of Fig. 1b. The length of the fatigue crack was measured by a COD gauge attached to the specimen. The following equation was used to determine the stress intensity factor (SIF, ΔK) [33]:

$$\Delta K = \frac{\Delta P}{B\sqrt{W}} \cdot Y \tag{1}$$

where $\Delta P = P_{max} - P_{min}$ is the constant external load, B is the specimen thickness, W is the width of the specimen, and Y is a geometrical factor, which is derived for linear elastic material for compact tension specimens:

$$Y = \frac{2 + (a/W)}{(1-(a/W))^{3/2}}\left[0.886 + 4.64\left(\frac{a}{W}\right) - 13.32\left(\frac{a}{W}\right)^2 + 14.72\left(\frac{a}{W}\right)^3 - 5.60\left(\frac{a}{W}\right)^4\right] \tag{2}$$

where a is the crack length.

2.4. Material characterization

Transmission electron microscopy (TEM, JEM-2100, JEOL), operated at a voltage of 200 kV, was employed to study the influence of LSP on the microstructural evolution in the alloy. The alloy specimen was first cut into a thin sheet of 500 μm. Specimens were then mechanically ground with SiC paper (#1000 and #2000) down to about 100 μm in thickness and punched out to 3 mm diameter discs. This was followed by ion-milling by Ar + bombardment with proper incident angles (5 degrees on both sides). Residual stress in depth direction was measured using "Prism" measurement system (StressTech, Finland) based on the incremental hole drilling method. It is equipped with an optical electronic speckle pattern interferometer system that provides high-quality full-field data for accurate residual stress calculation. This technique

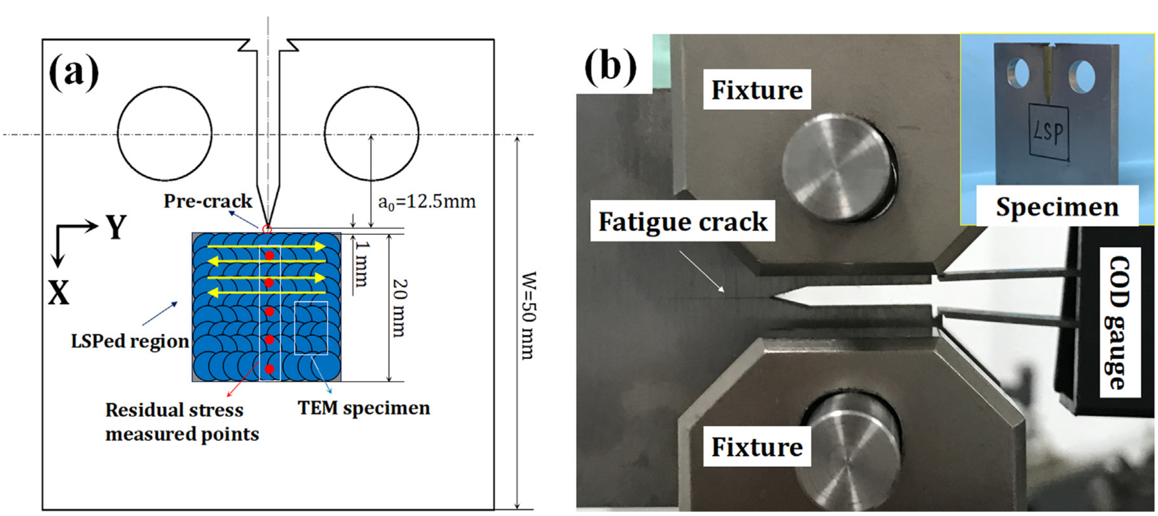

Fig. 1. (a) Dimensions of the CT specimens with the illustration of LSP patterns and (b) the assembly of CT specimens on the fatigue machine.