Optics and Lasers in Engineering ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at SciVerse ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

# Effects of laser peening on residual stresses and fatigue crack growth properties of Ti–6Al–4V titanium alloy

J.Z. Zhou, S. Huang*, L.D. Zuo, X.K. Meng, J. Sheng, Q. Tian, Y.H. Han, W.L. Zhu

*School of Mechanical Engineering, Jiangsu University, Zhenjiang 212013, PR China*

ARTICLE INFO

*Article history:*
Received 28 January 2013
Received in revised form
21 May 2013
Accepted 20 June 2013

*Keywords:*
Laser peening
Residual stress
Fatigue crack growth rate
Ti–6Al–4V titanium alloy
Coverage rate

ABSTRACT

The effects of laser peening (LP) with different laser peening coverage rates on residual stresses and fatigue crack growth (FCG) properties of Ti–6Al–4V titanium alloy were investigated. Residual stresses after LP and micro-structure with different fatigue striation patterns on fracture cross-sections were analyzed. Compressive residual stresses and dense dislocation arrangements can be obtained in the superficial layer after LP. The influence of compressive residual stresses induced under different LP coverage rates on FCG properties was revealed. LP coverage rate had an apparent influence on FCG properties as confirmed by the fatigue striation spacing on fracture cross-sections. Moreover, FCG rate decreased with the increase of compressive residual stresses perpendicular to the crack growth direction, which indicated that LP had an obvious inhibitory effects on FCG.

## 1. Introduction

Nowadays, fatigue crack growth (FCG) behaviors of titanium alloy is of great importance in the safety of critical components in engineering applications due to the wide use of titanium alloys [1,2]. Thus, it is of great significance to focus on improving the fatigue lives of titanium alloy. Shot peening (SP) is the common technique to improve FCG properties of titanium alloy due to the beneficial compressive residual stresses [3–5], however, the surface roughness is high and the amplitude of the compressive residual stress is low. Thus, some alternative new peening technologies have emerged, such as laser peening (LP) [6,7], ultrasonic peening [8] and micro-shot peening [9]. Among these peening technologies, LP is a competitive surface treatment technique with deeper and higher compressive residual stresses as well as lower surface roughness. Compared with SP, LP has stronger effects on reducing FCG rate of titanium alloys [10–12].

Several authors have studied the effects of different LP parameters on FCG properties of titanium alloy. King et al. [11] studied the effects of residual stresses distribution on fatigue and fretting fatigue of SPed and LPed Ti–6Al–4V samples, and the results indicated that LP could induce greater fatigue resistance than traditional SP. Zhang et al. [12] experimentally investigated the effects of LP impact numbers and LP intensity on residual stresses, micro-hardness and fatigue properties of Ti–6Al–4V titanium alloy, which could be improved with LP impact numbers.

In addition, many existing papers have studied the effects of LP processing parameters including spot size [13], power densities [14,15], impact number [6,12] as well as peening path [16,17] on residual stress distribution and FCG behavior, but few attentions have been paid to the effects of LP coverage rate on residual stress distribution and fatigue performance. Kim et al. [18] investigated the effects of different weld coverage areas on FCG behavior of friction stir welded aluminum alloy, and the results showed that processing coverage area apparently affected the FCG property. In our previous study [16,17], we also found that LP coverage area can greatly influence the FCG property of 7050-T7451 aluminum alloy, and it is found that there exists an optimal value for the coverage area size parallel to crack in the CT (Compact Tension) samples [19,20]. It can be concluded that residual stress distribution change with the LP coverage area, moreover, the stronger residual stress distribution along FCG driving force direction could produce the greater inhibition effects on FCG [16–20]. Therefore, it is crucial and necessary to investigate the influence of LP coverage rate along the FCG driving force direction on FCG properties of titanium alloy. In this study, coverage rate is defined as the ratio of coverage area size vs the overall size along the direction perpendicular to crack, while the size parallel to crack maintains as a constant value.

This work is to investigate the effects of LP coverage rate on residual stress distribution on the surface of Ti–6Al–4V titanium alloy, and the direction of LP coverage is both parallel and perpendicular to crack growth direction. Furthermore, the

---

* Corresponding author. Tel.: +86 511 88786318; fax: +86 511 88780241.
*E-mail address:* huangshu11@sina.com (S. Huang).

0143-8166/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.optlaseng.2013.06.011

Please cite this article as: Zhou JZ, et al. Effects of laser peening on residual stresses and fatigue crack growth properties of Ti–6Al–4V titanium alloy. Opt Laser Eng (2013), http://dx.doi.org/10.1016/j.optlaseng.2013.06.011

improvement mechanism of FCG property is revealed based on micro-structure.

## 2. Experiments and methods

### 2.1. Material and sample

Ti–6Al–4V titanium alloy was chosen in this work. Typical mechanical properties of the bulk material are listed in Table 1, and the CT samples used for FCG tests are illustrated in Fig. 1. All the CT samples were processed with the loading axis parallel to rolling direction. They were pre-cracked with the length of 2.5 mm before LP. The total crack length of the initial crack after pre-cracking was 15 mm.

### 2.2. Laser peening process

LP process was performed by an experimental set-up containing a *Q*-switched Nd: YAG laser system and a five-axis-cooperating numerically-controlled precision working table. Laser beam wavelength used was 1064 nm with a repetition-rate at 5 Hz, and the pulse duration was 20 ns with a spot diameter of 3 mm. Laser pulse energy was 9 J. Table 2 shows the LP processing parameters in detail. LP experiment was carried out with a confined plasma configuration. A thin aluminum foil adhesive tape was selected as the energy absorbing layer to protect the surface of samples from thermal effects and a water curtain with a thickness of about 2 mm was used as the plasma confinement layer. Fig. 2a–c show the swept direction and coverage rate perpendicular to crack growth path of CT samples during two-sided LP. The coverage rate perpendicular to crack growth direction were 20% (15 mm × 12 mm, LP-1), 40% ( 15 mm × 24 mm, LP-2) and 80% (15 mm × 48 mm, LP-3), respectively. The overlapping rate of adjacent spots was 50%.

### 2.3. Measurements and methods

All residual stress measurements were performed by a standard X-ray diffraction technique. Measurement points were collected at different LP regions both parallel and perpendicular to the crack growth direction. Residual stresses along the depth direction were obtained by successive electromechanical removal. The FCG tests were performed on MTS-809 servo-hydraulic system at room temperature in the air. The maximum external load was maintained at 4.0 kN and load ratio *R* was 0.5. The tensile sinusoidal form with a frequency of 10 Hz was used in the tests. Twelve samples were chosen for FCG tests. Samples 1–3 were untreated, samples 4–6, 7–9 and 10–12 were treated by LP-1, LP-2 and LP-3, respectively. The fatigue fracture micro-structure was analyzed by a JSM-7001F field emission scanning electron microscopy (SEM) operated at a voltage of 15 kV.

## 3. Results and discussions

### 3.1. Residual stresses

The residual stresses along the crack growth direction are presented in Fig. 3a. It is found that there exits a tensile residual stress with the value of 54 MPa at the crack tip of untreated sample after pre-cracked, and this value decreases to a stable value (almost 50 MPa) of matrix. However, the LPed samples are completely distinct, the residual stresses are -298 MPa, -320 MPa and -361 MPa at the crack tip, and then increase to -330 MPa, -350 MPa and -400 MPa after LP-1, LP-2 and LP-3, respectively, when the measurement region is about 7 mm away from the crack tip, and keep almost stable until 22.5 mm away from the crack tip. Subsequently, the compressive residual stress value decreases gradually for all the LPed samples. They all turn into tensile stress at 28.3 mm, 31 mm and 32.5 mm away from

**Table 1**
Typical mechanical properties of Ti–6Al–4V titanium alloy.

| Material | Young modulus (GPa) | Yield stress (MPa) | Ultimate stress (MPa) | Elongation at fracture |
|---|---|---|---|---|
| Ti–6Al–4V | 110 | 826 | 1050 | 9.6% |

**Table 2**
The processing parameters used in LP.

| Pulse energy (J) | Spot diameter (mm) | Export stability | Pulse width (ns) | Laser wavelength (nm) |
|---|---|---|---|---|
| 9 | 3 | < 5% | 10 | 1064 |

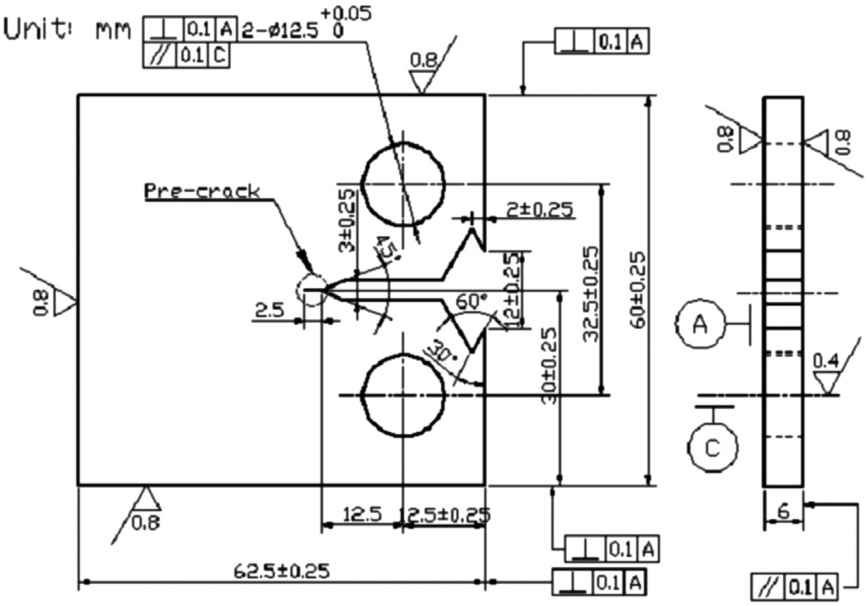

**Fig. 1.** Dimension of Ti–6Al–4V compact tension samples used in the fatigue tests.

Please cite this article as: Zhou JZ, et al. Effects of laser peening on residual stresses and fatigue crack growth properties of Ti–6Al–4V titanium alloy. Opt Laser Eng (2013), http://dx.doi.org/10.1016/j.optlaseng.2013.06.011