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On the influence of laser peening with different coverage areas on fatigue response and fracture behavior of Ti–6Al–4V alloy

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ABSTRACT

Laser peening (LP) with different coverage areas was carried out on Ti–6Al–4V titanium alloy specimens. Residual stresses, fatigue lives and fracture morphologies of specimens subjected to LP were analyzed. The LP-induced compressive residual stresses under different coverage areas were revealed in the superficial layer. The results show that LP coverage area has significant effect on fatigue response and fracture behavior. The decreased fatigue striation spacing and increased dislocations observed in the treated specimens further confirmed the effect of LP on decelerating fatigue crack growth (FCG). In addition, the strengthening mechanism of LP-induced compressive residual stress and surface nanocrystallization was theoretically investigated.

1. Introduction

Titanium alloys (particularly Ti–6Al–4V) have been widely applied in manufacturing aircraft components (airfoils, fan/compressor turbine blades, etc.) due to their excellent performance. In general, aircraft components are subjected to high-cycle fatigue loading associated with high frequency vibration in flight [1]. Under such severe conditions, fatigue cracks generate and propagate, eventually cause a fracture failure. A significant correlation between the near-surface residual stress distribution and fatigue crack growth (FCG) behavior has been clearly proven [2–4]. In most cases, micro-cracks initiate on the surface of titanium alloys components, but can be mitigated by the induced compressive residual stress [5,6]. To improve the fatigue strength and crack growth resistance of components, advanced surface modification technologies, such as shot peening, deep-rolling, roller-burnishing or low-plasticity burnishing were performed to introduce near-surface compressive residual stress and favorable micro-structures [7–9]. However, as the above technologies are increasingly utilized, the limitations are evident. For instance, the depth of residual stresses induced by shot peening is limited, usually not exceeding 0.25 mm; moreover, a roughened surface produced by shot peening is likely to lead to a reducing of fatigue life cycles [10,11]. The process of deep-rolling is restricted to certain component geometries, largely influencing the application in complex-shaped components manufacturing [8]. The low-plasticity burnishing is capable of producing high amplitude pressure to decrease the FCG rate. However, as a patent technology of Lambda Research Inc., the applicability and versatility of low-plasticity burnishing is still pending [12].

Laser peening (LP) is a competitive surface modification technology which can significantly improve the fatigue properties by inducing higher amplitude and greater depth of compressive residual stress, while keeping lower roughness on the surface of treated specimen [13–15]. Furthermore, LP based micro-structures evolution, such as grain refinement and

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Nomenclature

φ	diameter
$\sigma_{0.2}$	yield strength
σ_b	ultimate strength
δ	elongation
E	elastic modulus
ρ	specific gravity
v	Poisson's coefficient
$\Delta\sigma$	fatigue limit stress
ΔK_{th}	threshold stress intensity factor
y	groove shape factor
h	depth of surface crack groove
a_0	critical crack length
ΔK	threshold stress intensity factor
R	stress ratio
C, m	constants
LP	laser peening
FCG	fatigue crack growth
FCI	fatigue crack initiation

dislocation density increasing, were observed in previous researches [13,16]. The associated mechanical properties and fatigue performance of laser peened specimens were improved [17]. Attributed to its contributions in prolonging fatigue lives, LP has been intensively investigated onto titanium alloys. The literature shows that laser peened Ti–6Al–4V specimens exhibited a far deeper compressive residual stress layer than shot peened and as-machined specimens by introducing a greater subsurface tensile residual stress [18]. It was also found that for the notched, laser peened Ti–6Al–4V aerofoil specimens with low stress ratio had a significant enhancement of FCG resistance compared with the untreated specimens [19]. The results may be closely related to the influence of induced compressive residual stress on FCG behavior [20]. Furthermore, even at elevated temperatures, LP can be quite effective in retarding fatigue crack initiation (FCI) and growth in Ti–6Al–4V alloy [8,21]. As researches develop rapidly, more attention has been focused on the effect of LP processing parameters on surface integrity and fatigue life, such as laser pulse density [22,23], impact number [13], laser spot size [24]. In particular, it has been noticed that the LP coverage rates can affect FCG, which was verified by the observed fatigue striations spacing on fracture cross-sections [15]. The fatigue lives of laser peened specimens with four paths obviously increased compared with those with two paths during two-sided LP process in the previous work [25]. We can infer that the laser shock spots, which overlap and form the whole coverage area, will have interaction on changing the micro-structures in the superficial layer. It is widely acknowledged that the changed micro-structures exert a great influence on FCG properties. However, little research has been focused on the evolution of dislocation arrangement and fatigue striation on fracture surface induced by LP with different coverage areas on Ti–6Al–4V alloy. Detailed mechanism study of FCG resistance based on micro-structures on Ti–6Al–4V alloy still lags well behind. Thereby the enhancement mechanism of LP with different coverage areas on the resistance of fatigue crack initiation and growth is worth investigating.

With the above background in mind, the aim of this study was to evaluate the effect of LP on fatigue response and fracture behavior of Ti–6Al–4V titanium alloy, focusing especially on the evolution of fatigue fracture morphology with different LP coverage areas. The underlying relation between the induced compressive residual stress and fatigue crack growth rate was also investigated.

2. Experiments and methods

2.1. Experimental material and specimens

The specimens manufactured by Ti–6Al–4V titanium alloy were cut into dog-bone shape with a central-hole of Φ 2 mm. The dimension of the specimens used for FCG tests was defined on the basis of GB/T 3075-2008 as shown in Fig. 1. The chemical composition and typical mechanical properties of Ti–6Al–4V are shown in Tables 1 and 2, respectively. All the specimens were processed with the loading axis parallel to rolling direction, polished with SiC papers of different grades (from 320# to 1000#), followed by ethanol ultrasonic cleaning before LP.

2.2. Laser peening process

LP process was performed using 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 of 5 Hz. Laser pulse energy was