Surface & Coatings Technology 347 (2018) 398–406

Contents lists available at ScienceDirect

Surface & Coatings Technology

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

Surface integrity and fatigue lives of Ti17 compressor blades subjected to laser shock peening with square spots

Shikun Zou[a], Junfeng Wu[a,b,*], Yongkang Zhang[c], Shuili Gong[a,**], Guifang Sun[b], Zhonghua Ni[b], Ziwen Cao[a], Zhigang Che[a], Aixin Feng[d]

[a] Science and Technology on Power Beam Processes Laboratory, AVIC Manufacturing Technology Institute, Beijing 100024, China
[b] Jiangsu Key Laboratory for Design and Manufacture of Micro-Nano Biomedical Instruments, School of Mechanical Engineering, Southeast University, Nanjing, Jiangsu 211189, China
[c] School of Electro-mechanical Engineering, Guangdong University of Technology, Guangzhou, Guangdong 510000, China
[d] College of mechanical &Electrical Engineering, Wenzhou University, Wenzhou, Zhejiang 325035, China

ARTICLE INFO

Keywords:
Laser shock peening (LSP)
Ti17 compressor blades
Surface integrity
Vibration fatigue lives
Fatigue strengthening mechanism

ABSTRACT

To address the effects of laser shock peening (LSP) on surface integrity and high cycle fatigue (HCF) vibration fatigue lives of Ti17 compressor blades, LSP experiments on the 1st-order bending vibration nodal region of the blades were performed by a Neodymium-doped Yttrium Aluminum Garnet (Nd:YAG) laser system with square spots. Surface roughness, in-depth residual stresses both on the pressure and suction surfaces, local bending deformations at the leading and trailing edges, and surface microstructure were analyzed by surface profiles, X-ray diffraction (XRD), three-coordinate measurement and transmission electron microscopy (TEM), respectively. HCF vibration fatigue tests were carried out on a DC-4000 electric vibration system and fatigue fracture morphologies were analyzed by scanning electron microscope (SEM). Results showed that surface roughnesses values were not more than Ra 0.4 μm both on the pressure and suction surfaces of the blades with and without LSP. Compressive residual stresses layers with about 1 mm were generated both on the pressure and suction surfaces of the blade and the maximum values were located at the topmost surface. Two-way local bending deformations induced by LSP were convex bending deformation at the trailing edge and concave bending deformation at the leading edge. High density dislocations, twinning and nano-grains were observed on the surface microstructure. Compared with as-received blades, HCF vibration fatigue lives of the blades with LSP were increased by one order of magnitude. Fatigue strengthening mechanism was implied by establishing the relationship between fatigue fracture morphologies and effects of compressive residual stresses and refined grains.

1. Introduction

Titanium alloy, for example Ti17 alloy, is commonly utilized as aero-engine fan blades and compressor blades due to good mechanical property and stable flow stress, which meets the damage tolerance fatigue life design, and high efficiency, high reliability and low cost of the structures [1]. However, Ti17 blades are subjected to the severely combined mechanical and thermal loadings in service. Especially important, high cycle fatigue (HCF) failures of Ti17 blades occur in advance because of high frequency vibrations resulted from take-off, flight and landings of airplane [2], and fatigue cracks are initiated at the location of surface maximum tensile stress of the blades [3].

Surface treatment technologies, such as deep rolling (DR), shot peening (SP) and laser shock peening (LSP), have been successfully used to improve the fatigue performances of metal materials [4–6]. Comparing with SP and DR, LSP is more effective in improving the mechanical properties of metal materials, such as fatigue, corrosion and wear resistance [7,8]. The key reasons are the deep compressive residual stress layer (about 1 mm), low surface roughness and surface nano-grains in the surface layer induced by LSP [9–11]. In addition, through-thickness compressive residual stress could also be generated at the leading edge of the blades treated by LSP with double sides, which will largely increase the resistance to foreign object damage of the blades [12]. Moreover, it has been proved that LSP can efficiently improve the HCF performances of the components [13].

Shock wave with high pressure (several GPa) and high strain rate (several $10^7\,s^{-1}$) is formed by the blast of laser-induced plasma, which spreads into the target and causes the severe plastic deformation in the

* Correspondence to: J. F. Wu, Science and Technology on Power Beam Processes Laboratory, AVIC Manufacturing Technology Institute, Beijing 100024, China.
** Corresponding author.
E-mail addresses: wjf88813@163.com (J. Wu), gongshuili@sina.com (S. Gong).

https://doi.org/10.1016/j.surfcoat.2018.05.023
Received 16 August 2017; Received in revised form 11 April 2018; Accepted 10 May 2018
0257-8972/

surface layer. It improved surface integrity and mechanical properties of titanium alloy [14–16]. Many researchers paid their attention to this area. Cao et al. [17] studied the surface integrity of TC17 alloy (approximately corresponding to ASTM Ti17 alloy) treated by LSP with square spots. Nie et al. [18] found refined grains layers and severe plastic deformation layers in the surface layer of TC17 alloy with LSP. Compared with as-received material, surface micro-hardness of TC17 alloy with LSP was increased by 21% and the vibration fatigue lives of TC17 blades with LSP were improved by 200%. Huang et al. [19] found that compared with the substrate material, impact toughness of Ti17 alloy treated by LSP with different laser energies was improved by 2.1% for 1 J, 11.7% for 3 J, 64.1% for 5 J and 53.5% for 7 J, respectively. Wu et al. [20] studied the grains refinement mechanism and mechanical properties improvement of Ti17 alloy with combined LSP and SP. Zhang et al. [21] reported that three-point bending fatigue performance of TC4 alloy increased with LSP impact times, and reached a maximum value after three LSP impacts. In addition, nano-grains layers were also observed in the surface layers of TC6 alloy, TC17 alloy and TC4 alloy after LSP [20,22–24]. Nie et al. [25] showed that compressive residual stresses layers and nano-grains layers of TC11 alloy were induced by LSP, which delayed the fatigue crack initiation (FCI) and retarded the fatigue crack growth (FCG) rate through the reduction of stress intensity factor range $\triangle K$ and stress ratio R. However, so far, surface integrity, HCF vibration fatigue lives and fatigue strengthening mechanism of industrial Ti17 compressor blades with LSP have not yet been studied previously. Therefore, the result of this study will be beneficial to the application of LSP in aviation industry.

Surface roughness, in-depth residual stresses distributions and surface microstructure both on the pressure and suction surfaces, and local bending deformations at the leading and trailing edges were investigated to analyze the effects of LSP on surface integrity of Ti17 compressor blades. HCF vibration fatigue lives were compared on 1st-order bending vibration nodal region of the blades with and without LSP. Fatigue fracture morphologies were analyzed to reveal the fatigue strengthening mechanism. These topics discussed could provide important insights on the maintenance of failed blades.

2. Experimental procedures

2.1. Materials and LSP experiments

The investigation has been carried out on Ti17 compressor blades with alpha-beta two phases basket weave structure, as shown in Fig. 1. Its microstructure was obtained by 800 °C/4 h solution and 630 °C/8 h aging treatment. Its chemical composition (in wt%) and mechanical properties are given in Table 1. The minimum thicknesses of Ti17 compressor blades were about 0.5 mm at the leading edge and about 0.4 mm at the trailing edge, respectively. The thicknesses on the 1st-order bending vibration nodal region of the blades were complex nonlinear changes from the leading edge to the trailing edge and the maximum value was about 2.2 mm.

To improve the HCF vibration fatigue lives of Ti17 compressor blades, LSP treatments were carried out both on the pressure and suction surfaces of the 1st-order bending vibration nodal regions. LSP experimental parameters are listed in Table 2. LSP setup is shown in Fig. 2(a), which consists of a Neodymium-doped Yttrium Aluminum Garnet (Nd:YAG) laser system (1064 nm wavelength and 15 ns pulse width), a beam shaping device (a focus lens and a beam shaping lens) [17], a 6-axis manipulator and a deionized water curtain supplying system. The schematic diagrams of LSPed region and LSPed path are illustrated in Fig. 2(b) and (c). LSPed region is from line 1 to line 3/blade root and the distance from line 1 to 1st-order bending vibration nodal line is kept to be 10 mm. LSPed path is from the leading edge to the trailing edge and then from line 1 to line 3. Adjacent laser pulse spacing is 3.6 mm both in the chord-wise and the span-wise directions. An absorbed wave layer consisting of a 3 M aluminum foil and a water curtain was adhered and sprayed on the rear free surface of the blade with LSP in order to avoid the spall of the blade and the bulging on the adhered aluminum foil.

2.2. Surface integrity measurements

The surface integrity of Ti17 compressor blades before and after LSP was systematically characterized by surface roughness, and in-depth residual stresses distributions and surface microstructure both on the pressure and suction surfaces, and local bending deformations at the leading and trailing edges. Surface morphology was measured by a WYKO NT 1100 optical profiler based on light interference technology with measured regions of 120 μm × 90 μm each time. Surface roughness was measured by a Talysurf PGI 1230 three-dimensional surface topography instrument with the line trace length of 20 mm. In-depth residual stresses distributions were measured by a Proto LXRD (laboratory X-ray diffraction) instrument with sin2ψ-method and electro-polishing the material layer by layer. The X-ray beam diameter was about 2 mm and the diffracted Cu-Kα characteristic X-ray from hexagonal α-phase {213} plane was detected with a diffraction angle (2θ) of 142°. Local bending deformations were measured by Hexagon three-coordinate measuring machine with the measurement precision of (2.7 + 3.5 L/1000) μm. The surface microstructure was characterized by JEM-2100 transmission electron microscopy (TEM) operated at a voltage of 200 kV. TEM observation was performed on thin foils with −15 μm and 0 μm below the topmost surface. TEM samples were prepared by using standard technologies of mechanical grinding, polishing, dimpling and ion beam thinning.

2.3. Fatigue tests

HCF vibration fatigue tests were carried out on a DC-4000 electric vibration system to evaluate the fatigue lives of Ti17 compressor blades before and after LSP at fatigue stress of 480 MPa (stress ratio R = 0.1), room temperature and resonant frequency, in air, as shown in Fig. 3. The tip amplitudes of the blades were read from an optical microscope and monitored by a laser displacement sensor in the test. Gauges glued on 1st-order bending vibration nodal region were used to monitor the strain in the vibration test. Once a fatigue crack was initiated in the surface layer of the blades during the vibration test, the resonant frequency of the blades would shift. The vibration test would be stopped when the resonant frequency was reduced by 1%. Fatigue fracture morphologies were observed by a ZEISS SUPRA 55 field scanning electron microscope (SEM) at a voltage of 15 kV.

3. Results and discussions

3.1. Surface roughness

The profiles of the micro-indent induced by LSP with single laser pulse are shown in Fig. 4. The micro-indent exhibits the square profiles with the maximum depression H of 4.59 μm in the X direction and 4.87 μm in the Y direction. The position of 0.1H distance from the upper limit of the square profiles is defined as the measuring datum line. Intersection spacing between the measuring datum lines and the square profiles is defined as laser shocked size, as shown in Fig. 4(b) and (c). Therefore, laser shocked sizes are 3.97 mm in the X direction and 3.93 mm in the Y direction, respectively. According to laser shocked sizes and overlapping rate of 10%, the moving spacing of LSP both in the X and the Y directions is determined of 3.6 mm. Table 3 presents the surface roughnesses (Ra) of Ti17 compressor blades before and after LSP. The surface roughnesses of as-received blades are Ra 0.28–0.36 μm on the pressure surface and Ra 0.30–0.39 μm on the suction surface, respectively. Surface roughnesses of LSPed blades are Ra 0.32–0.38 μm on the pressure surface and Ra 0.25–0.40 μm on the suction surface, respectively. It indicates that surface roughnesses of Ti17 compressor