Optics and Laser Technology 100 (2018) 309–316

Contents lists available at ScienceDirect

Optics and Laser Technology

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

Full length article

Deformation of single and multiple laser peened TC6 titanium alloy

A. Umapathi, S. Swaroop *

Surface Modification Laboratory, School of Advanced Sciences, VIT University, Vellore 632014, India

ARTICLE INFO

Article history:
Received 3 July 2017
Received in revised form 13 October 2017
Accepted 23 October 2017

Keywords:
Laser peening without coating
TC6 alloy
Residual stress
Microhardness
Synchrotron radiation
Microstructure

ABSTRACT

Laser peening without coating (LPwC) was done on the titanium TC6 alloy at a wavelength of 532 nm using an Nd:YAG laser. The laser power densities of 3, 6 and 9 GW cm^{-2} were used to peen the samples. Samples were also peened multiple times (1, 3 and 5 passes) at 6 GW cm^{-2}. Microhardness showed an overall 23% increase from the baseline value. Further, softening of α phase in the bulk was observed above 6 GW cm^{-2} in the samples peened once and above 1 pass in multiply peened samples. A similar trend was observed from the residual stress analysis of the samples. The maximum compressive residual stress was −1780 MPa at a depth of 50 μm at 9 GW cm^{-2}. The observed softening of α phase was proposed due to adiabatic heating. Microstructural changes due to adiabatic heating resulting in increased β volume fractions were observed and confirmed by synchrotron radiation measurements.

1. Introduction

Titanium based alloys have been extensively used in aerospace applications due to their excellent properties such as high strength, low weight, weldability, toughness and corrosion resistance. These alloys are mainly used to fabricate gas turbines, compressor blades and disks of advanced aero engine components. However, these components continuously deteriorate due to fatigue loading all through their service conditions. The conditions worsen when tensile stresses develop on the surface of the components, which leads to early crack formation and eventual failure. Therefore it is necessary to improve the fatigue life of these components. The fatigue life of the material can be increased by inducing compressive residual stresses (CRS) on the surface and subsurface where cracks initiate, thereby delaying or inhibiting crack propagation. CRS are introduced on the surface and subsurface of the material by surface modification techniques such as shot peening, ultra-shot peening, ball-burnishing, surface mechanical attrition treatment, water jet peening, deep rolling and laser peening (LP) or laser peening without coating (LPwC).

As far the peening methods, for the past six decades conventional shot peening has been used to improve the fatigue life of the metallic materials by introducing CRS. Shot peening induces limited CRS in shallow regions. To overcome this problem LP or laser shock peening (LSP) which induces large and deep CRS with very less roughened surface is used in recent times. The development, background processes, benefits and importance of LP on surface modification was reviewed by Montross et al. [1]. The LP technique has been established as more effective than shot peening [2]. There are two variants of the LP process. The normal process of LP uses a coating (sacrificial coating like black paint, Al foil or vinyl tape [1]) and the other variation that does not use coating is called LP without coating (LPwC) [3–5]. LPwC technique was introduced to the peening community in the reports of Mukai et al. in 1995 [3] and Sano et al. in 1997 and 2006 [4,5]. LPwC takes advantage of high strain rate plastic deformation process induced by high pressure laser shock wave to enhance the mechanical properties of metallic materials. The benefits of LPwC over LP were recently reviewed by us [6]. Additionally, in our laboratory, LPwC was applied to titanium and other alloys resulting in the increase of CRS, fatigue life and corrosion resistance [7–16]. Further, LPwC is reported to have decreased fatigue crack growth rate (FCGR) [17], improvements in cycles in high cycle fatigue (HCF) regime [18–21], stress corrosion cracking (SCC) [22], corrosion resistance [23] and wear resistance [24] in many metallic alloys. All the mentioned properties were mainly influenced by LPwC parameters, such as laser energy, laser power density and pulse density. One additional variant within LP is called multiple peening wherein the same area is peened with different passes or scans [21,25–31]. Multiple peening appears promising because of the propensity to obtain nano grained surface and subsurface of the peened alloys [21,25–31].

In this work near alpha titanium alloy TC6 (widely used in the Chinese aviation industry) is used. There is some limited data on the LP of TC6 [21,25,32]. Further, grain refinement is reported in

* Corresponding author.
E-mail addresses: umapathia@vit.ac.in (A. Umapathi), sathyaswaroop.n.r@vit.ac.in (S. Swaroop).

https://doi.org/10.1016/j.optlastec.2017.10.022

TC6 as a consequence of 5 times multiple LSP impacts with absorbent coating, with formation of nanocrystallites distributed uniformly on the surface with grain size in the 30–60 nm range [25]. Additionally, work hardening and enhanced fatigue life were observed. To date there has been no information available on LPwC of TC6 alloy (the focus of the present paper). In this paper we focus on the surface and bulk mechanical properties of the TC6 alloy influenced by different LPwC parameters like power density and multiple impacts. In order to achieve this, a laser wavelength of 532 nm was used at three different power densities (3, 6 and 9 GW cm^{-2}) and multiple impacts (1, 3 and 5 passes) were performed at 6 GW cm^{-2}. The resulting microhardness, residual stress, microstructural changes and surface roughness were analyzed. Further, the phase analysis of the sample was carried out with synchrotron radiation.

2. Experimental

2.1. Material preparation

The titanium TC6 alloy in the form of 5 mm thick cold rolled plates was purchased from Tianjin Haixing Steel Import and Export Co. Ltd., China. Its nominal chemical composition (in wt.%) is 5.5–6 Al, 2–3 Mo, 0.8–2.3 Cr, 0.2–0.7 Fe, 0.15–0.4 Si and Ti (balance). Small samples ($15 \times 15 \times 5$ mm^3) were obtained from as received plate with the help of electric discharge mechanism (EDM) wire cutting. The samples were first solution heat treated at 870 °C for 2 h in air and cooled to room temperature in air followed by ageing at 550 °C for 2 h in air and cooling in air. The samples were further annealed for relieving stress in the inert gas atmosphere at 400 °C for 2 h. Further, samples were polished with silicon carbide sheets ranging from 220 to 3000 grit size and further polished with colloidal silica of particle size 0.04 μm. The samples were chemically etched for 10 s with Keller's reagent (85 ml of H_2O, 5 ml of HNO_3 and 10 ml of HF). The resulting microstructure of the sample is shown in Fig. 1, depicting equiaxed grains with predominantly α phase. Tensile tests performed on the samples indicated ultimate tensile strength and percentage elongation at break as 950 MPa and 13.5% respectively.

2.2. Laser peening without coating (LPwC)

The LPwC experimental setup is schematically shown in Fig. 2. The sample was fixed on a steel tray ($200 \times 200 \times 100$ mm^3) and the tray movements in x and y-directions were controlled by two servo motors, operated through a software. The sample was submerged in 10 mm thick water inside the tray. This water worked as a transparent overlay to create the plasma on the sample surface. Experiments were performed with a pulsed Nd:YAG laser system with a pulse duration of 10 ns and at a repetition rate of 10 Hz. Water penetrable frequency doubled 532 nm wavelength (second harmonics) radiation was used. The laser pulse was first reflected at an angle of 45° by a dichroic mirror and the beam was focused using a bi-convex lens of focal length 758 mm. Finally, a 0.8 mm diameter beam was focused on the sample surface. The overlapping rate was constant at 70% (equivalent to a pulse density of 17 pulses mm^{-2}). The samples were peened at three different power densities of 3, 6 and 9 GW cm^{-2}. Further, multiple peening with 1, 3, and 5 impacts at power density of 6 GW cm^{-2} was also done.

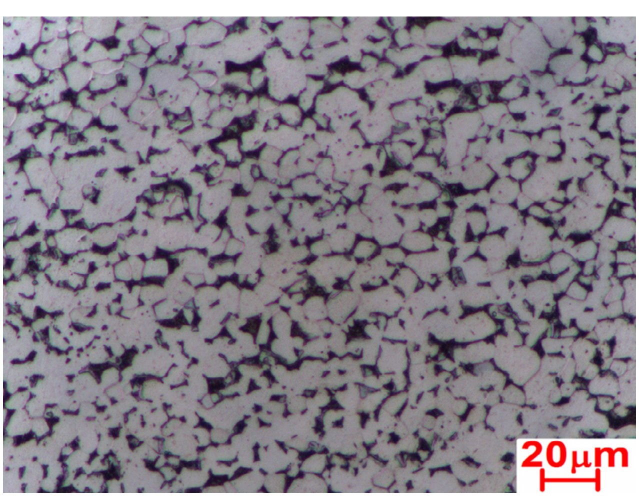

Fig. 1. Optical microstructure of TC6 alloy solution heat treated (870 °C, 2 h), air cooled, aged (550 °C, 2 h), air cooled and finally annealed at 400 °C, for 2 h for stress relieving (inert gas atmosphere).

2.3. Microhardness

The depth-wise microhardness of the unpeened and peened samples was measured using a MATUZAWA-MMT-X Vickers hardness tester. The polished cross section of samples was used to measure the microhardness with a constant load of 500 g and holding time of 10 s. An average of three measurements was used for each depth.

2.4. Residual stress

The residual stress measurement was carried out using an X'pert Pro system (PANalytical, Netherlands). The analysis of the data was performed using the standard X-ray diffraction $\sin^2 \psi$ method. A 2 mm diameter beam and X-ray source of Cu-Kα radiation were used. The tilt angle ψ was varied from −40 to 40° and the lattice plane of (201) belonging to α phase was used to calculate the stress. The diffraction elastic constants were obtained using the elastic modulus (115 GPa) and Poisson ratio (0.34). The depth wise residual stress was measured by progressive electro polishing to remove layers up to a depth of 500 μm. The resulting stress relaxation was corrected as per the methods of Moore et al. [33] and Fitzpatrick et al. [34].

2.5. Surface roughness

The surface roughness of the unpeened and peened samples was measured using MAHR-GD120 automatic digital surface roughness measurement instrument. A 0.8 mm high pass cut off filter and a scanning length of 5.6 mm along the peened direction was used. For each sample, surface roughness was analyzed in three different places to obtain an average of mean arithmetic roughness (R_a).

2.6. Synchrotron radiation

The phase content was analyzed with high energy spatial resolution synchrotron based X-ray diffraction (SR-XRD) measurement, using beamline line BL-11, located at INDUS-2, RRCAT, Indore, India. The diffraction patterns were obtained in an angle-dispersive X-ray diffraction (AD-XRD) mode with the Bragg angle ranging from 10° to 40°. The beam energy of 20 keV (corresponding to a wavelength of 0.600307 Å) was used.

2.7. Microstructure

In order to investigate the microstructures before and after LPwC, the cross-sectioned samples were mounted with phenolic powder and prepared for metallographic investigation using