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Effects of laser shock peening on microstructure and residual stress evolution in Ti–45Al–2Cr–2Nb–0.2B alloy

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ABSTRACT

Laser peening is a novel surface treatment technique for improving the mechanical properties of metal parts' surface. To investigate and evaluate the effect of laser peening on the microstructural changes, texture evolution, and residual stress distribution changes, laser peening experiment was undertaken using Nd:YAG laser system with the pulse–width of 20 ns and max pulse–energy of 9 J. Micro-hardness measurements of the untreated and treated specimens were carried out with Vickers indenter. Depth-resolved characterization of the residual stresses and strains was achieved using X-ray diffraction. The structure–texture–phase–stress combined analysis was performed based on the X-ray diffraction patterns using the whole pattern fitting method. The relationship between laser peening processing parameters, microstructure, texture, residual stress distribution and hardness are presented and discussed. The results showed that laser peening could improve microstructures and properties of TiAl alloy.

1. Introduction

Recently, TiAl alloy materials have received considerable attention for high temperature structural applications in aerospace and automotive industries [1,2]. Many studies have been undertaken on the mechanical properties and microstructure evolution of these materials [3,4]. However, in the literature to date, few of it reports the high strain rate response of TiAl materials. Some dynamic compression or tensile tests at strain rates up to 4000 s^{-1} were performed for these materials with various compositions and microstructures [5–15]. Few dynamic deformation tests at higher strain rate have yet been tried by now. Laser peening is a novel surface treatment process that generates deep compressive residual stresses and microstructural changes and thereby dramatically improves service life of critical metal aircraft engine parts [16–18]. This surface treatment technology has been developed to enhance wear, corrosion and fatigue properties in titanium alloy, aluminum alloy, nickel alloy and steel [19]. During the laser peening process, powerful shock waves are generated and forced to propagate into the metal, and the intensity of the resulting peak pressure on the surface of the specimens, which lasts no more than 50 ns and can approach up to 6 GPa, leads to 10^6 s^{-1} strain rate deformation at the surface [19]. The strain rate achieved by this laser peening method is two times higher than the strain rate of 10^4 s^{-1} generated by conventional high strain rate tests using the split-Hopkinson-pressure-bar method. Meanwhile, only low level plastic strain close to 1% introduced by laser peening due to several or tens ns loading duration [20].

Therefore, the present study was undertaken to develop a basic understanding of the effects of laser peening on the deformation microstructure, texture evolution and residual stress distribution induced by ultra-high plastic strain and strain rate in a TiAl alloy. Micro-hardness measurements of the untreated and treated specimens were carried out with Vickers indenter. The microstructure of untreated and laser peening treated TiAl intermetallic material was analyzed. A Rietveld software MAUD 2.43 beta version was adopted to fit TiAl X-ray diffraction patterns collected by area detector [21–23]. Microstructural characterization of phase percentage, unit cell parameters, texture and residual stress were measured by this whole pattern refinement method. The depth profiles of residual stress and plastic strain in the laser peened TiAl intermetallic were estimated by X-ray diffraction. The results of all characterization show the effectiveness of this processing method for inducing elastic and plastic deformation in TiAl alloy, and the TiAl alloy performance is improved.

2. Experimental details

2.1. Materials preparation

The alloy under study was cast Ti–45Al–2Cr–2Nb–0.2B. The cast material was hot isostatic pressed at 1260°C, 150 MPa for 4 h. Ambient temperature tensile test gave tensile strength of about 810 MPa and yield strength of about 720 MPa. The 70 mm by 14 mm slices with the thickness of 2.4 mm were machined using electrical discharge

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wire-cutting machine. Prior to the peening process, the intended peening surfaces of specimens were grounded with 1200 grit SiC abrasive sandpaper followed by final mirror polishing using colloidal silica to the surface roughness Ra of 0.05 μm. Specimens were treated by stress relieving device from Huayun Inc. (Jinan, China) to eliminate stress of specimens' surface. The principle of the stress-relieving device is vibration aging, not a thermally treated method. The essence of vibration aging is to exert a dynamic stress through vibration on specimen. When the dynamic stress and the residual stress of specimen are superimposed, meet or exceed the material micro yield limit, the specimen will occur the local micro elastic plastic deformation at the same time. So, through the vibration, the internal and surface residual stress were released. The vibration frequency of 45 kHz, the vibration amplitude of 50 μm, and the duration time of vibration of 10 min were used in this stress relieving treatment experiment. Laser peening was carried out with self-developed laser peening system with pulse energy of 0–10 J, wavelength of 1064 nm, pulse duration (full width at half maximum, FWHM) of 20 ns, and frequency of 5 Hz. The laser beam which comes from lasers traveled through optical microscope, homogenized microscope and focusing lens irradiated onto a material surface with a square laser beam spot, the side length of the beam spot is 3 mm. Three laser shock energy levels 9 J, 6 J and 3 J were applied to do the laser peening process. 50% overlapped dimples peening patterns 4 patches of 14 mm by 14 mm was used. During the peening process a black tape (thickness of 100 μm) was painted on one side of the sample surface and water (thickness of 2 mm) was used as confining medium. The black tape was used as an ablative medium to protect the sample from thermal effects.

2.2. Characterization methods

2.2.1. Microstructure and hardness

Surface microstructures of TiAl prior and after laser shock peening processed were characterized using a KEYENCE VHX-1000 optical microscope, Shimadzu SSX-550 SEM, and JEM-2100 transmission electron microscopy. The JEM-2100 transmission electron microscopy operated at a voltage of 200 kV. For cross-section microstructure, the sample was etched with Kroll etchant, then examined using Zeiss Axiovert 200 MAT optical microscope. The micro-hardness of the samples before and after laser peening was measured using a FM-300 micro-hardness tester from Future-tech Inc. (Japan), with a load of 200 g and holding time of 10 s, an average of five measurements was used for each test point. Micro-hardness testing was performed on sample surfaces and along the thickness of cross section. Before and after laser peening, a MicroXAM-1200 3D non-contact optical profiler was used to measure the surface roughness.

2.2.2. X-ray diffraction with area detector

The X-ray diffraction experiments were carried out on a Bruker D8 Advanced diffract meter with a Hi-Star area detector and General Area Detector Diffraction System (GADDS). A collimated Cu Kα radiation source and 0.5 mm diameter pinhole was used. All the X-ray diffraction data were collected at a distance of 15 cm from sample to detector. The angle of X-ray incidence ω is 16° and 2θ is 34°. Collecting time of each frame was 120 s. For each sample two measurements were made at tile angles χ of 0° and 35°. Fig. 1 shows the basic setup used in X-ray diffraction experiments.

2.2.3. Residual stress profiles measurement

A Proto LXRD Residual stress measurement system was used to measure the in-depth residual stress profiles in all samples. A Cr X-ray tube with 2 mm round aperture was used. All measurements were based on the 311 diffraction peak of Kα radiation from the major gamma phase of Ti–46.5Al–0.2B alloy. V filters were used to reduce the intensity of the Kβ radiation. The diffraction angle (2θ) is 144.2°. X-ray elastic constants of $S_1 = -1.72 \times 10^{-6}$ MPa^{-1} and $S_2/2 = 7.74 \times 10^{-6}$ MPa^{-1} were used to calculate the residuals stresses [24]. Two position sensitive scintillation detectors with 18.4° 2θ spectra each were applied to collect data. The Lorentz–Polarization–Absorption (LPA) correction is applied to the raw X-ray profiles. A Pearson VII peak fitting method was used to determine the center of the diffraction peak on the 85% of the diffraction peak. The zero stress Ti power sample was used to calibrate the alignment of the instrument. Two Phi angles 0° and 90° were used to perform biaxial stress measurements. The $\sin^2\psi$ technique was applied to compute the residual stress value. The ψ values are in the range of −1° to −45° and 1° to 45°. Eleven ψ tilt angles were used for the computation in each ψ direction. Elliptical regression was applied to fit the plots of d versus $\sin^2\psi$. Both normal and shear stresses were calculated. In order to get residual stress depth profile in laser peening processed, sample measurements were taken at original surface and seven different depths which obtained by electro-polishing with saturated NaCl solution. Both corrections for macro-stress gradient and corrections for layer removal were applied on the measured residual stresses on a series of depth.

3. Results

3.1. Surface morphology and microstructure

No cracks can be seen on the peened surface of all laser peening processed specimens from visual observation of eyes. It shows that there were no obvious burn injury and scuffing occurs on the specimens' surface during laser shock peening. The surface morphological maps of virgin and laser peened TiAl samples were shown in Fig. 2. The surface morphology changes induced by laser peening can be related to laser energy level. When laser pulse energy was high enough, lots of micro-dents and micro-convexities were generated after laser peening treatment, because the plastic deformation was introduced into TiAl alloy surface by high pressure shock waves. The surface roughness parameters of original mirror polished sample and laser peened samples

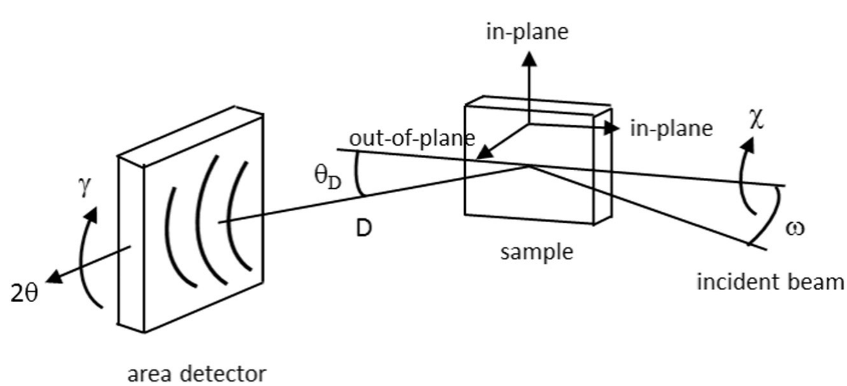

Fig. 1. Basic setup of X-ray diffraction experiments with area detector.