High Strain and Microstructure Transforming in Laser Peening Ti-6Al-4V

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In order to analyze high strain produced by laser peening during tens of ns, which can’t be performed in so short process, the surface profile of after laser peening with square spots was compared with that with circle spots, steep sidestep showed high strain and deformation produced in laser peening with square spot. The microstructure transforming in laser peening titanium alloy Ti-6Al-4V in the center of shocked zone and at the edge of square spot was researched in this paper. The results showed that nanometers size crystals were formed at the edge of square spots because of the shearing strain produced during laser peening of titanium alloy Ti-6Al-4V.

Key Words: Laser peening, Surface profile, Square spot, Deformation, Ti-6Al-4V, Nanometers crystals

1. Introduction

Laser peening (LP) is a surface enhancement technique that induces compressive residual stresses in the surface regions of metallic components to increase fatigue life.1) During laser peening, a high intensity (more than 1 GW/cm²) laser pulse vaporizes a thin layer of metallic target, and produces rapid expanding high pressure plasma (more than 1 GPa). Laser induced shock waves deform surfaces at a very high strain rates approaching 10⁷/s. Under such intensive and rapid loading condition, materials behave like a fluid and plastic deformation is induced. The depth and area of plastic strain layer induced by laser peening is much deeper or higher that generated by shot peening, as the results, laser peening can produce higher and deeper compressive residual stress layer than those generated by conventional shot peening. At the same time, laser peening can also keep a smoother surface, which is very beneficial for improvement of fatigue properties.

Each laser spot produces a dent with depression of 3~15 μm. The laser spot is usually geometrically similar to the shape of the impacting laser pulse. Circle spots and square spots are the most common shape used in laser peening. A residual compressive stress is produced in the shocked zone, which improve the fatigue properties of the metal parts.

Due to high specific strength and excellent corrosion resistance, Ti-6Al-4V is widely used in aeronautical turbine engine, such as fan blades and compressor blades. The fatigue property of blades (particularly at the edge area) is very critical for the whole turbine engine. These components are subjected to fatigue and fail due to flaws or cracks initiated on the surface.2) It is hard to produce plastic deformation in titanium alloy at normal temperature. The stress-strain curves of Ti-6Al-4V at elevated temperatures have different forms and rules. High temperature super-plastic deformation is often used in forming of Ti-6Al-4V sheet parts.3,4) Laser peening can improve the fatigue properties of blades, but effects of shock waves on the deformation and residual stress are more difficult to control in laser peening of components with thin cross-section.5) Shock waves loading of materials could produce effects of instantaneous high temperature, high pressure and high strain rate. Since the processing time of laser peening is less than 100 ns, it’s very difficult to investigate the evolution of adiabatic shear bands in typical microstructures of Ti-6Al-4V. The surface profile of laser peening with square spots was compared with that of circle spots. The microstructure of laser peened titanium alloy Ti-6Al-4V in the center of square spot and at the edge of square spot was researched in this paper.

2. Experimental

Laser peening experiments were performed with a Q-switch Nd:glass laser, which has a circular laser output with beam diameter of 20 mm, pulse energy of 30~50 J, and pulse duration of 30 ns. Highly uniform laser beam intensity distribution is coupled to the part using a special optical shaping delivery system. Using optical shaping mirrors the circular laser spot can be transferred into laser spot with uniform energy distribution.

Several sets of nominally identical Ti-6Al-4V samples have been produced for this study. The samples for surface profile have a gauge size of 50 × 50 × 10 mm, and the samples for microstructure have a gauge size of 10 × 10 × 10 mm. The laser peening was carried out with laser pulse energy of 240 J/cm² applied over 30 ns, with a spot area of 4 × 4 mm. Aluminum foil tape was used as absorbing layer and flowing water as cooling layer.

3. The surface profile of laser peening

Figure 1 shows the surface profile (smooth bottom concave) generated by laser peening with square spot,2) the depression is near 5 μm, high plastic strain was produced in tens of ns, the strain rate is up to 10⁷/s.

Compared with a circle spot, a square spot can get even residual stress around the shock zone (Fig. 2). Single circle spot has smoother transition profile near the edge, but overlapped circle spots produce accidental surface in spite of different
overlap form (see Fig. 3). Single square spot may produce a smoother bottom concave but with steep sidestep. At the same time, the array of square spots can get very smooth overlapped effects. Peening pulses are applied sequentially in complete rows without the need of re-coating the surface ablation layer.

The surface after laser peening with separated square spots looks like a square farmland, and the interspace of square spots looks like the ridge of a field, and the height of ridge is only 1–2 μm. The height is less than the depression of single square spot in evidence, which indicate that the interspace is partly treated by laser peening with two sides laser spots, and the total plastic deformation of edge is little less than the center zone of square spot.

3. Microstructure of Ti-6Al-4V

3.1 Microstructure of Ti-6Al-4V without laser peening

Ti-6Al-4V is α + β phase structure titanium alloy. Figure 4 shows a transmission electron micrograph of microstructure on of Ti-6Al-4V without peening. The inset shows the diffraction spots of this portion, diffraction spots showed single phase α'-Ti phase, the main structure is α' phase, diffraction point 2, 3, 4 respectively present the α'-Ti of(0002), (-2112), (-2110) faced crystal.30

Figure 5 shows a transmission electron micrograph of big angular crystal boundary found in Ti-6Al-4V with μm size grains. It is clear that, the α' phase lath is the main structure in the raw materials, and the lath width is 40-50 nm.

3.2 Microstructure in the center of laser peened zone

According to the surface profile after laser peening with
square spot (Fig. 1), high train produced in the eadg of square spot, TEM samples were taken in the boundary of square spots. After laser peening, the lath structure disappears in the origin materials and presents micro poly - crystal within the surface layer of 200 μm. Figure 7 shows a transmission electron micrograph of laser-peened surface layer of Ti-6Al-4V, the inset shows the diffraction rings of titanium alloy.

The discontinuous diffraction ring showed, after laser peening, the material surface layer organization was transformed from the bulky monopole crystal into microlite. A dark field image of laser-peened surface layer of Ti-6Al-4V is shown in Fig. 7. It is clear that titanium alloy is changed into material with nanostructure size (less than 10 nm) microstructures.

The rings from inside to outside are (-110), (011), (2-10) crystal plane of α-Ti.

3.3 Microstructure in overlapped edge of square spots

After laser peening, the lath structure in the surface layer (about 200 μm) of origin materials disappears and presents microlite. A transmission electron micrograph of laser-peened surface layer which contains microlites (Fig. 8), the inset shows the continuous diffraction rings of this portion, the material structure change into smaller microlite. Figure 9 shows a dark field of laser-peened surface as same as Fig. 8, which presents that the material is broken into ten nanometers, even several nanometers.

In Fig. 8, diffraction ring from inside to outside one by one in order is (-110) α, (101) β (011) α, (200) β and (2-10) α crystal plane.

4. Conclusion

During laser peening, adiabatic shearing strain and its high strain rate (up to 10⁶/s) at the edge of square spots may cause the formation of nanometers sized crystals and depression. Single square spot produce a smooth bottom concave with steep sidestep of several microns. The materials at the edge of square spots show more intense plastic strain than in the center. Within the surface layer of 200 μm, near the edge of square spots, ten nanometers, even several nanometers sized microlite was produced in the shocked zone.

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