Surface residual stress, micro-hardness and geometry of TC6 titanium alloy thin-wall parts processed by multiple oblique laser shock peening

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Abstract
The titanium alloy thin-walled part with light in weight and high specific strength is widely used in the aviation engine fan, turbine and compressor. The fatigue damage of the thin-walled part often happens under the action of the cyclic loads and high temperatures. Laser shock peening (LSP) is an innovative surface treatment process, which has been used to improve the fatigue life of metallic materials. Considering the shape and size of the thin-walled parts, the TC6 titanium alloy thin-wall parts were treated by the oblique incident laser beam in this work. The purpose of this study is to investigate the effects of multiple oblique LSP on TC6 titanium alloy thin-wall parts. Nd: YLF laser with a wavelength of 1053 nm was applied. The laser incidence angle was determined first by experiment. The effects of laser energies, impact times, pulse durations and pulse frequencies on the surface residual stress, micro-hardness and geometry of TC6 titanium alloy thin-wall parts were investigated. The results showed that by the use of oblique LSP, the higher surface residual stress and surface micro-hardness could be induced on the surface of treated specimens. However, surface deformation and surface roughness of treated specimens can also increase.

1. Introduction
The complex shape titanium alloy thin-walled part characterizes light in weight, high specific strength, so it is widely used in the aviation engine fan, turbine, compressor and other parts [1, 2]. However, the fatigue damage of the thin-walled part often happens under the action of the various loads. The accumulation of fatigue damage causes surface fatigue cracks, sometimes and even results in fracture of the component. Therefore, it is necessary to strengthen the surface of titanium alloy [3, 4]. LSP has been identified as an ideal surface strengthening technology, which has shown more advantages in improving fatigue life, wear, and corrosion resistance of metallic components in contrast to traditional surface treatment techniques [5–8]. During LSP, the metal target is coated with an ablative layer (such as black tape) and confined by transparent confining medium (such as water). When a laser pulse with power density of several GW cm$^{-2}$ impacts the material surface, the absorbent layer material absorbs the laser energy, vaporizes, and finally creates plasma. This plasma is confined by the confining layer, creates an extremely high-pressure. The plasma pressure propagates into the target as a shock wave. When the stress created by the shock wave exceeds dynamic yield strength of the material, this induces local plastic deformation of the target surface, generating compressive residual stresses. Considering the complex shape and dimension of aeronautical thin-walled parts, it is necessary to shock the target surface under laser oblique incidence angles [9, 10]. A principle description of a typical oblique LSP is shown in figure 1. The incidence angle is the angle between the normal direction of the target surface and the direction of the laser beam.

In the previous work, several works have focused on the incidence angle of LSP. For instance, the effects of the incidence angle on the surface residual stress, deformation and micro-hardness of TC4 alloy were studied.
through single-point LSP experiments, and the results showed that the surface central residual stress increases at first and then decreases, the surface dent depth decreases, the micro-hardness decreases with the increase of the incidence angle [11]. The influences of various laser incidence angles on in-depth residual stress were studied by the finite element analysis techniques, and the simulation results showed that the influence depth of residual stress decreases with increasing incidence angles [12]. Shen et al [13] analyzed the effects of oblique LSP on rotary bending fatigue of aero-engine fan shaft. After LSP, the experimental results showed that the micro-hardness and bending fatigue life of the fan shaft increased by 11%, 160%, respectively. The experiment of LD31 aluminium sheet formed by a single oblique LSP was performed [14]. The results showed that the residual stresses of the aluminium sheet surface and bottom were less than 100 MPa. The effects oblique LSP on fatigue strength of S1100 crankshaft were analyzed, and the experimental results showed that the micro-hardness, the residual stress and the fatigue life increase 65%∼75, 80%∼100%, 150%, respectively [15]. Vasu et al [16, 17] presented 3D finite element models to investigate the effects of differences in plasticity on residual stresses generated on curved geometries and applied 2D finite element models to predict the residual stress for convex and concave geometry. Yang et al [18] used 3D finite element models to investigate geometrical effects of metallic target with curved surface on the residual stress by LSP. Hill et al [19] studied the effects of the different incident angle on in-depth residual stress distribution induced by LSP in 8.73 mm thick Ti–6Al–4V specimens. Other researchers have studied residual stress field of thin-wall pieces by laser peened with a vertical incidence [20–23]. The above-mentioned studies have explored the oblique LSP of the thicker metal parts. However, very little is known about the effects of LSP parameters on the surface integrity of the thin-wall parts. Especially, the effects of the laser energies, impact times, pulse durations and pulse frequencies on the surface integrity of titanium alloy thin-wall parts processed by multiple oblique LSP are still unknown and unreported.

In this work, TC6 titanium alloy was used as the target material oblique LSP. The objective of the current work was to characterize the effects of multiple oblique LSP treatments on the surface residual stress, micro-hardness and geometry of TC6 titanium alloy thin-wall components. First of all, the laser incidence angle was selected, and then the influences of LSP parameters such as laser energy, impact times, pulse duration and pulse frequencies were analyzed.

2. Materials and methods

2.1. Experimental material

TC6 titanium alloy was used in the present study, which is an α + β type alloy with excellent combined mechanical properties. The nominal chemical composition (wt%) of TC6 alloy includes 5.5%–7%Al, 2%–3% Mo, 0.8–2.3Cr, 0.2–0.7Fe, 0.15–0.4Si, and balanced Ti. The physical and static tensile properties of this alloy at 20 °C were as follows: density of 4500 kg m$^{-3}$, Young’s modulus of 113 GPa, Poisson’s ratio of 0.33, Yield strength of 840 MPa, Ultimate tensile strength of 980 MPa, Elongation rate of 10% [24, 25].

2.2. Oblique LSP experiments

The Procudo 200 Laser Peening System by LSP Technologies, Inc. was employed in this experiment. The laser system using Nd:YLF laser with a wavelength of 1053 nm produces pulses up to 10 J at 1–20 Hz. The transparent water flow with a pressure of about 0.368 MPa was used as a restraint layer, and the black tape with a thickness of
100 μm was used as an ablative layer. The diagram of LSP equipment and the water flow indicator are shown in figure 2. The geometry of the specimens is a 30 × 25 × 1 mm³ rectangle thin plate and the laser scanning path is shown in figure 3. The spot diameter used was 2.7 mm and the overlapping rate was 30%. The detailed LSP parameters for different specimens are listed in table 1. The specimens treated by multiple LSP with various incidence angles (50°, 40°, 30°) are shown in figure 4. It can be observed that the surface of two specimens treated by LSP was scoured when laser incidence angles were 40° and 30°, respectively, and so the 50° was selected as the laser incidence angle.

Table 1. LSP- processing parameters for different specimens.

| Specimens number | Incidence angle | Laser energy(J) | Impact times(n) | Pulse durations(ns) | Pulse frequencies(Hz) |
|------------------|-----------------|-----------------|-----------------|---------------------|-----------------------|
| #0               | —               | —               | —               | —                   | —                     |
| #1               | 30°             | 6               | 1               | 20                  | 5                     |
| #2               | 40°             | 6               | 1               | 20                  | 5                     |
| #3               | 50°             | 5               | 1               | 20                  | 5                     |
| #4               | 50°             | 6               | 1               | 20                  | 5                     |
| #5               | 50°             | 7               | 1               | 20                  | 5                     |
| #6               | 50°             | 6               | 2               | 20                  | 5                     |
| #7               | 50°             | 6               | 3               | 20                  | 5                     |
| #8               | 50°             | 6               | 1               | 18                  | 5                     |
| #9               | 50°             | 6               | 1               | 16                  | 5                     |
| #10              | 50°             | 6               | 1               | 20                  | 1                     |
| #11              | 50°             | 6               | 1               | 20                  | 10                    |
increases with decreasing laser durations. The laser power density increased with decreasing laser duration. This leads to surface deformation.

\[ \frac{18}{5} \times 16 \text{ns} = 11.7 \mu m \]

The values of residual stresses were examined by using the XL–640 x-ray diffractometer (Handan, China) with \( \sin^2 \psi \) method. X-ray beam diameter was about 1 mm. The target material was CuK\( \alpha_1 \), and the diffraction plane was at the \{213\}. The tube voltage and tube current were 26 KV and 6 mA, respectively. The single-point measuring time was 60 s. The scanning angle (2\( \theta \)) was from 147° to 137°. The values of Micro-hardness were measured by using HXD-1000TMSC/LCD Vickers indenter (Shanghai, China). An indentation load of 1000 gf was used for a hold time of 10 s. The surface topography of TC6 alloy was measured by using white-light interferometer (ContourGT-X, Bruker Nano Inc., America). The measurement was carried with the 1 \( \times \) eyepiece at 10 \( \times \) lens.

2.3. Measurements
The values of residual stresses were examined by using the XL–640 x-ray diffractometer (Handan, China) with \( \sin^2 \psi \) method. X-ray beam diameter was about 1 mm. The target material was CuK\( \alpha_1 \), and the diffraction plane was at the \{213\}. The tube voltage and tube current were 26 KV and 6 mA, respectively. The single-point measuring time was 60 s. The scanning angle (2\( \theta \)) was from 147° to 137°. The values of Micro-hardness were measured by using HXD-1000TMSC/LCD Vickers indenter (Shanghai, China). An indentation load of 1000 gf was used for a hold time of 10 s. The surface topography of TC6 alloy was measured by using white-light interferometer (ContourGT-X, Bruker Nano Inc., America). The measurement was carried with the 1 \( \times \) eyepiece at 10 \( \times \) lens.

3. Results and discussion
3.1. Surface deformation
The effects of laser parameters on the surface deformation of the oblique LSP treated specimens were shown in figure 5 and listed in table 2. Figure 5(a) shows 3D morphology and 2D surface profile of the untreated TC6 alloy specimen. Figures 5(b)–(d) show 3D morphology and 2D surface profile of TC6 alloy specimens treated at various laser energies (5 J, 6 J, 7 J), and table 2 shows the amplitude in X profile of treated specimens. It can be seen that the deformation of the TC6 alloy thin-wall parts is convex relative to the orientation of laser shock. The fluctuation of the untreated TC6 alloy surface profile is from \(-0.71 \mu m\) to \(2.08 \mu m\). The altitude difference of untreated specimen is \(2.79 \mu m\). The fluctuation of the surface profile treated with 5 J, 6 J, and 7 J is from \(-2.27 \mu m\) to \(6.6 \mu m\), from \(-2.6 \mu m\) to \(9.1 \mu m\), and from \(-5.1 \mu m\) to \(9.57 \mu m\), respectively. The altitude difference of specimens treated with 5 J, 6 J, and 7 J is \(8.87 \mu m\), \(11.7 \mu m\), and \(14.67 \mu m\), respectively. It is not difficult to find that the surface deformation of the oblique LSP treated specimens has visible changes compared with the untreated specimen, and the surface deformation increases with the laser energy. It can be explained that the increase of the laser energy leads to the increase of the laser shock wave pressure. Finally this causes the increase of the deformation.

Figures 5(c), (e), (f) show 3D morphology and 2D surface profile of TC6 alloy specimens treated at various impact times (one impact, two impacts, three impacts), and table 2 shows the amplitude in X profile of treated specimens. The fluctuation of the surface profile treated with one impact, two impacts, and three impacts is from \(-2.6 \mu m\) to \(9.1 \mu m\), from \(-15.1 \mu m\) to \(36.97 \mu m\), and from \(-19.2 \mu m\) to \(45 \mu m\), respectively. The altitude difference of specimens treated with one impact, two impacts, and three impacts is \(11.7 \mu m\), \(52.07 \mu m\), and \(64.2 \mu m\), respectively. It can be seen that the surface deformation increases with the impact times, but the further increased amplitude is limit.

Figures 5(c), (g), (h) show 3D morphology and 2D surface profile of TC6 alloy specimens treated at various pulse durations (20 ns, 18 ns, 16 ns), and table 2 shows the amplitude in X profile of treated specimens. The fluctuation of the surface profile treated with 20 ns, 18 ns, and 16 ns is from \(-2.6 \mu m\) to \(9.1 \mu m\), from \(-5 \mu m\) to \(8.96 \mu m\), and from \(-3.56 \mu m\) to \(11.14 \mu m\), respectively. The altitude difference of specimens treated with 20 ns, 18 ns, and 16 ns is \(11.7 \mu m\), \(13.96 \mu m\), and \(14.7 \mu m\), respectively. Since the laser energy during oblique LSP was constant, the laser power density increased with decreasing laser duration. This leads to surface deformation increases with decreasing laser durations.

Figures 5(c), (i), (j) show 3D morphology and 2D surface profile of TC6 alloy specimens treated at various pulse frequencies (5 Hz, 1 Hz, 10 Hz), and table 2 shows the amplitude in X profile of treated specimens. The fluctuation of the surface profile treated with 5 Hz, 1 Hz, and 10 Hz is from \(-2.6 \mu m\) to \(9.1 \mu m\), from \(-7.3 \mu m\) to \(15.2 \mu m\), and from \(-3.5 \mu m\) to \(9.15 \mu m\), respectively. The altitude difference of specimens treated with 5 Hz, 1 Hz, and 10 Hz is \(11.7 \mu m\), \(22.5 \mu m\), and \(12.65 \mu m\), respectively. It indicates that surface deformation is maximum at the pulse frequency of 1 Hz. It can be explained that the laser power supply and the thickness of
water flow are stable and have small fluctuations at the low-frequency. This leads to the formation of a bigger shock wave pressure.

3.2. Surface roughness
Arithmetical mean deviation of the surface profile Ra was chosen to describe the effects of the oblique LSP treatment on surface roughness of TC6 alloy. The surface roughness Ra of TC6 alloy specimens treated at various laser parameters is shown with column charts in figure 6. The surface roughness of oblique LSP specimens was significantly higher than that of the unpeened specimen. It was 0.46 μm for the unpeened specimen and 2.97 μm, 4.1 μm, 4.347 μm for the specimens (#3, #4, #5) treated at 5 J, 6 J, 7 J, respectively. Compared with the initial surface roughness, the Ra values of the specimens treated at 5 J, 6 J, 7 J, respectively increased by 2.51 μm, 3.64 μm, 3.887 μm. It indicates that by increasing the laser energy with a higher Ra roughness is generated. This can be explained as a result of local surface plastic deformation caused by the laser.
shock wave pressure. A local plastic deformation occurs in the form of the surface dimple. These dimples together form the texture thereby affecting the surface roughness.

The surface roughness Ra of TC6 alloy specimens (#4, #6, #7) treated at various impact times is also shown with column charts in figure 6. We can see that the surface roughness increases with impact times. Similar results were reported by Qiao et al [26] who found that the surface roughness of laser peened TiAl alloy increases with the increase of laser shock times. It was 4.1 μm, 10.3 μm, 15.6 μm for the specimens treated at one time, two

|     | #0 | #3 | #4 | #5 | #6 | #7 | #8 | #9 | #10 | #11 |
|-----|----|----|----|----|----|----|----|----|-----|-----|
| Highest(μm) | 2.08 | 6.6 | 9.1 | 9.57 | 36.97 | 45 | 8.96 | 11.14 | 15.2 | 9.15 |
| Lowest(μm) | -0.71 | -2.27 | -2.6 | -5.1 | -15.1 | -19.2 | -5 | -3.56 | -7.3 | -3.5 |
times, three times, respectively. Compared with the initial surface roughness, the Ra values of the specimens treated at one time, two times, three times, respectively increased by 3.64 $\mu$m, 9.84 $\mu$m, 15.14 $\mu$m.

Figure 6 shows the surface roughness of Ra of TC6 alloy specimens (#4, #8, #9) treated at various pulse durations. It indicates that surface roughness increases with decreasing laser duration. It was 4.1 $\mu$m, 4.2 $\mu$m, 4.75 $\mu$m for the specimens treated at 20 ns, 18 ns, 16 ns, respectively. Compared with the initial surface roughness, the Ra values of the specimens treated at 20 ns, 18 ns, 16 ns, respectively increased by 3.64 $\mu$m, 3.74 $\mu$m, 4.29 $\mu$m.

Figure 6 shows the surface roughness of Ra of TC6 alloy specimens (#4, #10, #11) treated at various pulse frequencies. It can be seen that surface roughness is largest at the pulse frequency of 1 Hz. It was 8.4 $\mu$m, 4.1 $\mu$m, 4.3 $\mu$m for the specimens treated at 1 Hz, 5 Hz, 10 Hz, respectively. Compared with the initial surface roughness, the Ra values of the specimens treated at 1 Hz, 5 Hz, 10 Hz, respectively increased by 7.94 $\mu$m, 3.64 $\mu$m, 3.84 $\mu$m.

3.3. Surface micro-hardness

Figure 7 shows the surface micro-hardness of TC6 alloy specimens (#3, #4, #5) treated at various laser energies. As shown in figure 7(a), the surface micro-hardness increases with increasing of laser energies. Similar results were reported by Siddaiah et al [27]. A gradual work-hardened layer forms easily in response to the plastic deformation induced under the action of laser shock wave pressure. The severe plastic deformation of specimen results in high dislocation densities and grains refinement. The increase of grain boundaries after grain refinement enhances the bonding force between the grains. The increase in dislocation densities can improve the resistance of dislocation motion. Consequently, the micro-hardness will increase after LSP [28, 29]. The average values of surface micro-hardness are presented in figure 7(b). It indicates that the surface micro-hardness is 354.2 HV, 359.5 HV, 367.2 HV for the specimens treated at 5 J, 6 J, 7 J, respectively. The average micro-hardness
of the specimens treated at 5 J, 6 J, 7 J, respectively increased by 7.9%, 9.5%, 11.9% in comparison with that (328.2 HV) of the unpeened specimen.

Figure 8 shows the surface micro-hardness of TC6 alloy specimens (#4, #6, #7) treated at various impact times. As shown in figure 8(a), the surface micro-hardness increases with increasing of impact times. The average values of surface micro-hardness are presented in figure 8(b). The original average value of micro-hardness is 328.2 HV. The average micro-hardness values of specimens treated by one impact, two impacts, and three impacts are 359.5 HV, 367 HV, 376.6 HV, respectively. The average micro-hardness increases by 9.5%, 11.8%, and 14.7% respectively for one time, two times, and three times.

Figure 9 shows the surface micro-hardness of TC6 alloy specimens (#4, #8, #9) treated at various pulse durations. As shown in figure 9(a), the surface micro-hardness decreases with increasing of pulse durations. This is due to the laser shock wave pressure decreases with increased the pulse durations, and smaller plastic deformation is generated. The average values of surface micro-hardness are presented in figure 9(b). The original average value of micro-hardness is 328.2 HV. The average micro-hardness values of specimens treated by 20 ns, 18 ns, and 16 ns are 359.5 HV, 363.2 HV, 381.1 HV, respectively. The average micro-hardness increases by 9.5%, 10.6%, and 16.1% respectively for 20 ns, 18 ns, and 16 ns.

Figure 10 shows the surface micro-hardness of TC6 alloy specimens (#4, #10, #11) treated at various pulse frequencies. As shown in figure 10(a), the surface micro-hardness value of treated specimen with pulse frequency of 1 Hz is even bigger than the treated specimens with pulse frequency of 10 Hz and 5 Hz. The average values of surface micro-hardness are presented in figure 10(b). The original average value of micro-hardness is 328.2 HV. The average micro-hardness values of specimens treated by 1 Hz, 5 Hz, and 10 Hz are 372 HV, 359.5 HV, 366.6 HV, respectively. The average micro-hardness increases by 13.3%, 9.5%, and 11.7%, respectively.
3.4. Surface residual stress

Figure 11 shows the effect of laser energies on surface residual stress of TC6 alloy specimens (#3, #4, #5). As shown in figure 11(a), the surface residual stress increases with increasing of laser energies. In the LSP, the plastic deformation can be induced at surface of the material, often resulting in compressive residual stresses. The average values of surface residual stress are presented in figure 11(b). It indicates that the surface residual stress is −285.5 MPa, −319.8 MPa, −355.9 MPa for the specimens treated at 5 J, 6 J, 7 J, respectively. The average micro-hardness of the specimens treated at 5 J, 6 J, 7 J, respectively increased by around 250.5 MPa, 284.8 MPa, 320.9 MPa in comparison with that (−35 MPa) of the unpeened specimen.

Figure 12 shows the effect of impact times on surface residual stress of TC6 alloy specimens (#4, #6, #7). As shown in figure 12(a), the surface residual stress increases with increasing of impact times. The average values of surface residual stress are presented in figure 12(b). It indicates that the surface residual stress is −319.8 MPa, −414.28 MPa, −473.1 MPa for the specimens treated at one time, two times, three times, respectively. The average micro-hardness of the specimens treated at one time, two times, three times, respectively increased by around 284.8 MPa, 379.28 MPa, 438.1 MPa in comparison with that (−35 MPa) of the unpeened specimen.

Figure 13 shows the effect of pulse durations on surface residual stress of TC6 alloy specimens (#4, #8, #9). As shown in figure 13(a), the surface residual stress decreases with increasing of pulse durations. Similar residual stress results were reported by Fournier et al [30]. The average values of surface residual stress are presented in figure 13(b). It indicates that the surface residual stress is −319.8 MPa, −342.5 MPa, −366.1 MPa for the specimens treated at 20 ns, 18 ns, 16 ns, respectively. The average micro-hardness of the specimens treated at 20 ns, 18 ns, 16 ns, respectively increased by around 284.8 MPa, 307.5 MPa, 331.1 MPa in comparison with that (−35 MPa) of the unpeened specimen.
Figure 12. Effect of impact times on residual stress. (a) Residual stress distribution at different positions; (b) average residual stress.

Figure 13. Effect of pulse durations on residual stress. (a) Residual stress distribution at different positions; (b) average residual stress.

Figure 14. Effect of pulse frequencies on residual stress. (a) Residual stress distribution at different positions; (b) average residual stress.

Figure 14 shows the effect of pulse frequencies on surface residual stress of TC6 alloy specimens (#4, #10, #11). As shown in figure 14(a), the surface residual stress value of treated specimen with pulse frequency of 1 Hz is even bigger than the treated specimens with pulse frequency of 10 Hz and 5 Hz. Similar residual stress results were reported by Allan H. Clauer [31]. The average values of surface residual stress are presented in figure 14(b).
It indicates that the surface residual stress is $-385.8 \text{ MPa}$, $-319.8 \text{ MPa}$, $-345.1 \text{ MPa}$ for the specimens treated at 1 Hz, 5 Hz, 10 Hz, respectively. The average micro-hardness of the specimens treated at 1 Hz, 5 Hz, 10 Hz, respectively increased by around $350.8 \text{ MPa}$, $284.8 \text{ MPa}$, $310.1 \text{ MPa}$ in comparison with that ($-35 \text{ MPa}$) of the unpeened specimen.

4. Conclusions

The present study aimed to investigate the effects of oblique LSP on the surface integrity of the TC6 alloy thin-wall parts. The effects of the laser energies, impact times, pulse durations and pulse frequencies on the surface residual stress, micro-hardness, deformation and roughness were investigated and compared. The conclusions can be summarized as follows:

1. Compared to the incidence angles of 40° and 30°, the 50° was selected as the laser incidence angle. The surface of two specimens treated by LSP with incidence angles of 40° and 30° was scoured.
2. The deformation of the TC6 alloy thin-wall parts was convex relative to the orientation of laser shock. The surface deformation, surface roughness, surface micro-hardness and surface residual stress were proportional to laser energies, impact times.
3. The surface deformation, surface roughness, surface micro-hardness and surface residual stress were inversely proportional to the pulse durations.
4. Compared with the pulse frequencies of 10 Hz and 5 Hz, surface deformation, surface roughness, surface micro-hardness and surface residual stress of the specimens treated by the pulse frequency of 1 Hz were greater.

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