Effect of process temperature on mechanical properties of Ti6Al4V titanium alloy with warm laser shock peening

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Abstract. Warm laser shock peening (WLSP) is a thermomechanical strengthening technique with tempering treatment during laser shock peening (LSP) to optimize the mechanical properties of a metallic material. In WLSP, processing temperature plays a key role in regulating the final product’s mechanical properties. In this work, Ti6Al4V titanium alloy is used to evaluate effect of temperature on mechanical properties during warm laser shock peening. The compressive residual stress (CRS) generated by WLSP at different temperature was measured by X-ray diffraction (XRD) and the surface hardness was investigated to reveal the surface strength features under different heat treatments as well. It was found that regardless of which temperature applied during the WLSP process, the treated specimens all displayed high-amplitude CRS on the surface or in depth, but the surface peak CRS decreases gradually as temperature increases. Specially, when the WLP temperature exceeded 250℃, the decreasing slope raised. The CRS affected width increased first, and then decreased with the increase of temperature. The maximum CRS affected width was about 6.25 mm, appearing at a temperature of 250 ℃. For the affected depth of CRS, firstly, as the temperature increases from 20 to 250 ℃, the thickness of affected layer rises with temperature. However, when the temperature exceeds 300℃, the affected depth of CRS sharply declines. In addition, the WLSP technology could improve the hardness of Ti6Al4V titanium alloy from 389 HV at room temperature to 418 HV at 350 ℃.

1. Introduction

Due to their favorable mechanical properties, titanium alloys can be seen in many fields, including aerospace and aircraft industries [1, 2]. However, working conditions of titanium components face are extremely adverse (e.g., high-temperature and high-pressure) and are likely to deteriorate their fatigue properties [3-5] and reliability[6, 7]. In order to solve this problem, the study and application of surface strengthening technologies is developed rapidly [8-13]. Among these techniques, laser shock peening (LSP), as an effective and fast growing surface treatment process, can considerably enhance the fatigue life of metal by inducing high amplitude CRS and hardness [14, 15]. And it has been proved by many literatures that high-amplitude CRS and surface hardness induced by LSP has beneficial effects to improving fatigue life of metals and alloys by delaying the crack initiation and by decelerating the crack propagation rate[16-19]. In practice, the compressive stress and surface hardness values are often considered as the key parameters when assessing the effect of LSP [20].

However, some literatures have reported that residual stress are relaxed significantly after cyclic loading or thermal heating process, which can greatly decrease the fatigue improvement induced by LSP [21-23]. In order to further improve LSP effectiveness and obtain more stable CRS distribution, warm
laser shock peening (WLSP) was proposed [24-27]. And the details of the process are: first of all, the specimen is heated to a definite temperature, and then the pre-warmed specimen is conducted LSP experiment. Under the couple effects of thermal assistant produced by external input and ultra-strain phenomenon of the high pressure shock wave induced by LSP [28], a comparable and even higher CRS distribution is obtained [25, 26]. Moreover, WLSP treated specimens exhibited the lower initial release rate of CRS under cyclic loads or thermal heating process, which indicates the stability of CRS is significantly improved [29-32]. Besides the CRS, the WLSP samples exhibit a greater surface strength[30, 33-36]. And during the WLSP process, CRS and hardness distribution is remarkably affected by the processing temperature and different materials exhibit different mechanical responses [23, 25, 26, 31, 37]. For example, Ye [26] studied the CRS distribution of the specimens treated by LSP at the elevated temperature. It was observed that the CRS magnitude on the surface increased with decreasing temperature and the depth of CRS increased with increasing temperature. Cheng [25] compared the CRS distribution generated by LSP and WLSP on AA6061 aluminum alloy. In Cheng’s study it was found that compared with LSP, the magnitudes of CRS at 50 μm below the surface of the metal treated by WLSP is 47.6% higher. In addition, the surface hardness magnitude of WLSP AA6061 sample increased by 27.5% from 102 to 130 HV. S. Prabhakaran et al. [33] investigated CRS characteristics of low-alloy spring steel SAE 9254 treated by LSP and WLSP (250 ℃). And results show that higher magnitude of CRS is obtained after WLSP process, and surface hardness increases by 24.48% from the untreated workpiece. In addition, the CRS of WLSP specimen authentically exhibited a better stability under thermal exposure.

From the above-mentioned, we can see that during WLSP process heating temperature plays a key role in regulating the distribution of CRS and surface hardness. Therefore, it is necessary to study the effects of process temperature on CRS and surface hardness of metallic materials during WLSP process. At the same time, Ti6Al4V titanium alloy, as a double-phase alloy, may exhibit different mechanical responses under thermo-mechanical coupling effect. Thus, in this paper, LSP of Ti6Al4V titanium alloy at different temperatures are selected to systematically study the effects of process temperature on CRS distribution and surface hardness. The CRS generated by WLP at different temperature (20,150,200,250,300 and 350℃) was measured by X-ray diffraction (XRD) and the surface hardness was investigated to reveal the surface strength features under different heat treatments as well. Finally, influence of temperature on mechanical properties of specimen are given.

2. Materials and experimental procedure

2.1. Materials and specimens

Ti6Al4V titanium alloy was selected to be investigated in this paper. And its chemical composition is shown in Table 1.

| Table 1. Chemical composition of Ti6Al4V titanium alloy (%) |
|-----------------|---|---|---|---|---|---|---|---|
| Al   | V  | Ti | Fe  | C  | N  | H  | O  |
| 5.5~6.8 | 3.5~4.5 | 3.5~4.5 | ≤0.24 | ≤0.24 | ≤0.05 | ≤0.125 | ≤0.13 |

2.2. WLSP processing

Figure 1 shows the whole WLSP process. The experiment was performed with Nd: YAG laser system with wave length of 1064 nm and pulse width of 20 ns. Due to the high-temperature working environment, traditional water confining medium used in LSP process was not applicable for the WLSP process. Therefore, we selected BK7 glass (thickness was 2 mm) with around 90% of transmittance as the confining medium of WLSP, and an aluminum foil (100 um thickness) was adopted as a protective layer. During WLSP process, due to the ultra-high expanding vapor-plasma pressure induced by laser, the glass broke every time an impacted point was obtained, and lost its confining effect. In addition, aluminum foil was also damaged due to direct laser ablation. Thus, when each impact was completed
and for the next point, there is a need to renew the glass and aluminum foil. In the process of replacement, all aspects of the process remained unchanged except for the glass and aluminum foil. And when the replacement was completed, the position of the specimen would move to the next point position waiting for the impact[38]. As is shown in figure 1, the overlap was 50%, each specimen had a 4.8 * 4.8 mm² impact area, which involved nine 2.4 mm diameter impacted points. In order to achieve six different temperatures (20, 150, 200, 250, 300, and 350°C), a temperature-controlling system was utilized. Based on the study of Fabbro [39], in order to attain higher pressure while at the same time guaranteeing great surface integrity, the WLSP processing parameters are shown in Table 2.

**Table 2.** WLSP condition utilized on Ti6Al4V titanium alloy.

| Condition | Wavelength (nm) | Spot size (mm) | Overlap | Pulse energy (J) | Pulse width (ns) |
|-----------|-----------------|----------------|---------|-----------------|-----------------|
| LSP       | 1064            | 2.4            | 50%     | 4               | 10              |

![Figure 1. Schematic of the WLSP process.](image)

2.3. Residual stress test

The residual stress of the workpieces treated by WLSP with different temperature were measured by a LXRD X-ray diffractometer and the \( \sin^2 \psi \) analysis method was conducted [40]. The test parameters used in XRD measurement is shown in Table 3. And the selected test points on the surface are along path AB (1 mm) in the WLSP regions as shown in Figure 2. For the residual stress in depth, a specific procedure of gradual stripping[41] was employed. The surface material was removed layer-by-layer through the electropolishing machine. The composition of the polishing solution was 10% HClO4 + 90% CH3OH. In order to reduce errors during the test, the same point was measured three times and the mean value taken was as the final value.

**Table 3.** Parameters used in the residual stress test.

| Item          | Description            |
|---------------|------------------------|
| Radiation     | Cu-Kα                  |
| Tilt angles   | 0˚, ±2.58˚, ±9.07˚, ±12.45˚, ±18.8˚, ±23.0˚ |
| Filter        | Ni                     |
| Spot diameter | 2mm                    |
| Crystal plane | 213                    |
| Diffraction angle | 142˚                  |
2.4. Microhardness test
Microhardness test was conducted using a Vickers microhardness tester (Taiming, Shanghai, China). The load was 200 gf and the holding time was 15s. In order to improve the reliability of results, the mean value of three measurements was used to characterize the microhardness at this point.

3. Results and discussions

3.1. Distribution of residual stresses

3.1.1. Surface residual stress distribution at different temperatures. The comparison of the surface CRS distribution of the WLSP-ed specimens treated at different temperatures is shown in Figure 3. It is noted that a high amplitude CRS is introduced in the peened region. The surface peak CRS at different temperature is studied. As show in Figure 3 (b), at the temperatures of 20, 150, 200, 250, 300 and 350°C, the peak CRS of specimens were -806, -751, -732, -680, -614, and -502 MPa, respectively. It is clearly seen that the maximum CRS with a value of -806 MPa was introduced at the room temperatures. And when the WLSP temperature increased, the value of CRS decreased gradually. Compared with the room temperatures, the peak CRS values are decreased by 6.8, 9.2, 15.6, 23.8, and 37.7%, respectively. This indicates that when the temperature exceeds 250°C, the decline slope was raised.
This result suggests that the effect of temperature on surface CRS distribution of the materials is notable and the underlying mechanism may be explained from the following two aspects. On the one hand, as we know, the generation of CRS depends on severe plastic deformation which is affected by the flow stress of materials [42]. According to Zhou[23], strain/strain rate hardening is responsible to the flow stress of the materials. Meanwhile, the thermal softening also has a great effect on it. During the WLSP process, severe plastic deformation with high strain rate occurs due to the high pressure wave induced by laser. Strain hardening and strain rate hardening increase correspondingly, which results in the increment of the flow stress. However, with the temperature increasing, the flow stress will reduce with thermal softening decreasing. And the final CRS distribution results suggest that during the thermomechanical treatment the effects of strain/strain rate hardening on the flow stress exhibited the different response from the effects of thermal softening. Clearly, the effects of the thermal softening dominate the process from the beginning and are more and more obvious, which results in a final CRS distribution. On the other hand, from the micro-view, high processing temperatures is conducive to dislocation movement under the pre-warmed environment [43]. As the temperature increased, WLSP-induced dislocation accumulation may decrease as a result of the softening effect, which led to a decrease of residual stress[31]. Besides, due to the energy input for the material, the kinetic energy of atoms increases, and the atomic motion is greatly excited by the temperature, which accelerates atoms in returning to the balance position[30], and thus the CRS values decreased. At the same time, when the processing temperature was too high, the heat treatment exacerbated the relaxation of CRS through dynamic recovery, which resulted in the improvement of the slope of decrease.

The results of surface CRS affected width at different temperatures are shown in Figure 4. We selected the peening area with CRS exceeding -350 MPa as the CRS affected area and measured its width (Figure 4 (a)). The measurement results are plotted in Figure 4 (b), which implies that the CRS-affected width gradually increased as temperature increased from 20 to 250 ℃. As compared to 20℃, the CRS-affected width values increased by 25.1, 33.3, and 38.9%, respectively, at 150, 200, and 250℃. When the WLSP temperature reached 300℃, the CRS affected width slightly decreased, but at the temperature of 350℃, there was a significant decline. The reason for this phenomenon is mainly because the dynamic yield strength of the material decreases with high temperature, and the deformation is greater under the same shock wave[38]. Therefore, a larger CRS field is produced in the specimen. But when the temperature increased over 250 °C, the speed of CRS release was accelerated at elevated temperatures, leading to the further reduction in distribution range of CRS.

![Figure 4. Surface CRS affected width at different temperatures. (a) a diagram of the selected area. (b) affected width.](image)

3.1.2. Residual stress distribution in depth at different temperatures. Figure 5 compares the in-depth residual stress distribution under different working temperature. It can be seen that a deeper CRS affected layer with exceeding 1mm is introduced into the specimen and all the WLSP-ed specimen...
treated at different temperature show similar profile in the distribution of CRS. The maximum CRS is produced on the surface. Then, the value of CRS decreases gradually with depth of subgrade. A large number of investigations [16, 18, 44-47] indicates that higher and deeper CRS is very favorable for the improvement of fatigue life of the materials. With the exception of 350°C, it is not too different for CRS values in the same depth under other temperatures. From Figure 5, we can also see that among different temperatures CRS at the room temperature always remains maximum from top peened surface to 900 μm, but as the depth continues to increase, the maximum CRS appears at the temperature of 300 °C. This indicates that temperature has an important influence on the CRS distribution in depth.

As shown in Figure 6, the depth of the affected layer presents the remarkable difference under different temperatures. We defined the depth with CRS as the CRS affected layer and measured its depth (as shown in Figure 6 (a)). It can be found that the CRS distribution is deeper after WLSP. As shown in Figure 6 (b), as temperature increases from 20 °C to 300 °C, the affected depth of CRS displays an upward tendency, and at the temperatures of 20, 150, 200, 250 and 300°C, the CRS affected depth of specimens are 1.19, 1.27, 1.31, 1.31 and 1.45 mm, respectively. But when exceeding the temperature of 300°C, the affected depth (about 1.12 mm) of CRS declined obviously which is caused by thermal softening effects. For samples treated at 300°C, the CRS is as deep as 1.45 mm, while this value increases by 21.8%, as compared to that of 20°C. Therefore, it can be concluded that, despite the peak CRS shows a downward trend as temperature elevates, a deeper CRS is enhanced by the elevated temperature.

Figure 5. Residual stress distribution in depth at different temperatures.

Figure 6. The depth of CRS affected layer at different temperatures. (a) a diagram of the selected area. (b) affected depth.
The generation of CRS is closely related to the plastic deformation of the material [38]. During the WLSP process, only when the shock pressure induced by laser exceeds the Hugoniot elastic limit (HEL) of the material, plastic deformation will occur. HEL[48] can be defined as follows:

\[ HEL = \sigma_{dy} \times \frac{1-v}{1-2v} \]  

where \( \sigma_{dy} \) is the dynamic yield stress and \( v \) is Poisson’s ratio. Based on the work of Chang [49], the dynamic yield stress decreases with temperature. And HEL decreases consistently with it, which results in the softening effect. Compared with LSP at the room temperature, deeper deformation depth occurs under the same shock pressure during WLSP process. But when the temperature exceeds 300 ℃, the couple effects of dynamic recovery and CRS thermal relaxation of material at high temperature will lead to the reduction of CRS affected depth.

3.2. Distribution of microhardness and analyse

Figure 7 compares the hardness of the samples before and after WLSP at different processing temperatures. It can be seen that after LSP at the room temperature, the average hardness increased from 345 HV (Vickers hardness number) to 389 HV, which corresponds to a 12.8% increase. And compared with LSP at the room temperature, all the WLSP-treated samples exhibit higher surface microhardness. For instance, when compared with 20 ℃, the surface microhardness was increased by 2.0, 2.3, 3.6, 5.7 and 7.5%, respectively at the temperatures of 150, 200, 250, 300, and 350 ℃. This indicates the hardening behavior during LSP and WLSP is significantly different. During LSP process, the improvement of microhardness is the results of the strain hardening induced by the severe plastic deformation[11, 50-53]. But for WLSP, besides the strain hardening, the dynamic strain aging (DSA) and heat-assisted dynamic precipitation (DP) are both contributed to the work-hardening[24, 26, 30, 31, 34-36, 54]. During WLSP, the triple effects of the strain hardening, DSA and DP leads to higher dislocation density and higher resistance for dislocation movement. In addition, many authors reported the grain-refinement phenomenon after WLSP [30, 32, 34]. Grain refinement may increase the hardness of treated samples because more grain boundaries mean more obstacles to dislocation movement. At the same time, Ti6Al4V titanium alloy, as a double-phase alloy, the behavior of \( \alpha \) and \( \beta \) phases will remarkably affect the strength of the materials and it may exhibit different microstructure change under thermo-mechanical coupling effect. Next, it is necessary to conduct further research to confirm this. And the complicated relationships between microstructure and mechanical properties of Ti6Al4V titanium alloy under thermomechanical treatment may be of specific interests and importance.

![Figure 7. Microhardness distribution at different temperatures.](image)
4. Conclusion

In order to investigate the effect of temperature on mechanical properties of Ti6Al4V titanium alloy with warm laser shock peening, the measurements of residual stresses and microhardness were carried out on specimens treated at different temperatures. The related phenomena were analyzed systematically. The following conclusions can be drawn:

1. The surface peak CRS of the Ti6Al4V titanium alloy treated by WLSP displays a downward trend as temperature increases. When the WLSP temperature exceeded 250°C, the decline slope was raised.

2. The CRS affected width gradually increased as temperature increased from 20 to 250 ℃. When the WLSP temperature reached 300℃, the CRS-affected width slightly decreased, but at the temperature of 350℃, there was a significant decline.

3. For the affected depth of CRS, firstly, as the temperature increases from 20 to 250 ℃, the thickness of affected layer rises along with the temperature. But when the temperature of 300℃ was exceeded, the affected depth of CRS declined obviously.

4. Compared with LSP at the room temperature, all WLSP-treated samples exhibit higher surface microhardness, which increases with temperature.

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