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Laser Peening Systems and the Effects of Laser Peening on Aeronautical Metals Sheet

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Keywords

Laser Peening (Lp), Surface Profile, Microstructure, Fatigue Life, Titanium Alloy, Superalloy, Thermal Cycle

In order to improve the fatigue properties of airplane and aero-engine structures, the mechanical performances of typical aeronautical metal alloys with laser peening (LP) were investigated in this paper, LP experiment was undertaken with Q-switched Nd:Glass and Nd:YAG laser systems. As the commonest lasers for peening, the performance of Q-switched Nd:Glass and Nd:YAG lasers was compared with each other. The surface profile of LP with square spots was compared with that of circle spots, the results indicated that the array of square spots can get very smooth overlapped effects. Then, the effect of LP on the mechanical performances of TC4 (Ti6Al4V) titanium alloy, 7050 aluminum alloy and GH2036 superalloy was researched, which were measured and observed by nondestructive X-ray diffraction method, SEM and TEM. High density dislocation and nanocrystallite were observed in LP zone of TC4. The average fatigue lives of laser peened 7050 samples with three different thickness were increased by 283%, 315% and 306% respectively, which benefit from crystal defect and high surface residual compressive stress in LP zone. LP could get thermal stable residual compressive stress and fine grain structures of GH2036, which is benefit to the fatigue properties of critical structures under cyclic stress and high temperature.

Introduction

TC4 titanium alloy, 7050 aluminum alloy and GH2036 superalloy are widely used in airplane structures, air-engine blade and turbine disk because of their high specific strength and good corrosion resistance [1-3]. As the blades accident accounted for one-third of the engine structure approximately, the fatigue life and fatigue strength of blades influence the security of aeroengine operating directly. Laser Peening (LP) is a new surface treatment technology for improving surface fatigue intensity of metals in which residual compressive stress and grain refinement are mechanically produced into the surface [4].

LP uses intense pulse laser induced impulsive waves to generate plastic strain in the surface layer of metal. It is an interaction between high-energy laser and material during a very short period of time [5], which has been proved to be a non-conventional surface mechanical treatment used to improve the wear resistance, corrosion resistance and fatigue properties of the metallic components [6-8]. LP produces extensive plastic deformation in the material, when the peak pressure of the laser shock wave is greater than the dynamic yield strength of the material [9, 10]. Compared to conventional shot peening, LP induces the deeper layer of plastic strain and compressive residual stresses, lower cold hardening and smoother surface [11-13].

In recent years, many researchers were paying more attention to LP systems and their application. Qiao [14] et al. studied the development of high peak power short pulse from Nd:YAG laser along with its peening application. It presented the design scheme of laser and the characteristic of laser beam transmission. Zhu [15] et al. discussed the influence of laser shock peening on surface morphology and mechanical property of Zr-based bulk metallic glass. Zhou [16] et al. proposed a grain refinement mechanism of mechanical twins and martensite bands in the austenitic stainless steel induced by ultra-high strain rate deformation during multiple LSP impacts based on the microstructural observations. Ren [17] et al. stated the residual stress thermal relaxation behavior in iron GH2036 alloy by laser shockprocessing using experimental and simulation methods. It reveals the main mechanism of thermal relaxation is the mechanism involving rearrangement and annihilation of dislocation.

A more comprehensive research work was designed to evaluate the effect of LP on the mechanical properties of three typical aeronautical structural materials in this paper. As the commonest lasers for peening, Q-switched Nd:Glass and Nd:glass lasers were compared with each other. The surface morphology of LP with square-spot was compared to that of circular-spot. The effect of LP on the surface profile, residual stress and microstructure of TC4 titanium alloy, 7050 aluminum alloy and GH2036 superalloy were studied by means of white light interference method, nondestructive X-ray diffraction method, Transmission Electron Microscopy observations (TEM) and scanning electron microscope(SEM). It revealed the mechanism of the thermal cycling stability of residual stress of superalloy.

LP Systems

Usually two types of intense pulse lasers are used for LP, one is Q-switched Nd:Glass laser and the other is Q-switched Nd:YAG laser. Two kinds of lasers were compared in Table 1. Nd:Glass laser can get high pulse energy but low frequency, Nd:YAG laser is just on the contrary, low pulse energy but high frequency. Two types of LP systems were set up in Beijing Aeronautical Manufacturing Technology Research Institute (BAMTRI) as shown in Fig. 1. Nd:Glass (silicate glass with diameter 20mm and length 280mm) laser can output pulse laser with 30ns and 50J, but the repetition is only 0.1Hz. Q-switched Nd:YAG laser with 10ns pulse duration was developed by ourselves, in order to ensure stable pulse energy and uniform distribution, Diode pumped master oscillator and two-pass amplifier with saturated gain was used in YAG laser, two laser beam (Diameter 15mm) can be combined to provide 12J × 10Hz.

In order to get high pulse energy, it's necessary to enlarge Nd:YAG rod cross-section but it's very difficult to grow large size Nd:YAG rod and ensure the good quality. The difficulty with the suppression ASE (by Sm3+), the more lost of effective pumping and more lamps required, the less transfer efficiency of input electric power to laser power.

Table 1. *The parameters of Nd:Glass and Nd:YAG lasers.*

Parameter	**Nd:Glass**	**YAG**	**Characteristic of YAG**
Conductivity	**1,02 (W/mK)**	**14 (W/mK)**	**High repetition rate**
Emission cross section	3.6×10^{-20} (cm^2)	2.8×10^{-19} (cm^2)	High gain, but ASE
Saturation fluence	~ 6 (J/cm^2)	0,62 (J/cm^2)	High extraction efficiency
Damage threshold	Phosphate/silicate 20/40 (J/cm^2)	~7-10 (J/cm^2)	Larger aperture required
Dimensions	any	≤ Ø30 (mm)	Many beamlets

Fig. 1. *Q-switched Nd:Glass and Nd:YAG lasers in BAMTRI.*

LP Experiment and Results

TC4 titanium alloy, 7050 aluminum alloy metals sheet were treated by LP with a Q-switch Nd:Glass laser system capable of delivering about 50J of laser energy and 30ns of pulse width (FWHM) with diameter ф 20mm. The spot size on target was about 4-6mm, laser energy was 36J-40J and laser power density was about 4GW/cm^2 for aluminum alloy and 7GW/cm^2 for titanium alloy. GH2036 superalloy specimens were treated by high frequency Nd:YAG laser, the laser parameters were 10J/10ns and focused toф4mm on the target. The surface morphology of the metals sheet was measured on WYKO NT1100 optical profiler based on white light interference technology. The residual stress measurements were performed by a standard X-ray diffraction technology. The microstructure change of the metals sheet without and with LP was charactered by TEM and SEM.

Surface Morphologies of LP with Square-spot and Circular Spot

The surface profile of LP with square spots was compared with that of circle spots as shown in Fig. 2 and Fig. 3. High peak power pulse laser and uniform intensity distribution is coupled to the part using a special optical shaping delivery system, which can transfer circle laser spot to square laser spot with uniform energy distribution. Fig. 2 showed the surface profile (smooth bottom concave) generated by LP with square spot. A square spot can get even residual stress around the shock zone. Single circle spot has smoother transition profile near the edge, but overlapped circle spots produce a dented surface in spite of different overlap form as shown in 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.

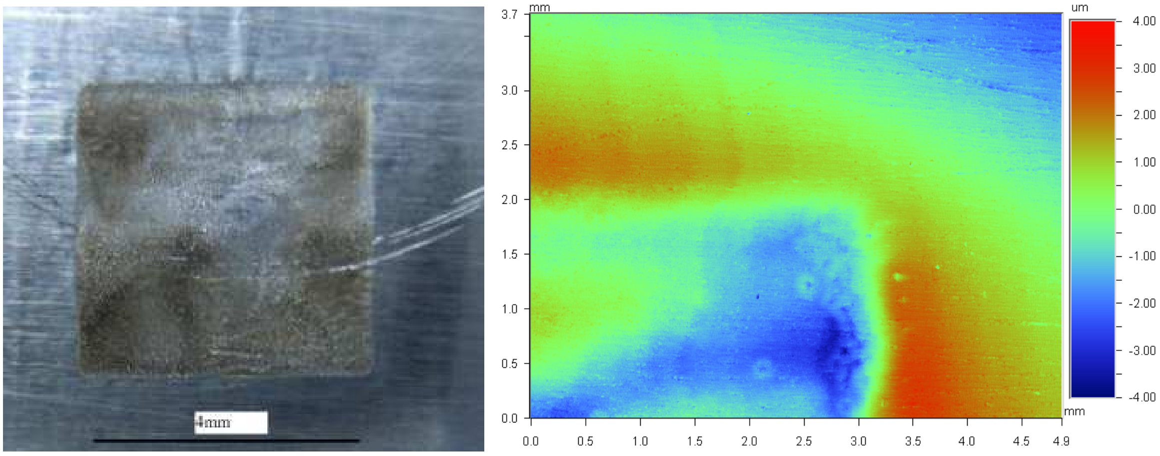


***Fig. 2.** The surface profile and power density of LP with square spot.*

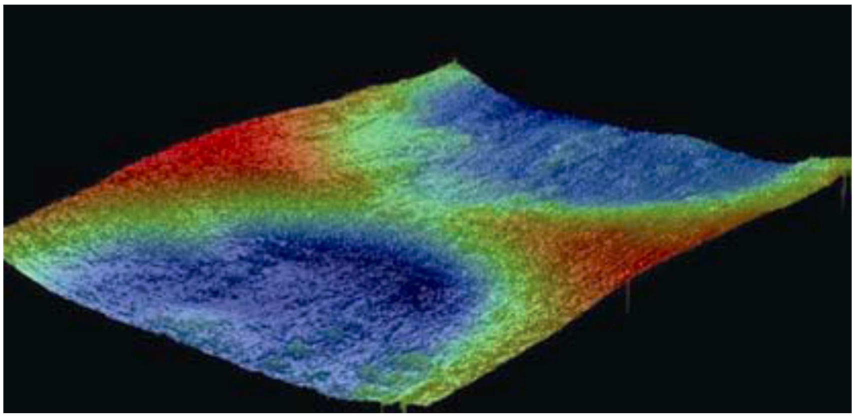


***Fig. 3.** The surface profile of LP with overlapped circle spots.*

The Effect of LP on TC4 Titanium Alloy

In order to study the effect of LP on the fatigue properties of TC4 blade, a TC4 sample was prepared to observe the microstructure without and with LP. It can be seen from Fig. 4 that the microstructure of TC4 with LP is refined that the fatigue performance is improved. In Fig. 4(a), the main structure of TC4 without LP is α' phase, diffraction spots show single phase α'-Ti phase and diffraction point 2, 3, 4 respectively present the α'-Ti of (0002), (-2112), (-2110) faced crystal. After LP, the lath structure in the surface layer (about 200μm) of origin materials disappears and presents microlite. As shown in Fig. 4(b), the continuous diffraction ring enunciates the material to organize thin change into smaller microlite. In Fig. 4(b), diffration ring from inside to outside in order is (-110)α, (101)β(011) α, (200) β and (2-10) α crystal plane. In Fig.4(c), nanocrystallite appears on the surface of LP region. The average grain size is about 70 nm. The lath structure in the raw material disappears.

The plastic deformation of metals with high stacking-fault energy is through movement of dislocation, and that of metals with low stacking-fault energy is through mechanical twin. The plastic deformation of TC4 includes both dislocation slippage and mechanical twin due to medium stacking-fault energy, which makes the evolution process of structure more complicated. The plastic deformation manner of TC4 titanium alloy with LP has several processes as follows [18]: (1) Evolution of dislocation wall and tangle in the grain and refined cell; (2) Dislocation wall or tangle transforms the low angle boundaries of divided single cell and subcrystal; (3) The transformation from low angle subcrystal boundaries to high ones; (4) The high dislocation density will form equiaxed nano-crystalline structure with random orientation.

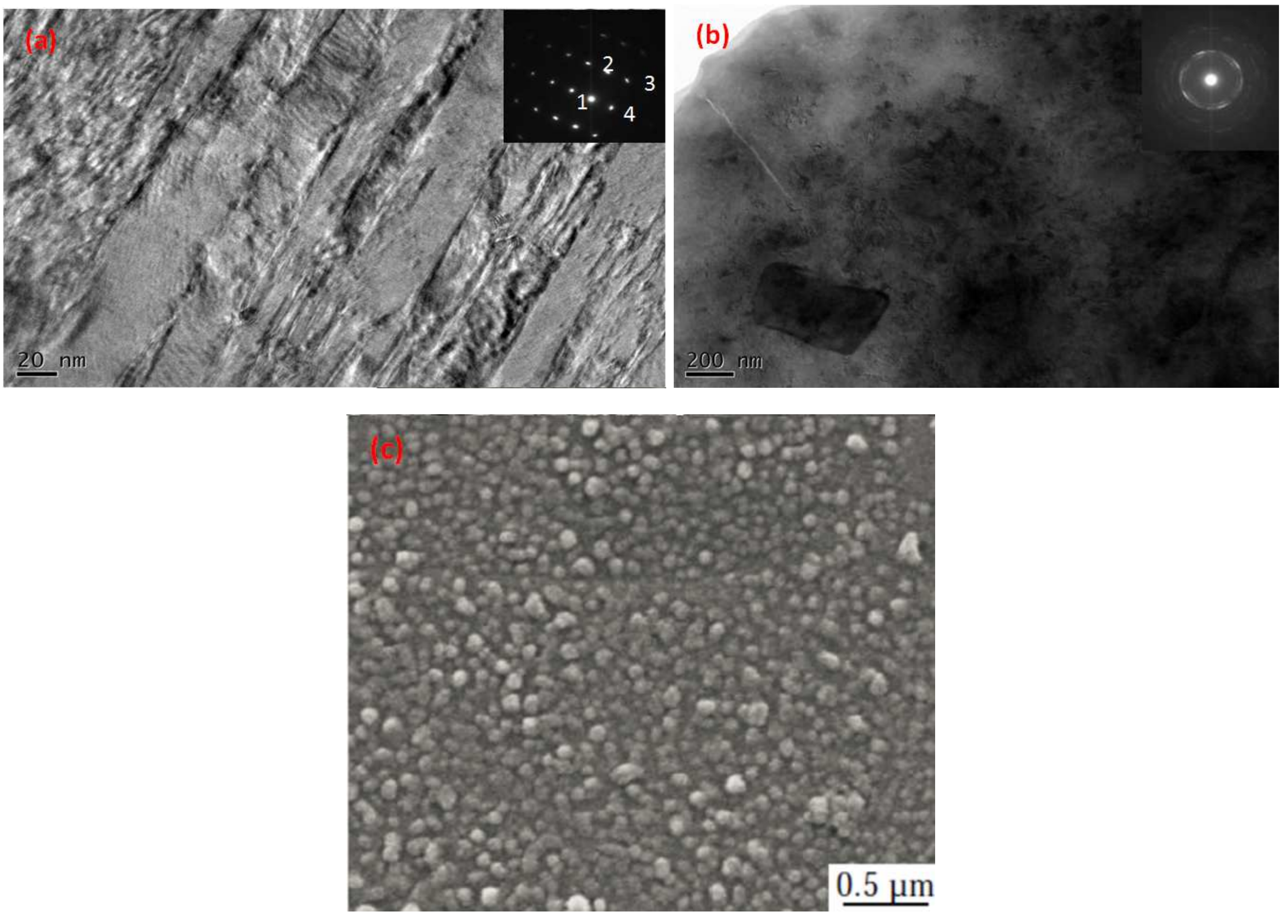


Fig. 4. *Microstructure of TC4 titanium alloy, (a) without LP(TEM), (b) with LP(TEM), (c) nanocrystallite with LP(SEM).*

Fatigue samples of TC4 were made as the design in Fig. 5, one hole was shot peened or laser peened with a ф5mm circle spot and two sides before drilling. Fatigue test were processed with the parameter: σ_{max}=384MPa, R=0.1 and Frequency=20Hz, the results showed the average fatigue cycles of untreated samples, shot peened samples and laser peened samples were 96716, 192309 and 424620 respectively, which mean that laser peening got the best effects.

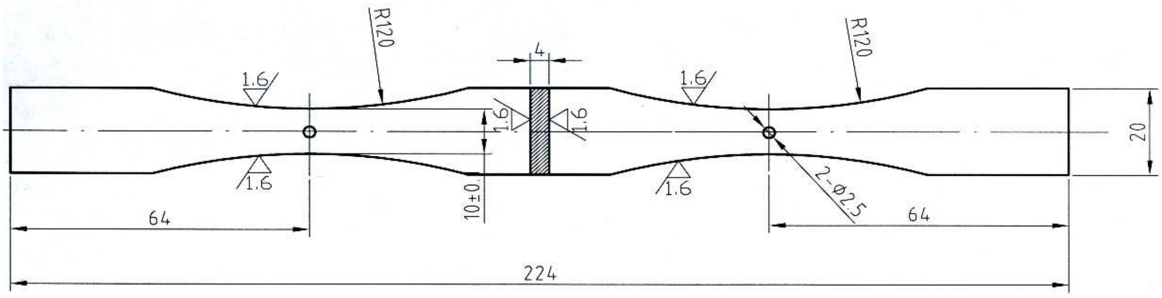


Fig. 5. *Fatigue sample (one hole with laser peening before drilling and the other without peening).*

The Effect of LP on 7050 Aluminum Alloy

Fatigue sample design of 7050 aluminum alloy was shown in Fig. 5. A notch with 2.5mm diameter was drilled at the center of each neck of fatigue sample. One hole of the sample was two-sided LP and the other hole was original statu. The thickness of the sample was 2mm, 3mm and 4mm, respectively. Fatigue tests of the samples were taken under a special flight spectrum for mid-airframe structures, and each flight spectrum representing 150 flight hours. The maximum load in spectrum was 8.1kN, which was equal to 270MPa tensile stress in the minimal cross section. During the fatigue life test, if the hole in one end broke down, data was recorded as the fatigue life of the hole, the fatigue life test continued on the remaining sample until the other end also broke down, and the data was then recorded as the fatigue life of the later hole.

The fatigue test results indicated that average fatigue lives of three different thickness-samples with 2mm, 3mm and 4mm were increased from 423297, 286393, 467726 (without LP) to 1198448, 901746, 1429638 (with two-sided LP). The fatigue lives were increased by 283%, 315% and 306% respectively. Fig. 6 showed that the surface layer microstructure of 7050 aluminum alloy with and without LP by TEM. It can be observed from Fig.6 that high intense twins, dislocations and the dislocations tangles each other are induced in LP zone. The average value of surface residual stress along the central line of the shocked zone was about -200MPa and the surface residual stress of the base material was only tens of MPa.

The strengthening mechanism of 7050 aluminum alloy with LP might be concluded as 3 reasons: (1) In the fatigue crack initiation stage, the compressive residual stress is very important. Compressive residual stress could reduce the working stress in the surface layer, so the initiation of fatigue cracks at the vulnerable surface area is prevented. Meanwhile, crystal defects and refined grain bring in the improvement of material strength according to Hall–Petch formula [19]. Therefore, the crack initiation of 7050 aluminum alloy with LP is more difficult than the ones of without LP; (2) The compressive residual stress could improve the threshold of crack growth in the growth stage of fatigue crack. Compressive residual stress greatly increases the closing force of microscopic cracks and retards crack propagation. And some cracks are compelled to swerve or blocked to propagate, therefore they consumes large amount of energy; (3) The refined grains and high density dislocations bring in more grain boundaries which can restrain the slip deformation and plastic flow for crack growth.

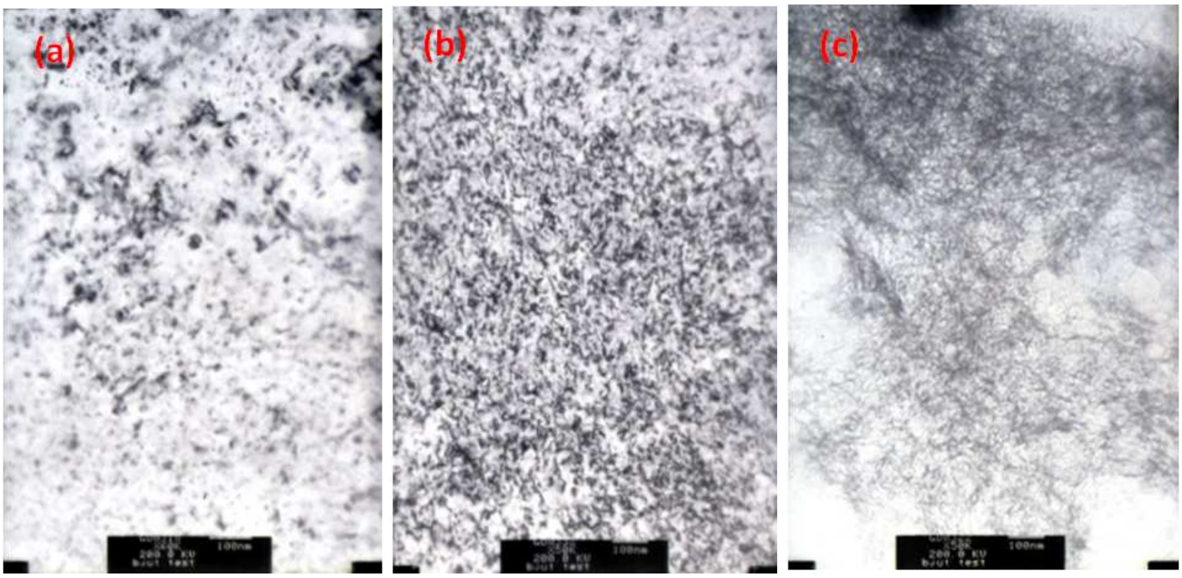


Fig. 6. *Microstructure of 7050 aluminum alloy, (a) without LP, (b) with LP, (c) with LP (dislocation tangles).*

The Effect of LP on GH2036 Superalloy

A Fe-based superalloy GH2036 of turbine disk is operated in temperature near 600°C. Therefore, it should be researched that the effect of LP with overlapped circle spots on the thermal cycling stability of residual stress of GH2036 superalloy. The samples with and without LP were conducted high temperature thermal cycles experiments using automatic heat recirculation furnace with heating speed of 50°C /min. Thermal cycle temperature was set in Fig. 7. The samples were exposed to the thermal cycling temperature ranged from room temperature to 600°C (top temperature keep for one hour). The surface morphology of GH2036 superalloy with different thermal cycles after LP were shown in Fig. 8. The surface residual stresses of LP GH2036 superalloy were measured after different thermal recycles and the results were shown in Fig. 9. It can be observed from Fig. 9 that the surface residual stress in GH2036 superalloy with LP will decrease with the increase of thermal cycle times. The surface residual stresses basically keep stable after 50 cycles and the value of surface residual stress remains -300MPa, which is 56% of residual compressive stress of GH2036 superalloy with LP and without thermal cycles. After LP and thermal cycles, more and smaller carbide was produced in the sample. Nanometer size fine grain can be observed by TEM and the size of grain is about 100nm as shown in Fig. 10.

The main reason of thermal cycles stress relaxation is as follows: (1) Grain refinement, high dislocation density and the low cold hardening rates induced by LP have significant influence on thermal stability of residual stress of GH2036 superalloy at elevated temperatures. Researchers [20, 21] found that dynamic thermal recovery and recrystallization is the main mechanism causing thermal relaxation of residual stress at elevated temperatures. Essentially, dynamic recovery is caused by dislocation glide; (2) The effect of thermal cycles times on thermal relaxation are controlled by thermally activated mechanism. Thermal relaxation of residual stress can be described by using Zener-Wert-Avrami function [22, 23].

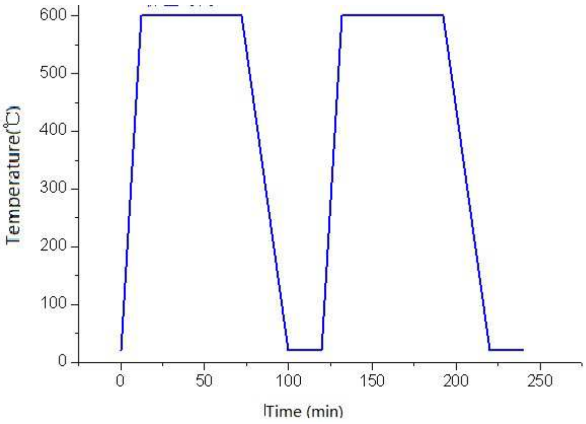


Fig. 7. *Thermal cycle temperature setting.*

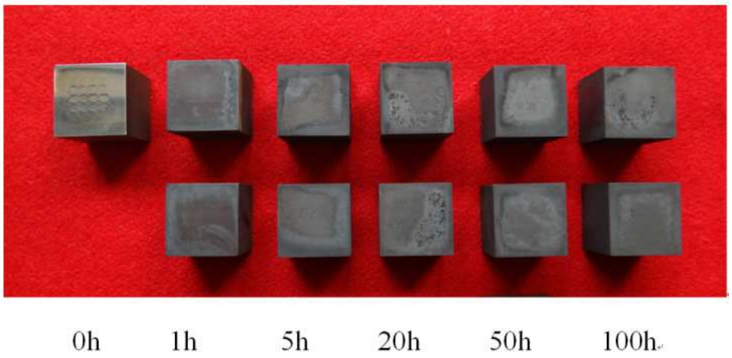


Fig. 8. *Samples of GH2036 with different times of thermal cycles after LP.*

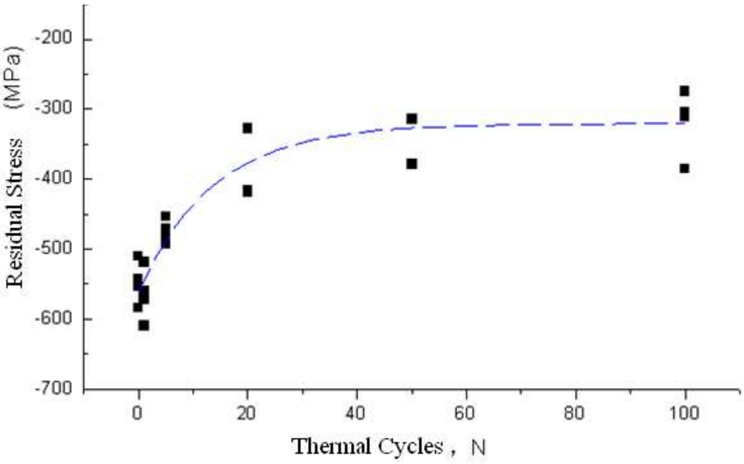


Fig. 9. *Surface residual stress of GH2036 with different times of thermal cycles after laser peening.*

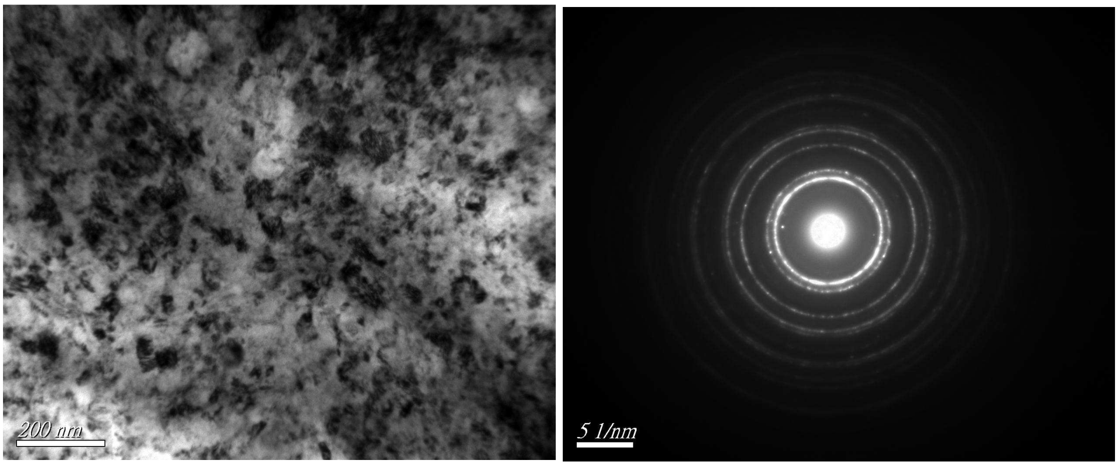


Fig. 10. *Microstructure of GH2036 with LP and 20 thermal cycles (TEM).*

Conclusions

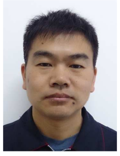
The paper presents the effect of LP on the mechanical performance of TC4 titanium alloy, 7050 aluminum alloy and GH2036 superalloy. The relative conclusions are as follows:

(1) Single circle spot has smoother transition profile near the edge, but overlapped circle spots produce a dented surface. The array of square spots can get very smooth overlapped effects.

(2) The plastic deformation mechanism of TC4 with LP includes both dislocation slippage and mechanical twin due to medium stacking-fault energy. After LP, the lath structure in the surface layer of about 200 µm disappears and presents microlite. Nanocrystallite with the average grain size of 70 nm appears on the surface of LP region.

(3) Compressive residual stress and crystal defect and refined grain were induced by LP in the surface layer of 7050 aluminum alloy. Compressive residual stress could reduce the working stress in the fatigue crack initiation stage and could improve the threshold of fatigue crack growth in the fatigue crack growth stage. Meanwhile, crystal defect and refined grain bring in more grain boundaries which can restrain the slip deformation and plastic flow for crack growth. Therefore, average fatigue lives of three thickness-samples with 2mm, 3mm and 4mm were increased from 423297, 286393, 467726(without LP) to1198448, 901746, 1429638 (with two-sided LP). The fatigue lives were increased by 283%, 315% and 306% respectively.

(4) LP can keep GH2036 superalloy stable residual stresses and fine grain structures even after thermal cycling. With the increase of thermal cycles, surface residual stresses release with times, but the relaxation processing mainly produce in the beginning 50 cycles, the final stress is found to be -300MPa, which is 56% of the original value. Dynamic thermal recovery and recrystallization is the main mechanism causing thermal relaxation of residual stress at elevated temperatures. And the effect of thermal cycles times on thermal relaxation are controlled by thermally activated mechanism.



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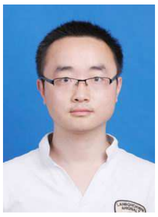

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