Investigations on TC4-DT titanium alloy using laser shock processing with high energy

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Laser shock processing (LSP) is an innovative surface treatment technique with high peak power, short pulse, and cold hardening for strengthening metal materials. This process induces intensive plastic deformation and deeper compressive residual stress and improves the surface performance of materials. The titanium alloy of TC4-DT is the important materials in many industry fields including aviation, which is used widely on hole and welding structure. However, the researches of surface treatment on TC4-DT welding structure using LSP technology are seldom reported by now. The performances of TC4-DT, including mircrohardness and surface profiles, are improved through the technology of LSP.

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Laser shock processing or laser peening has become an advanced and promising surface treatment technique and has been shown to be effective in increasing the resistance of metallic components to high-cycle fatigue (HCF), stress corrosion cracking (SCC), wear, etc., through imparting compressive residual stress on the surface of a number of metals and alloys. The higher laser energy/power density could induce the deeper effect layer, larger action area, and better treatment effect.

The property of damage tolerance has become the design concept and selection criterion of breakage-safety of meeting the requirements for advanced aircraft and engine structural integrity. The TC4-DT is two phases titanium alloy of damage tolerance with high fracture toughness and resistance fatigue extension through component optimization design, pure smelting, and β heat processing technology basing the titanium alloy of TC4. The advantages of TC4-DT are low metallurgy defect, high plasticity and toughness, fine welding performance, and long life. Therefore, this alloy has widely been applied in the field of aerospace[1]. The amount of TC4 is 25.6% of the total weight in the fourth generation fighter of US, while 73% for TC4-DT. It can be said that TC4-DT is one of the preferred structure materials for main bearing parts of future aircraft[2].

The damage tolerance shows the behavior under the combined actions of load and defect. The fracture toughness of titanium alloy is half of steel ones. Therefore, it is very important to improve the performance of titanium alloys. The specimens of TC4-DT titanium alloys are treated using laser shock processing (LSP) in this investigation. The principle of LSP was presented and the improved pressure model was used to estimate shock pressure of plasma. The pulse laser is focused to a diameter of 5-6 mm onto the samples. Energy of about 20 J with infrared (1 064 nm) radiation was used. The Nd:glass laser with 30-ns pulse width was used in this experiment, as shown in Fig. 1. The objective of this work is to examine the effect of laser shock processing on the TC4-DT, including hardness, surface profile and roughness. The properties of samples were improved after LSP.

The principle of LSP is shown in Fig. 2. The surface of target is plastered with a coating layer (also called sacrificial layer, normal organic paint or metallic foil, such as tape, zinc or aluminum) after polishing[3]. The laser pulse with high peak value power (>1 GW/cm^2) , short duration (nano second level) irradiates on the surface of coating layer traveling transparent confined medium (water or glass) by focusing lens. The coating layer absorbs the laser energy, explodes and forms plasma in very short time. The plasma is restrained by the confined medium during expanding and products high pressure shock wave[4]. When the peak value of stress wave exceeds the hugoniot elastic limit (HEL) of the material for a suitable time, the dense and stable dislocations (or twin crystal) are formed. The surface strain hardening is produced at the same time. The elastic deformation energy with shock wave is greater than or equal to the plastic and yielding deformation energy of target material. The compressive residual stress is generated on the surface and in material due to the plastic deformation layer restraining the resuming of the elastic deformation energy. The existence of compressive residual stress alters the distribution of stress field and improves the fatigue performance of material surface. So the technique of LSP can evidently improve the performance of

Fig. 1. Setup for laser shock processing in BAMTRI.

corrosion and fatigue resistance[5,6]. The heat effect can be ignored due to the existence of coating layer and the very short time of interaction and protecting the target from thermal damage. The confined medium is used to enhance the pressure of shock wave and prolong the action time[7].

The HEL of material is related to the dynamic yield strength according to[8]

$$\mathrm{HEL} = \frac{\lambda + 2\mu}{2\mu}\sigma_{\mathrm{Y}}^{\mathrm{dyn}} = \frac{1-\nu}{1-2\nu}\sigma_{\mathrm{Y}}^{\mathrm{dyn}}, \qquad (1)$$

where

$$\mu = \frac{E}{2(1+\nu)},$$

$$\lambda = \frac{E\nu}{(1+\nu)(1-2\nu)},$$

where ν is the Poisson's ratio, E is the Yong's modul, and $\sigma_{\mathrm{Y}}^{\mathrm{dyn}}$ is the dynamic yield strength of material at high strain rates.

The distributions of hardness were measured both shocked and unshocked areas. The results showed that the HV hardness increases after LSP in some extent. Especially, higher HV hardness was measured in the center of laser spot, which was caused by the Gaussian distribution of laser spot.

The pressure calculation of LSP is the foundation of determining the technique parameters. The pressure model can be obtained as[9]

$$P(\mathrm{GPa}) = 0.01\sqrt{\frac{2\alpha}{3(2\alpha+3)}} \times \sqrt{Z(\mathrm{g/cm^2 s})} \times \sqrt{I_0(\mathrm{GW/cm^2})}, \qquad (2)$$

where Z is the combined shock wave impedance relating with the shock wave impedance of target material (Z_1), the confined medium (Z_2) and the left absorbing layer (Z_3), $3/Z = 1/Z_1 + 1/Z_2 + 1/Z_3$. The pressure model is accordant with the practical situation and has more accurate calculation results than previous model due to the left coating layer being considered. The pressure value obtained by this model is accurate in pressure prediction and simulation calculation of finite element method (FEM).

Due to the intensive plastic deformation and high peak pressure, the high density dislocation and fine deformation twins are produced in the laser shock processed surface layers. The microhardness could increase within the shocked area. The shocked areas are indicated in Fig. 3.

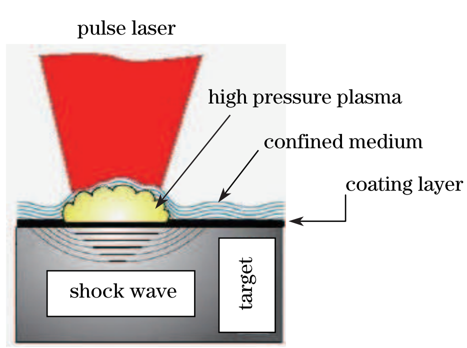

Fig. 2. Scheme of LSP.

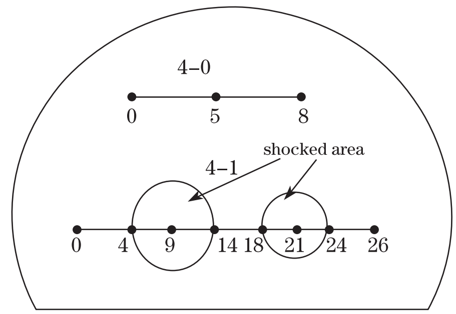

Fig. 3. Distribution of measurement point on sample.

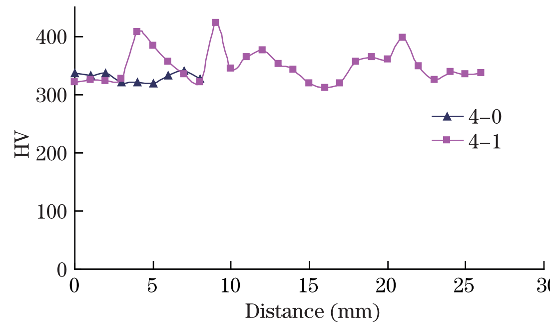

Fig. 4. HV Hardness variation of the distance.

The numbers show the test point on the surface of sample. The distributions of hardness are shown in Fig. 4. The Vickers hardness before LSP (4-0 line) are between 320 to 336 HV, while reaching 422 HV after LSP (4-1 line and circle area) shown in Fig. 4. Especially on the shocked area, from No. 4 to 14 and No. 18 to 24, the HV hardness increases significantly. The maximum value reaches 422 HV. Due to the pulse fluctuating energy difference, the maximum of the left circle area is larger than that of the right circle area for larger pulse energy. The irregular distributions of value in Fig. 4 are due to the Gaussian distribution of laser spot energy. As shown in Fig. 4, the shock hardness effect decreases with increasing distance from the center of laser beam, especially out of the shock area. The hardness is higher near to the center of laser beam. This is attributed to the higher pulse energy near to the center, which results in greater dislocation generation and motion. The surface hardness is improved apparently compared with that of unshocked region.

To quantitatively characterize the deformation, the interferometry-based optical with a vertical resolution of 50 nm is used to profile deformed regions. Figure 5 shows the measurement results of dent geometry using optical profilometer after LSP on the surface of TC4-DT. The diameter of dents is about 4–5 mm, near to the size of laser spot of 5–6 mm. The difference between measurement value and laser spot diameter lies in the boundary effect and the existence of absorbing layer. In face, the dimension of dent by LSP is correlative directly with the diameter and the energy of laser spot. The cross-sectional measurements of the dents are shown in Fig. 5 with the X and Y Profiles. The depths reach 8 and 6 μm, respectively.

In conclusion, the left coating layer is considered in the pressure model in LSP process, which provids more accurate pressure calculating formula. This is accord with

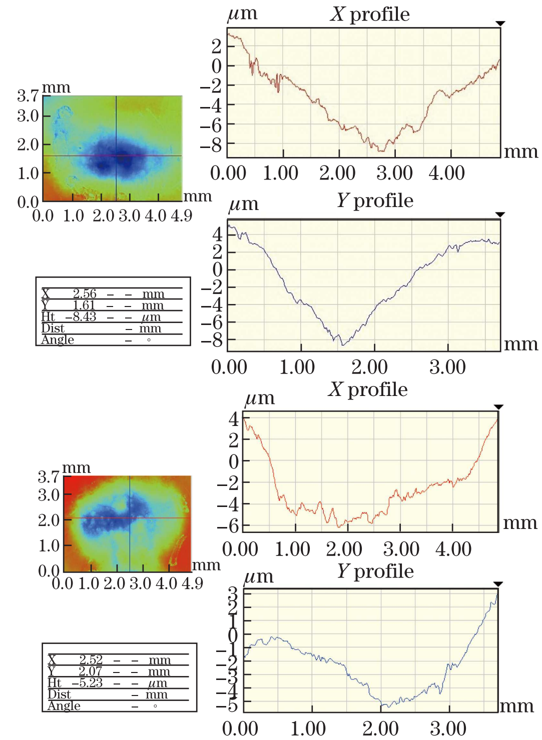

Fig. 5. Typical optical micrograph of dent geometry using optical profilometer of different energies.

the actual situation. After all, very thin coating layer is left after LSP whatever treating any material. The distributions of hardness is measured both shocked and unshocked area. The results show that the HV hardness increases after LSP in some extent. Especially, higher HV hardness is measured in the center of laser spot, which is caused by the Gaussian distribution of laser spot. The surface profiles are correlative directly with the diameter and the energy of laser spot. The diameter determines the area of the dent, and the energy of laser spot determines the depth of the dent.

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