Experimental investigation of laser shock peening on TC17 titanium alloy for Thin-wall Workpieces

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Abstract

To study the performance and microstructure of TC17 thin-walled parts in shock wave and its reflection wave induced by laser, TC17 titanium alloy samples are processed using YAG laser with the wavelength of 1064 nm, pulse energy of 7J and pulse width of 15ns. Thus, its residual stress, microhardness and microstructure of overlapping shock with different thickness are obtained. The results show that with the thickness increasing, the front micro-hardness increases, and the reverse micro-hardness increases firstly and then decreases. The variation of residual stress with the thickness is consistent with the micro-hardness. The front residual stress maximum reaches -496.5MPa at the thickness of 5mm, and the reverse residual stress maximum reaches -171.1MPa at the thickness of 2mm. With the increase of thickness, the distribution of surface dislocations is more uniform, the grain refinement effect is more obvious, and the strengthening effect is the better. The causes of the variation of the double-sided residual stress field with the thickness are explained by theoretical analysis of the propagation and reflection of the shock wave in the material. The conclusions of this investigation have significance for the optimization of laser shock peening thin-wall workpieces.

Keywords: laser shock peening; titanium alloy; thickness; microstructure

3 Results

3.1 Residual stress of double-sided surface

In laser peening, the surface of the material is shocked by high-pressure peak shock wave, often resulting in compressive residual stresses being produced at surface of the material. Fig.2 shows the double-sided residual stress of laser peened region with different thickness of specimens. From Fig.2, the compressive residual stress on the front surface increases with the increase of thickness. The residual compressive stress is -496.1MPa at the thickness of 5mm. When the thickness is 1mm, the residual compressive stress on the front surface decreases obviously which is only -211.2MPa, and the strengthening effect is reduced by 57.4% compared with 5mm. The reverse residual compressive stress is smaller compared with the front. The residual compressive stress on the reverse surface increases firstly and then decreases with the thickness decreasing. The residual compressive stress reaches the maximum which is -171.1MPa at the thickness of 2mm. Therefore, the specimens have better strengthening effect for the thickness of more than 2mm at the process parameters of this paper.

3.2 Micro-hardness of double-sided surface

Hardness is a basic mechanical property of metal material, which can be defined as the resistance to indentation. Higher hardness value can bring in a better property of resistance for the wear and foreign object damage to some extent. Fig.3 shows the double-sided micro-hardness of laser peened region with different thickness of specimens. From Fig.3, the micro-hardness on the front surface increases with the increase of thickness. The front micro-hardness is 440.9HV at the thickness of 5mm, increased by 14% compared with original material. When the thickness is 1mm, the front micro-hardness decreases obviously which is only 415.2HV. The reverse micro-hardness increases firstly and then decreases with the thickness increases. The reverse micro-hardness maximum reaches 416.1HV at the thickness of 2mm. Laser shock peening could improve micro-hardness onto the TC17 alloy surface, because plastic deformation, high density dislocations, and fine grain are induced on the material surface by high-pressure shock waves. According to the dislocations reinforcement theory, generation and motion of dislocations can lead to the work hardening. The micro-hardness value (H_v) can be described by equation (1) [9].

$$H_v = H_{v0} + aGb\beta^{1/2} \tag{1}$$

Where H_{v0} represents hardness of an ideal material without defects, a is a constant based on material itself, G denotes the shear modulus, b is the value of Burger vector; β represents the dislocation density. So, the hardness of the material is proportional to the dislocation density. As the thickness increases, the dislocation density of the surface on the front increases, and then the microstructure of the material is analyzed specifically in 2.3.

3.3 Surface microstructure

Fig.4 shows the microstructure of TC17 samples before and after LSP with different thickness. Fig.4a) indicates virginal features of the specimens without LSP. The microstructure is very regular and which is identified as α+β phase. There is a small amount of dislocations and twins on the surface of the material. The electoral electron diffraction of the material without LSP shows a certain directivity. Fig.4b) presents microstructure micrograph of the laser peened area at the thickness of 1mm. It shows that many dislocations are generated locally, and the dislocation distribution is uneven. The source of cracks is form easily at dislocation-intensive boundaries which unfavorable effects on fatigue performance, reducing the strengthening effect [10]. The electoral electron diffraction orientation is not obvious. The reflection wave in the vertical direction has a great influence on the microstructure of the material, the strengthening effect of the frontal shock wave is counteracted to a certain extent. Dislocation distribution is not uniform because the reflected wave direction and incident wave are not the same.Fig.4c) and d) presents microstructure micrograph of the laser peened area at the thickness of 3mm and 5mm respectively. It indicates that as the thickness increases, the density of dislocations increases, and the distribution is more uniform. Entanglement, annihilation and recombination of the dislocations caused by the dislocation movement of high-density dislocations make rotation of grains. The orientation difference between subgrain boundaries becomes larger and larger, which transforms into a large-angle grain boundary, finally achieving grain refinement. The shock wave makes the high density of dislocations which increase the randomness of the electoral electron diffraction on the surface. When the thickness is 5mm, the diffraction pattern shows an equiaxed tendency meaning that the grain size of the material surface is refined. Therefore, when the thickness is small, smaller energy parameter is suitable to reduce the impact of reflection waves.

4 Discussion

Fig.5 shows the surface topography of shock areas at the thickness of 1 mm and 5 mm. When the material has a certain extent thickness, reflection waves has less impact on the material surface due to attenuation. Thus, the shock wave only acts once, and the surface is smooth. When the thickness is small, the material is subjected to multiple impacts due to the reflection of shock waves on different interfaces.

Compared with 5mm, reflection waves make the surface rougher at the thickness of 1mm.

When the shock wave propagates from substance A to B, it will be reflected and transmitted. According to the conservation equation, both the reflection wave and the incident wave in the whole propagation process are continuous, and the motion of each particle in the material conforms to the mechanical equilibrium, as shown in equation (2) - (4) [11].

$$\sigma A\mathrm{d}t = \sigma A dx U_P \Rightarrow \sigma = \rho \frac{dx}{dt} U_P \Rightarrow \sigma = \rho D U_P \tag{2}$$

$$\sigma_1 + \sigma_R = \sigma_T \tag{3}$$

$$u_I + u_R = u_T \tag{4}$$

Where σ is the amplitude of the stress wave, A denotes the area, t is the time, ρ represents the density, D denotes the wave velocity in the medium, x denotes the distance in the depth direction, and U_p is the particle velocity. The subscript I represents the incident wave, T represents the transmitted wave, and R represents the reflected wave. The relationship between incident wave, transmitted wave and reflection wave amplitude can be deduced, as shown in equation (5) - (6).

$$\frac{\sigma_T}{\sigma_I} = \frac{2\rho_B D_B}{\rho_A D_A + \rho_B D_B} \tag{5}$$

$$\frac{\sigma_R}{\sigma_I} = \frac{\rho_B D_B - \rho_A D_A}{\rho_A D_A + \rho_B D_B} \tag{6}$$

From the equation (6), the direction of the reflection wave is determined by the acoustic impedance (ρD) of material. If $\rho_A D_A < \rho_B D_B$, the direction of the reflection wave is the same as the incident wave; If $\rho_A D_A > \rho_B D_B$, the direction of reflected wave is opposite to the incident wave. In this experiment, the reverse contacts with the fixture of the stainless steel whose impedance is about twice of the titanium alloy [12]. Thus, the direction of the first reflection wave is the same as the incident wave which is the compression wave and form a certain residual compressive stress at the reverse. When the first reflection wave reaches the impact surface, the front contacts with the black tape whose impedance is less than one-fifth of the titanium alloy. So, the direction of the second reflection wave which is the tensile wave is the opposite to the incident wave. It would offset residual compressive stress on the front surface to decrease maximum residual compressive stress. And as the thickness increases, the influence of the second reflected wave decreases. Therefore, the residual compressive stress of the front surface increases with the increase of the thickness. For the thickness of 1 mm, the second reflected tensile wave reaches the reverse and forms the third reflection wave. The direction of the third reflection wave is the same as the second reflection wave which is the tensile wave. It would offset residual compressive stress on the reverse surface to decrease maximum residual compressive stress. Therefore, the maximum residual compressive stress of the reverse surface at the thickness of 1 mm is smaller than the residual compressive stress at the thickness of 2 mm. The greater the thickness, the smaller the third reflected wave, and the larger the residual compressive stress on the reverse surface. However, if the thickness increases to a certain extent, the residual compressive stress formed by the first reflected begins to decrease. In summary, with the thickness increasing, the front residual stress increases and the reverse residual stress increases firstly and then decreases.

5 Conclusions

(1) The double-sided residual stress and microhardness of specimens with different thickness were tested by experiments. With the thickness increasing, the front residual stress increases and the reverse residual stress increases firstly and then decreases. The variation of microhardness with the thickness is consistent with the residual stress. The front micro-hardness maximum reaches 440.9HV at the thickness of 5mm, and the reverse micro-hardness maximum reaches 416.1HV at the thickness of 2mm.The specimens have better strengthening effect for the thickness of more than 2mm at the macroscopic level.

(2) The microstructure of specimens with different thickness were tested by experiments. With the increase of thickness, the distribution of surface dislocations is more uniform, the grain refinement effect is more obvious, and the strengthening effect is the better.

(3) The propagation and reflection law of shock wave in materials is studied by the surface morphology and theoretical analysis. The tensile wave and compressional wave generated by the shock wave between the different acoustic impedance interface have a great influence on the distribution of residual stress field that can explain the reasons for the variation of double-sided residual stress field. The results of this study can provide reference for the optimization of thin-walled workpieces.