Comparison of residual stress before and after shot peening on the surface of a Ti-6Al-4V titanium alloy by μ-X360n equipment

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Abstract. This comparison study is on the residual stress of a Ti-6Al-4V titanium alloy before and after shot peening. The Ti-6Al-4V titanium alloy is one of the most widely used materials due to a very good comprehensive performance. Testing the titanium alloy reveals that it adopts a Cu Kα for the target material because it has a strong diffraction peak under the crystal surface (213). The equipment used is the two-dimensional surface diffraction method to test the stress of the Ti-6Al-4V titanium alloy. The two-dimensional surface agent contains a detector and the detector consists of a complete probe. The core component of the detector is greater than 2 inches in diameter and the size of the detector determines its ability to collect the diffraction signal; the greater the acquisition ability, the stronger it is. This piece of equipment is currently the most advanced full two-dimensional piece of equipment. The residual stress in the x-direction on the upper surface of the Ti-6Al-4V titanium alloy before shot peening is 296 Mpa and the error is 12 Mpa. The residual stress in the y-direction was 106 MPa and the error was 16 Mpa. The residual stress on the surface x-direction of the Ti-6Al-4V titanium alloy after shot peening was –532 Mpa and the error was 27 Mpa. The residual stress in the y-direction was –87 Mpa and the error was 32 Mpa. The measurement results indicate that the stress orientation is not uniform and that there was an obvious texture. On the surface of the Ti-6Al-4V titanium alloy, the residual stress in the x-direction of the upper surface is –532 Mpa, which is consistent with the theory and principle. The two-dimensional detector needs only one exposure to get the complete material Debye ring according to the integrity of the Debye ring and its intensity distribution characteristics. It can be concluded that the Ti-6Al-4V titanium alloy has a texture after shot peening. The stress change principle of the Ti-6Al-4V titanium alloy was compared from tensile stress to compressive stress, before and after the shot peening treatment.

1. Introduction
The residual stress is the internal stress that exists in the internal equilibrium when there is no external action. Internal stress is divided into three categories: the first type of internal stress becomes “residual stress”, the second type of stress is called “microscopic stress”, and the third type is called “lattice distortion stress”. The full 2D detector technology is a new generation of portable X-ray residual stress analysis methods and equipment because of its reliability and portability of test data in welding, pipelines, pressure vessels, automobiles, ships, oil, bridges, high-speed trains, nuclear power. There are important applications in fields such as aviation, military, and major equipment manufacturing [1].

The Ti-6Al-4V titanium alloy has the advantages of good corrosion resistance, high specific strength, good toughness and weld ability, and so forth. It is widely used in the manufacture of general components for aerospace, petrochemical, power, and so forth [2–5]. The Ti-6Al-4V titanium alloy
also has a good heat resistance, plasticity, and formability, and its use accounts for 75%–85% of the total use of titanium alloys [6]. External forces can be derived through the calculation of mechanical formulas, and the residual stresses are difficult to obtain through this route. At present, the residual stress test methods with practical application value mainly include the X-ray diffraction method and the neutron scattering method. The two-dimensional surface exploration X-ray diffraction method is used in this paper [7]. The traditional X-ray diffraction method is used to measure the diffraction angles under different ψ angles in the same ϕ direction by changing ψ, so as to further calculate the strain εψϕ under different ψ angles, and finally obtain the measured material in ϕ through data fitting. The residual stress in the ϕ direction[8–9]. In 1978, Taira et al. [10] first proposed the two-dimensional surface exploration X-ray diffractometry to measure the residual stress, which was later generalized as a single exposure method and was continuously improved [11–12]. In this paper, the residual stress on the surface of the Ti-6Al-4V titanium alloy before and after shot peening was measured by twodimensional surface exploration. The test results can reflect whether the material has coarse grains and the preferred orientation.

2. The Two-Dimensional Surface Exploration of μ-X360n Residual Stress Test Principle

Figure 1 is a schematic diagram of the working principle of μ-X360n. The X-ray two-dimensional surface exploration residual stress test is, in principle, consistent with the traditional method, and the residual stress is calculated by the Bragg Equation relationship between the diffraction angle and the strain. The difference is that the two-dimensional surface exploration only needs to test a single exposure to the angle ψ0. To test the variation of the diffraction angle on a two-dimensional surface, the residual stress of φ0 in this direction can be calculated. The schematic diagram of the measurement equipment is shown in Figure 1 below.

![Figure 1. The schematic diagram of the working principle of μ-X360n.](image)

The Bragg Equation reflects the relationship between the crystal plane spacing and the diffraction angle, and its differential form shows the relationship between the diffraction angle change and the strain, as shown in Equation (1): [13]

\[ \varepsilon = \frac{\Delta d}{d} - (\theta - \theta_0) \frac{1}{\tan \theta_0} \]  

(1)

After determining the test angle ψ0, the diffractive surface direction \( \vec{n} (n_1, n_2, n_3) \) of all the directions on the test plane ψ0 can be obtained by vector addition, where
According to the elastic strain tensor, to calculate the strain in different directions, you can get the strain in the three directions of x, y, and z by substituting Equation (2) into Equation (3) which results in

\[
\varepsilon_a = n_1^2 \varepsilon_x + n_y^2 \varepsilon_y + n_z^2 \varepsilon_z + 2n_1 n_y \gamma_{xy} + 2n_2 n_z \gamma_{xz} + 2n_1 n_z \gamma_{zx}
\]

(3)

\[
\varepsilon_a = \frac{1}{E} \left[ n_1^2 - \nu(n_2^2 + n_3^2) \right] + \sigma_y \frac{1}{E} \left[ n_2^2 - \nu(n_1^2 + n_3^2) \right] + \sigma_z \frac{1}{E} \left[ n_3^2 - \nu(n_1^2 + n_2^2) \right]
\]

(4)

\[
\tau_{xy} \frac{2(1 + \nu)}{E} n_1 n_z + \tau_{xz} \frac{2(1 + \nu)}{E} n_2 n_3 + \tau_{zx} \frac{2(1 + \nu)}{E} n_1 n_2
\]

The definitions \( \alpha_1 \) and \( \alpha_2 \) are shown in Equation (5). Substituting Equation (4) into Equation (5) yields a residual stress calculation method for X-ray two-dimensional surface exploration, as shown in Equation(6)[15].

\[
\begin{align*}
\alpha_1(0) &= \frac{1}{2} \left[ (\varepsilon_a - \varepsilon_{x,0}) + (\varepsilon_a - \varepsilon_{y,0}) \right] - \frac{1 + \nu}{E} \sigma_x \sin 2 \psi_0 + 2 \tau_{xy} \cos 2 \psi_0 \sin 2 \eta \cos \alpha \\
\alpha_2(0) &= \frac{1}{2} \left[ (\varepsilon_a - \varepsilon_{x,0}) - (\varepsilon_a - \varepsilon_{y,0}) \right] \frac{2(1 + \nu)}{E} \tau_{yz} \sin \psi_0 + \tau_{zx} \cos \psi_0 \sin 2 \eta \sin \alpha \\
\alpha_3(0) &= \frac{1}{2} \left[ (\varepsilon_a + \varepsilon_{x,0}) + (\varepsilon_a - \varepsilon_{x,0}) \right] = \Phi \cos^2 \alpha + \psi
\end{align*}
\]

(5)

\[
\begin{align*}
\tau_{xy} &= \frac{E}{4(1 + \nu)} \frac{1}{\sin 2 \eta} \frac{1}{\sin \psi_0} \left[ \frac{\partial \alpha_2(\phi_0)}{\partial \sin \alpha} \right]_{\psi_0 > 0} - \left( \frac{\partial \alpha_2(\phi_0)}{\partial \sin \alpha} \right)_{\psi_0 < 0} \\
\tau_{yz} &= \frac{E}{4(1 + \nu)} \frac{1}{\sin 2 \eta} \frac{1}{\cos \psi_0} \left[ \frac{\partial \alpha_2(\phi_0)}{\partial \sin \alpha} \right]_{\psi_0 > 0} + \left( \frac{\partial \alpha_2(\phi_0)}{\partial \sin \alpha} \right)_{\psi_0 < 0} \\
\tau_{zx} &= \frac{E}{4(1 + \nu)} \frac{1}{\sin 2 \eta} \frac{1}{\cos \psi_0} \left[ \frac{\partial \alpha_3(0)}{\partial \cos \alpha} \right]_{\psi_0 > 0} + \left( \frac{\partial \alpha_3(0)}{\partial \cos \alpha} \right)_{\psi_0 < 0}
\end{align*}
\]

(6)

The two-dimensional surface detector has a detection detector. The detector is a complete probe. The detector of the core part is about 2 inches in diameter. The size of the detector determines the ability to acquire diffraction signals. The greater the acquisition capacity is, the more uniform it is. Distributed on one surface, it is currently the most advanced full-scale 2D surface finder. According to the diffraction angle measured by the detector to obtain the corresponding strain value, by substituting Equation(5), you can calculate the \( \alpha_1 \), the \( \alpha_2 \) for the \( \cos \alpha \) partial guide, and then the residual stress [15–16].

3. Text Materials and Methods

The materials studied in this paper are the Ti-6Al-4V titanium alloy before and after shot peening. The lattice type, crystal plane, Young’s modulus, Poisson’s ratio, and diffraction angle are shown in Table 1 below. Titanium alloys have strong diffraction peaks on Cu Kα to test the residual stress of the Ti-6Al-4V alloy. The test conditions are as follows: tube voltage of 30 kV, tube current of 1.5 mA, irradiation diameter of ~3 mm, X-ray incident angle of 45°.
4. Results and Discussion

Figure 2a, g are the front and back 2-dimensional Debye rings of the shot peened Ti-6Al-4V titanium alloy, respectively, and Figure 2b, h are the front and back three-dimensional Debye rings under X-ray diffraction, respectively. The complete Debye Ring (3D) of the Ti-6Al-4V titanium alloy is not broken in the middle. As long as it is complete, there is not much coarse crystal. Although the figure is complete, we can see a rule. That is, one side has a reddish diffraction intensity and the other side has a yellowish colour, which is biased toward the side where the diffraction intensity is low. This unequal intensity of the diffraction intensity is the characteristic of the texture and preferential orientation, that is, the shot peening. This preferred orientation exists on the surface of the back sample. Figure 2c, i are the images of the Debye ring-variant manifestation observed under a beam of radiation from the Cu Kα target (213) crystal plane. The diffraction intensity of the Debye ring is not uniform, indicating that it may contain directional grains. Figure 2d, j are the Debye rings unfolded in two-dimensional images; Figure 2e, k are the Debye unfolded three-dimensional images. From Figure 2e, k, it can be seen that the analysis result of the Ti-6Al-4V titanium alloy has only one diffraction peak and that the intensity of the diffraction peak varies with the angle α. This shows that the stress orientation of the materials is not uniform. It can also be seen from the figure that the measured Debye ring is uneven, indicating that there is a more obvious texture [17]. Figure 2f, i show that the three-dimensional Debye ring is developed in two dimensions with different central angles into two-dimensional diffraction intensity curves. It is an image of 500 diffraction peaks that are superimposed, that is, the diffraction intensity from the centre to the periphery of the Debye ring. The strongest diffraction peak was obtained at 140.077. The maximum peak intensity was about $6.26 \times 10^5$.

| Target Material | Crystal Structure | Diffraction Line(hkl) | Young’s Module(GPa) | Poisson’s Ratio(v) | Diffraction Angle (2θ) (°) |
|-----------------|-------------------|-----------------------|---------------------|-------------------|--------------------------|
| Ti-6Al-4V       | HCP+BCC           | 213                   | 137                 | 0.219             | 140.077                  |

Table 1. The properties of Ti-6Al-4V.
Figure 2. The analysis results of two-dimensional detector before and after shot peening.

The diffraction angles obtained from all directions are substituted into Equation (1) to obtain the strain in each direction, and then the strain is substituted into Equation (5). Then, \( \alpha_1 \) and \( \cos \alpha \) are fitted to obtain Figure 3. Figure 3c shows the relationship between \( \alpha_1 \) and \( \cos \alpha \) obtained from the four-point bending test, the results of which are shown in Figure 3. This winding may be due to deviations from the \( \cos \alpha \) method assumptions, plane stress conditions, constant stress within the diffraction volume, and elastic isotropy. The measurement is based on the measurement theory and the stress is approximated by the calculation of the above formula (Equation (5)), as shown in Figure 3c. Figure 3d shows the relationship between \( \alpha_1 \) and \( \sin \alpha \) from the four-point bending test, and the results also show the entanglement in the figure.
Figure 3. The $\alpha$-cos$\alpha$ and $\alpha$-sin$\alpha$ curves of the Ti-6Al-4V titanium alloy residual stress test before and after shot peening.

According to Figure 3a above, we can see that the slope of the curve is negative. By substituting the calculated slope result into Equation (6), we can obtain the residual of the sample Ti-6Al-4V titanium alloy before shot peening. The results of the stress test are shown in Table 3; the residual stress in the normal stress x-direction is 296 Mpa and the residual stress in the shear stress y-direction is 106 Mpa. According to Figure 3c above, we can see that the slope of the curve is positive. By substituting the calculated slope result into Equation (6), we can get the residual of the sample Ti-6Al-4V titanium alloy after shot peening. The residual stress values are shown in Table 3. The residual stress in the normal stress x-direction is –532 Mpa and the residual stress in the y-direction of the shear stress is –87 Mpa. The test results show that after the shot peening of the Ti-6Al-4V titanium alloy, the residual stress changes from tensile stress to compressive stress and that the residual compressive stress helps to inhibit the work piece from showing the propagation of micro-cracks and the improvement of fatigue life. At the same time, it also shows that the two-dimensional surface probing method used to test the residual stress of the Ti-6Al-4V titanium alloy material is a good test method.
Figure 4. The Full Width Half Maximum graph and peak strength before and after shot peening.

From Figure 4c above, it can be seen that before the shot peening of the Ti-6Al-4V titanium alloy, the entire half-height Debye ring has a variation of about 1.84–2.32. Figure 4g shows that the entire half-height Debye ring after the shot peening of the Ti-6Al-4V titanium alloy has a variation of about 3.2–4.6 and that its diffraction profile is sufficient to obtain the 2θ angle required to measure the stress. In addition, the reason for the variability of the full width at half maximum can be explained by the change in the diffraction intensity of the Debye ring shown in Figure 4f. The FWHM before and after shot peening corresponds to the 2θ corresponding to the position of the diffraction intensity because the intensity distribution curve is symmetrical. The same intensity corresponds to two peak positions. Figure 4d,h are the corresponding diffraction intensities at different central angles of the Debye ring before and after shot peening.

Table 2. The measurement results of residual stress before the shot peening in the x-direction and the y-direction.

| Stress          | Residual Stress (MPa) | Standard Deviation (MPa) |
|-----------------|-----------------------|--------------------------|
| Positive stress | 296                   | 12                       |
| Shearing stress | 106                   | 16                       |

Table 3. The measurement results of the residual stress after the shot peening in the x-direction and the y-direction.

| Stress          | Residual Stress (MPa) | Standard Deviation (MPa) |
|-----------------|-----------------------|--------------------------|
| Positive stress | –532                  | 27                       |
| Shearing stress | –87                   | 32                       |

5. Conclusions

a) The residual stress of the Ti-6Al-4V titanium alloy before and after shot peening can be measured by two-dimensional surface X-ray diffraction. The experimental results also show that the residual stress of the Ti-6Al-4V titanium alloy was measured by the two-dimensional surface exploration method.
b) From the analysis results, by comparing the residual compressive stress on the surface of the Ti-6Al-4V titanium alloy before and after shot peening, it was found that the residual tensile stress becomes residual compressive stress.

c) The test results also show that the residual stress in the x-direction after shot peening is more pronounced than in the y-direction in the shear stress. According to the Debye ring’s integrity and its intensity distribution characteristics, the residual stress can be judged after shot peening. The texture of the Ti-6Al-4V titanium alloy is not uniform and the residual stress distribution is not uniform.

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