Investigation on Surface Layers Characteristics of Pre-Stressed Shot Peening Inconel 625

Lihong Wu and Chuanhai Jiang*

School of Materials Science and Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, P. R. China

Surface layers characteristics of pre-stressed shot peening Inconel 625 was investigated. Residual stress and microstructure in the deformation layers were characterized by X-Ray diffraction method. The results showed that pre-stressed shot peening can further improve compressive residual stress and microstructure with the same intensity of traditional shot peening. Both surface compressive residual stress and maximum compressive residual stresses were produced in the deformation layers after various pre-stressed shot peening. The higher applied pre-stress resulted in more obvious effects of domain size refinement and micro strain generation. Compressive residual stress, finer domains and higher micro strain strengthened the effects of pre-stressed shot peening, which caused the further increment of micro hardness and yield strength of Inconel 625. [doi:10.2320/matertrans.MT-M2019106]

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1. Introduction

Shot peening process was well known for improving micro hardness, stress corrosion and fatigue resistance of materials. Hardness small balls impact the surface of material, which introduces high compressive residual stresses and cold work in the deformation layers of the material. In that way, smaller domains were refined and high micro strain was generated. Higher compressive residual stress and finer microstructure can improve the mechanical properties of material.1-5) Pre-stressed shot peening is a new modified process to strengthen the effects of traditional shot peening process.6,7) During pre-stressed shot peening, the components were pre-loaded with tensile stresses on a fixed direction first, then the applied loads were relieved after shot peening.

Due to the superior thermal, fine fatigue and creep properties, Inconel 625 has been widely used in aerospace, chemistry and nuclear power industry,8) such as turbine engines, nuclear reactor and pumps, etc. Many studies were more turned towards its mechanical properties after traditional shot peening process. However, few of them relates to residual stress and microstructure in the deformed layers after pre-stressed shot peening. Therefore, we especially focused on the effect of pre-stressed shot peening on residual stress and microstructure. Details will be presented in this study.

2. Experiments

Inconel 625 samples were cut and then polished from a hot rolled slab after 1080°C solution treatment, which was provided by Shanghai Baosteel group corporation. The dimension of the samples is 20 mm × 15 mm × 5 mm, and the chemical composition is 60.69Ni, 21.26Cr, 5.61Fe, 0.02Mn, 0.02Si, 0.03C, 3.69Nb, 0.19Al, 0.3Ti, 8.36Mo, 0.002S and 0.01Co (all in mass%).

Figure 1 shows the samples were pre-stressed 150 MPa, 250 MPa and 300 MPa by three-point bending method firstly before shot peening, which was determined by X-Ray diffraction residual stress analysis. Shot peening processes were carried out on the surface by a shot-peening machine (Shanghai Carthing Machinery). The samples were shot peened by Al2O3 ceramic balls (700 HV, 0.3 mm round) with the intensity of 0.15 mmA, 100% coverage. Intensity was measured by Type A Almen specimen before shot peening process.

To study the residual stress gradient, microstructure and micro hardness in the deformed layer, each 25 µm thin layer was electrolytically polished step by step from the top surface to a depth of 100 µm, subsequently a 50 µm layer was removed from 100 µm to 250 µm at ambient temperature. Residual stresses were measured in the deformation layers by a Proto laboratory X-Ray diffraction residual stress instrument (LXRD) employing ϕ-sin²ψ technique.9) The measurement parameters were chosen as follows: (311) hkl plane, Wavelength, Mn Kalpha for Mn anode, λ = 2.10314 Å. The speed of scanning is 2°/min, and the

*Corresponding author, E-mail: jiangchuanhaisjtu@gmail.com
step is 0.01°. The measured line profile \( h(x) \) can be expressed as:

\[
h(x) = \int_{-\infty}^{+\infty} g(y)f(x - y)dy
\] (1)

The integral breadth \( \beta \) is shown as following, Voigt method:

\[
\beta^h_C = \beta^i_C + \beta^i_G, \quad \beta^i_C = \beta^i_G = \beta^i_f
\] (2)

In this equation above, \( G \) and \( C \) means Gaussian and Cauchy integral breadth. The measured line profile, the structural profile and the instrumental profile were presented by \( h, f \) and \( g \), respectively. Accordingly, domain size and micro strain can be calculated by Cauchy and Gaussian integral breadth from \( f \) profile, Where \( \theta \) is the diffraction angle, and \( \lambda \) is the X-ray wavelength. The equation is:

\[
D = \lambda / \beta^i_C \cos(\theta), \quad \varepsilon = \beta^i_C / 4 \tan(\theta)
\] (3)

The distribution of micro hardness in the deformed layer was investigated through DHV-1000, a Digital Microhardness Tester (2.9 N, 15 s). Each data came from the average of five measurements, which were performed at different locations on the surface after layers removal.

3. Results and Discussion

The speed balls impact on the surface of samples caused a drastic increase of plastic deformation in the near-surface layer during shot peening process. The non-uniform plastic deformation resulted in the high compressive residual stress gradient.\(^{11,12} \) During pre-stressed shot peening, the components were pre-loaded with tensile stresses then released after shot peening process, which improved both surface compressive residual stress and maximum compressive residual stress with the same intensity of traditional shot peening.

Figure 2 revealed similar compressive residual stress distributions in the deformation layers of pre-stressed shot peening Inconel 625. With the increase of applied loads, compressive residual stress and the influence depths have been increased correspondingly. Surface compressive residual stress and maximum compressive residual stress of variously pre-stressed shot peening were shown in Table 1. Compare to traditional shot peening (pre-loaded stress 0 MPa), surface compressive residual stress in longitudinal direction were increased to \(-972\) MPa, \(-1031\) MPa and \(-1080\) MPa after pre-loaded 150 MPa, 250 MPa and 300 MPa, respectively. In the meanwhile, maximum compressive residual stresses were reached \(-1018\) MPa, \(-1074\) MPa and \(-1151\) MPa.

Before pre-stressed shot peening, the sample was pre-loaded by three-point bending method. When the applied tensile strain released after pre-stressed shot peening, only part of the elastic strain was recovered due to the constrain of the plastic deformation, so a higher level of compressive residual stress can be obtained in the pre-loaded direction.

The release of the additional load after the pre-stress shot is constrained by the plastic deformation of the surface, and only part of the elastic strain is restored, so a higher level of residual pressure stress can be obtained in the pre-bending direction.

Voigt linear analysis method was used to calculate the microstructure in the deformation layers which includes domain size and micro strain. Figure 3 and Fig. 4 showed that domain size and micro strain were significantly

<table>
<thead>
<tr>
<th>Pre-loadings</th>
<th>0 MPa</th>
<th>150 MPa</th>
<th>250 MPa</th>
<th>300 MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface compressive residual stress (MPa)</td>
<td>-972</td>
<td>-1031</td>
<td>-1080</td>
<td>-1018</td>
</tr>
<tr>
<td>Maximum compressive residual stress (MPa)</td>
<td>-976</td>
<td>-1018</td>
<td>-1074</td>
<td>-1151</td>
</tr>
</tbody>
</table>

Fig. 2 Compressive residual stress distribution of pre-stressed shot peening Inconel 625 in the deformation layers.

Fig. 3 Domain size distribution of various pre-stressed shot peening Inconel 625.
generated after various pre-stressed shot peening. The higher pre-stress applied, the smaller domains refined and higher micro strain generated in the deformation layers from the top surface layer to the subsurface layers.

Domain size of applied load 350 MPa was less than 20 nm, which was slowest changed in the depth. Micro strain has been reduced from the surface layer. Meanwhile, the influence depth of both domain size and micro strain after pre-stressed shot peening was about 200 µm. The applied pre-loading was the main factor affecting the domain size and the micro strain.

During traditional shot peening, compressive residual stress and microstructure can be improved by increasing the intensity. However, the material would also be damaged when shot peening intensity is too strong. Pre-stressed shot peening can further improve both compressive residual stress and microstructure with the same intensity than traditional shot peening.

Micro hardness distribution in the depth after variously pre-stressed shot peening was shown in Fig. 5. The results indicated a significant improvement of micro hardness in the deformed layers. The maximum micro hardness appeared in the surface layer then decreased along the depth. With applied loads 150 MPa, 250 MPa and 350 MPa, surface micro hardness reached to 541 HV, 571 HV and 588 HV, respectively. Micro hardness decreased gradually with depth, and the trend of relaxation was similar to micro strain. Main reason could be related to higher dislocation density that was introduced on the surface layer during shot peening process.

Residual stress and microstructure improved the mechanical properties in the deformed layers of Inconel 625. High compressive residual stresses improved the fatigue property because it delays or stops the initiation and propagation of micro-cracks. On the other hand, finer domain size and high micro strain slowed down the dislocation gliding to lead to an improvement on yield strength.

Micro hardness is a comprehensive reflection of the microstructure and residual stress, which is widely used to evaluate the mechanical properties of material. Tabor studied the yield strength of work hardening material and found that it can be embodied by the change value of microhardness. The relationship between the micro hardness and yield strength can be expressed by the following empirical equation:

$$\sigma_y = \sigma_y,0 \left(1 + \gamma \frac{\Delta HV}{HV_y,0}\right)$$

Where $\sigma_y$ and $\sigma_y,0$ the yield strength before and after pre-stressed shot peening. $\Delta HV$ and $HV_y,0$ is microhardness before and after pre-stressed shot peening. The material constant $\gamma$ is 2.8 for Inconel 625. Yield strength distribution of variously pre-stressed shot peening Inconel 625 was calculated. The surface yield strength was improved about 5 times with applied load 300 MPa. The reason was related to both residual stress and microstructure, which has been discussed above.

4. Conclusion

Surface layers characteristics of pre-stressed shot peening Inconel 625 including was investigated. It is revealed that surface compressive residual stress were increased to $-972$ MPa, $-1031$ MPa and $-1080$ MPa after pre-loaded 150 MPa, 250 MPa and 300 MPa, respectively. In the meanwhile, maximum compressive residual stresses were improved to $-1018$ MPa, $-1074$ MPa and $-1151$ MPa. When the applied tensile strain released after pre-stressed shot peening, only part of the elastic strain was recovered due to the constrain of the plastic deformation, so a higher level of compressive residual stress can be obtained in the pre-loaded direction.

Microstructure evaluation showed the higher applied pre-stress resulted in the more obvious effect of domain size refinement and micro strain generation in the deformation layers. The applied pre-stress was the main factor affecting the domain size and the micro strain.

Results indicate pre-stressed shot peening can further improve both compressive residual stress and microstructure with the same intensity of traditional shot peening. The refined coherent domains and high micro strain strengthened microstructure in the deformed layers, which caused the
further increment of micro hardness and yield strength of material.

Acknowledgments

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