Effect Analysis of Laser Shock Peening on Nickel-based Alloys by Laser Solid Forming

Wanli Ma, Changzhi Jia*
Army Engineering University, Shijiazhuang, China

*Corresponding author: mwlshr@163.com

Abstract. Laser solid forming has the advantages of rapid and complex shapes, but the stress caused by high temperature gradient changes during the forming process can easily lead to the deformation of parts and insufficient mechanical properties. This article focuses on laser solid forming GH4169 superalloy for laser shock peening. The influence of process parameters on surface morphology and toughness were analyzed. The mechanism of laser shock peening was analyzed. The results show: As the number of impacts increases, the depth gradually increases, and the increasing trend slows down. When the energy is small, the surface change cannot be observed. After 5J, as the energy increases, the depth of the pit increases. As the impact energy increases, the toughness of the material first increases and then decreases. The toughness of the material is the highest at 6J, reaching 65J/cm². The action mechanism of laser shock peening has three main methods, one is fine-grain strengthening, the other is twinning and work hardening, and the third is stress strengthening.

Keywords: Laser shock peening, nickel-based alloy, strengthening mechanism.

1. Introduction
GH4169 alloy is a kind of nickel-based alloy that is widely used, and is called superalloy. This alloy has good fatigue resistance, oxidation resistance and corrosion resistance. It has been widely used in weapons, aerospace and other fields. With the development of science and technology, GH4169 made by laser solid forming technology has received widespread attention. The laser solid forming process is a process of rapid melting and rapid solidification, and its processing involves complex energy conversion and energy transfer. It is difficult to control the crystal grain size, and it is easy to appear bubbles, holes, residual stress and other problems. Therefore, the preliminary exploration of the performance of strengthening laser solid forming GH4169 alloy is carried out.

Laser shock peening technology is an advanced metal surface modification technology that provides a new method for strengthening nickel-based alloys. The laser shock peening technology uses a short pulse high peak power density laser. When it acts on the metal surface, it vaporizes and ionizes in a short time to form plasma, and the plasma moves to form a high-pressure shock wave to modify the material.
2. Experimental materials and methods

2.1. Laser shock peening equipment.
Laser shock peening equipment mainly includes three parts, as shown in Figure 1. One is a laser, which can generate high-energy pulsed lasers, the other is a control system, which mainly controls the movement of the working platform, and the third is a high-power power supply.

The laser emits high-energy laser and irradiates the working area. The surface of the test piece is covered with two layers of materials. The lower layer is the absorption layer to absorb the laser energy and react. The upper layer is the constraining layer to enhance the role of the absorption layer and the sample.

The confinement layer is mainly used to limit the effect of high-energy plasma. When the laser energy causes the plasma to move with high energy, the confinement layer can control the loss of energy to the air, so that most of the energy acts on the surface of the sample. This has two main requirements for the confinement layer. One is that the loss of laser transmission should be as small as possible, and the other is that it has a better limiting effect on the energy-recoverable layer. At present, the constrained layers mainly include water and glass. Both materials have good constraining properties. Considering the uneven shapes of the parts, it is too much to process suitable glass confinement for each part, so water is selected as the constraining layer.

![Fig. 1 Laser Shock Strengthening System](image)

The absorption layer mainly generates plasma, and the plasma absorbs energy to generate shock waves. The energy of the shock waves is used to modify the surface of the material. This requires the absorption layer to absorb as much laser energy as possible from the confinement layer. Vinyl has a good effect of absorbing energy. In this experiment, this material was selected as the absorption layer.

2.2. Method of selecting process parameters.
Under the condition of one-dimensional strain shock compression, the Hugoniot elastic limit of alloy is formula (1). \( G \) is the shear modulus, \( K \) is the bulk modulus, and \( \sigma_{0.2} \) is the yield strength.

\[
\sigma_{HEL} = \left( \frac{K}{2G} + 2/3 \right) \sigma_{0.2} \tag{1}
\]

The laser-induced shock wave peak pressure model is formula (2). \( P \) is the peak pressure of the shock wave, \( \alpha \) is the energy conversion factor of the plasma shock wave, generally taken as 0.2, \( Z \) is the impedance of the target material and the constraining material, and \( I_0 \) is the power density.

\[
P = 0.01 \sqrt{\frac{\alpha}{2\alpha+3}} \sqrt{Z} \sqrt{I_0} \tag{2}
\]
The conversion formula of laser power density and pulsed laser energy is as formula 3. $E$ is the pulse laser energy, $D$ is the spot diameter, $\tau$ is the pulse width.

$$I_0 = \frac{4E}{\pi D^2 \tau} \quad (3)$$

3. Experimental results and discussion

3.1. Surface analysis of laser shock GH4169.

After laser shock peening the surface of the material, the surface will deform. Under different process parameters, the degree of surface deformation is different. The main process parameters of laser shock peening are pulse energy and strengthening times. Through a single variable method, the effect of different process parameters on the surface is studied. The influence law of provides a basis for resilience optimization.

The experiment is divided into two groups, one is to study the effect of different impact times on the surface of the material, and the other is to study the effect of different energy on the surface of the material. The surface condition was measured with the white light interferometer of Tsinghua University, and the depth was used as the evaluation index.

![Fig. 2 Impact number on surface](image1.png)

![Fig. 3 Energy impact on the surface](image2.png)

Figure 2 shows that as the number of impacts increases, the depth gradually increases, and the increasing trend slows down. This trend is mainly because the deformation of the surface has reached a large degree. If you continue to increase the number of times, the depth will not change too much. Figure 3 shows that when the energy is small, the surface change cannot be observed, and the depth is 0. After 5J, as the energy increases, the depth of the pit increases.

3.2. The effect of laser shock peening on the impact toughness of GH4169 alloy.

Figure 5 shows the effect of different energy on the impact toughness. It is observed that as the impact energy increases, the toughness of the material also increases. At 6J, the toughness of the material is the highest, reaching 65J/cm². After that, the energy continued to increase, but the material toughness began to decrease, indicating that as the impact energy increased, the defects increased correspondingly, which affected the further improvement of the material toughness.
The improvement of material impact toughness comes from the influence of laser shock peening on the microstructure of the material. According to the previous test results, it can be found that the rapid impact of high-energy plasma has an impact on the macroscopic morphology of the sample surface, forming a plastic deformation layer, a large number of dislocations and deformation twins appear in the deformation layer, and then a residual compressive stress layer is formed. And further reflected in the changes in the microstructure. The change rule of the results of the toughness test is consistent with the analysis results mentioned above.

3.3. Strengthening mechanism.

Under the action of laser shock peening, GH4169 alloy forms a certain thickness of plastic deformation layer on the surface of the material, the structure is optimized, and the mechanical properties are improved.

The first strengthening effect is fine grain strengthening. According to the results of microstructure analysis, laser shock caused strong plastic deformation, and at the same time, the structure was refined, grain size decreased, grain boundaries increased, dislocation slip was hindered, plastic deformation was difficult, and the alloy surface was strengthened. After the strengthening process, the dislocation density of the material increases, the substructure size decreases, and some materials even undergo phase change. Refined crystal grains and increased dislocations create obstacles to the movement of the crystal, limiting its slip to the interface between the strengthening layer and the base layer.

The second strengthening effect is twins and work hardening. Under the impact of high-energy plasma, a large number of deformation twins appear on the surface of the sample. As the impact weakens with depth, the density of twins also decreases. Although the densely arranged twins are similar to the matrix structure, their orientation and orientation are obviously different. Therefore, under the action of external load, only the plane slip process of dislocations in the slip system shared by the matrix and twins can proceed smoothly, and the plane slip of other dislocations will be hindered. In fact, there are very few slip systems shared by the two, so the plane slip of dislocations will be hindered by twins, and crack sources are difficult to appear.

The third strengthening effect is stress strengthening. After the laser shock peening process, a strong compressive residual stress field appears on the surface of the sample. The existence of the compressive residual stress field on the surface can well hinder or delay the initiation and propagation of fatigue cracks on the surface of the material, and reduce the material's external alteration. The tensile stress when the load acts, then the alloy surface is strengthened.

4. Conclusion

As the number of impacts increases, the depth gradually increases, and the increasing trend slows down. This trend is mainly because the deformation of the surface has reached a large degree. If you continue to increase the number of times, the depth will not change too much. When the energy is
small, the surface change cannot be observed. After 5J, as the energy increases, the depth of the pit increases.

As the impact energy increases, the toughness of the material also increases, and the toughness of the material is the highest at 6J. After that, the energy continued to increase, but the material toughness began to decrease, indicating that as the impact energy increased, the defects increased correspondingly, which affected the further improvement of the material toughness.

There are three main ways to strengthen the surface of GH4169 alloy by laser shock. One is fine grain strengthening, the other is twinning and work hardening, and the third is stress strengthening.

References
[1] Xinlei Pan, Xuede Wang, Zeng Tian, et al. Effect of dynamic recrystallization on texture orientation and grain refinement of Ti6Al4V titanium alloy subjected to laser shock peening[J]. Journal of Alloys and Compounds, 2020.
[2] Yang Tang, MaoZhong Ge, Yongkang Zhang, et al. Improvement of Fatigue Life of GH3039 Superalloy by Laser Shock Peening.[J]. Materials, 2020.
[3] Wang Yong, Wang Xibin, Liu Zhibing, et al. Effects of laser shock peening in different processes on fatigue life of 32CrNi steel[J]. Materials Science & Engineering A, 2020.
[4] Hao Wang, Yordan Kalchev, Hongcai Wang, et al. Surface modification of NiTi alloy by ultrashort pulsed laser shock peening[J]. Surface & Coatings Technology, 2020.
[5] Chen Si, Mu Juan, Wang Yandong, et al. Formation of omega phase induced by laser shock peening in Ti-17 alloy[J]. Materials Characterization, 2020.