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# Study on the effect of laser peening with different power densities on fatigue life of fastener hole

Y.F. Jiang [a,*], B. Ji [a,*], X.D. Gan [b], Ch. Hua [c], X. Li [a], H. Zhu [a]

[a] School of Mechanical Engineering, Jiangsu University, Zhenjiang 212013, PR China
[b] Chengdu Aircraft Design and Research Institute of AVIC, Chengdu 610091, PR China
[c] AVIC Chengdu Aircraft Industry (Group) Co., Ltd., Chengdu 637199, PR China

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ABSTRACT

Laser shock processing can improve the fatigue life of fastener holes. The purpose of this study is to investigate the effect of laser power density on fatigue life and fracture characteristics of 7050-T7451 aluminum alloy fastener hole specimens with 6 mm thickness. ABAQUS software is used to analyze the three-dimensional stress distribution. The fatigue test was carried out and the treated specimens were evaluated by scanning electron microscope. The results show that with the increase of laser power density, the fatigue life gain of fastener hole specimens increases firstly, then decreases, and then increases again. The fatigue life gain of the fastener hole specimen is related to the initiation position of the fatigue crack and the direction of the crack propagation. It is speculated that this is closely related to the three-dimensional stress distribution of the fastener holes after laser shock processing in different laser power density.

## 1. Introduction

The fastener hole is a typical stress-concentrated structure. In the cyclic alternating load, especially the corner of the fastener hole is easy to form a fatigue crack initiation, resulting in the final failure of the part [1]. In the trend of light weight of the aircraft, because the high-strength aluminum alloy has high strength to weight ratio, it is widely used in the aviation industry [2], many parts of the aircraft are aluminum alloy material. However, the anti-fatigue properties of the 7 series high strength aluminum alloy are lower under the cyclic loading of the high cycle. When the requirement of the cycle is not less than $5 \times 10^6$, the stress level of the 7 series aluminum alloy is only 140 MPa [3]. For aluminum alloy fastener hole parts, at this stage are often used mechanical shot peening and cold extrusion to strengthen them [4], but for the smaller holes with diameter smaller than 3 mm, mechanical shot peening and cold extrusion technology are difficult to strengthen them. Laser shock processing (LSP) is a kind of promising surface treatment technology that uses the high pressure shock wave induced by nanosecond pulse laser to load the material surface, resulting in small plastic deformation and the insertion of residual compressive stress [5].

LSP has the advantage of strengthening the small hole, blind hole and special hole, and the domestic and foreign scholars have done a lot of research on the laser shock processing of the hole structure [6]. Zhang et al. [7] discussed the residual stress fields induced by laser spots in different center distances with finite element methods and experiments. It was found that the spot overlap rate affected the residual stress field distribution on the surface of the workpiece. Salimianrizi et al. [8] studied the effects of laser shock on the surface residual Stress distribution. They evaluated the treated specimens by means of surface integrity with optical microscopy, scanning electron microscope, microhardness, surface roughness and induced residual stress using an X-ray diffraction method, and found that the laser shock can introduce very high residual compressive stress on the surface of the material. Correa et al. [9] studied the effect of the advancing direction of the laser scanning pattern on the induced residual stress fields and the fatigue life of stainless steel 316L samples using experiments and 3D finite element analysis, revealed the decisive role played by the advancing direction of the treatment and the generated residual stresses. Hemmesi et al. [10] applied the finite element approach to calculate the welding residual stresses in a tube out of S355J2H steel. X-ray and neutron diffraction measurements (XRD and ND) are carried out to determine the distribution of residual stresses in three orthogonal directions, on the surface and in the bulk of the material respectively. The numerical results are compared directly with the measured data. They observed that the

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* Corresponding authors.
*E-mail addresses:* 13914567669@163.com (Y.F. Jiang), jerryjibin@126.com (B. Ji).

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overall agreement is good except for some discrepancies in the surface and subsurface stress results over the weld area. However, many researches focus on the study of the residual stress distribution and the gain of fatigue life [11], and there are few reports about the relationship between the laser shock parameters, the fatigue life and the fatigue fracture characteristics. The study of fatigue life and fracture characteristics under different laser parameters can help to find the relationship between laser parameters and fatigue life and fracture characteristics, which makes us choose reasonable laser parameters and improve the strengthening effect in practical engineering application. This provides a new idea and method for improving the life and anti-fatigue properties of aluminum alloy fastener hole parts, which is of great engineering significance.

## 2. Experimental procedures

### 2.1. Sample material and analysis model

The chemical composition of 7050-T7451 aluminum alloy is listed in Table 1, and the related mechanical properties are shown in Table 2. The thickness of the specimen is 6 mm and the remaining dimensions are shown in Fig. 1 Since the strain rate of the material is up to $10^6\ \mathrm{s}^{-1}$ during laser shock processing, the yield strength of the material will change, and the Johnson-Cook model can better describe the effect of large strain and high strain rate on the yield strength of the material. The model is used as the constitutive model of dynamic display analysis, the simplified expression is:

$$\sigma_y = (A + B\varepsilon^n)\left(1 + Cln\,\dot{\varepsilon}\right) \tag{2.1}$$

where $\sigma_y$ is the yield stress, $A$ is the yield strength, $B$ is the hardening modulus, $\varepsilon$ is the plastic strain, $\dot{\varepsilon}$ is the strain rate, $n$is the hardening exponent, and $C$ is the strain rate sensitivity coefficient. The material parameters of the Johnson-Cook model are shown in Table 3.

The finite element analysis of ABAQUS is used to study the residual stress distribution of fastener hole after LSP, which is divided into two steps: dynamic explicit and static implicit. Fig. 2 shows the geometric model of the LSP analysis. The dimension of the model is 28 mm × 14 mm × 6 mm (length × width × thickness), the grid type is the explicit linear reduction integral unit C3D8R, and The mesh size in the treated area is 0.1 mm × 0.1 mm × 0.025 mm. The type of the constraint surface showed in Fig. 2 is full constraints. The surface A and the surface B are LSP surfaces, and the treatment area is shown in Fig. 2. In order to compare the residual stress distribution of the holes shocked by different laser power densities, three-dimensional stress measurement area and two stress data extraction paths are depicted in Fig. 2.

In the process of shock wave loading, the laser induced peak pressure $P$(GPa) can be estimated by the formula:

$$P = k\sqrt{I_0} \tag{2.2}$$

Where $I_0$is the laser power density, $K$is the correction factor, which is related to the absorbing layer material, the confining material, the test temperature and other factors, generally takes 1.0–2.0. Through experiment and simulation compared with the Almen test piece, $K$takes1.38 more appropriate.

### 2.2. Laser shock experiment

LSP was performed using a Q-switched laser system with a pulse duration of 20 ns, a laser beam wavelength of 1064 nm, the spot diameter was 2.6 mm, the overlap rate of the adjacent spots was 50%. Used aluminum foil as absorbing layer material and water as constraint layer. The laser pulse energies were 3 J, 4 J, 5 J, 6 J, 11.3 J. The relationship between laser pulse energy and power density is as follows:

$$I_0 = \frac{4E}{\pi d^2 t_p} \tag{2.3}$$

where $I_0$ is the laser power density, $E$is the laser pulse energy, $d$is the diameter of the laser spot, $t_p$ is the pulse duration. So the laser power density was 2.83 GW/cm$^2$, 3.77 GW/cm$^2$, 4.71 GW/cm$^2$, 5.65 GW/cm$^2$ and 10.62 GW/cm$^2$ respectively, and the specimens were treated in a double-sided LSP way. Double-sided LSP meant LSP was performed on surface A and surface B of the specimen, and each side of the specimen was treated twice. The treatment area and LSP path are shown in Fig. 3.

### 2.3. Fatigue test

The hole was drilled on the central of treatment area after LSP, and the drilling process is to drill the hole to $\phi$2.2 mm at first, then reaming to $\phi$2.5 mm, finally reaming to $\phi$2.6 mm. After the drilling, the fatigue test was carried out at room temperature according to the fatigue test of the metal material by the axial loading fatigue test method. The type of high-frequency fatigue testing machine is INSTRON8801. The fatigue test method was to clamp the specimen at both ends firstly, and when the fracture occurred at one hole, the fatigue test was carried out at both ends of the remaining specimen without fracture. The maximum stress during the test is 195 MPa, the stress ratio R = 0.1, and the frequency is 20 Hz.

## 3. Results and discussion

### 3.1. Residual stress distribution

Fig. 4 shows the three-dimensional stress distribution for different power densities (peak pressures). Fig. 5 is the residual stress distribution along the Path1 and Path2 direction after LSP. It can be seen from the figure that with the increase of the laser power density, the residual compressive stress increases gradually in the LSP treatment area (9mm × 9 mm in Fig. 3a). When the peak pressure reaches 3.5 GPa, residual compressive stress tends to be stable. The residual tensile stress increases gradually outside the LSP treatment area, and the residual tensile stress reaches a very high value showed in Figs. 4e and 5a. With the increase of laser power density (peak pressure), the stress distribution of the hole wall is shown in Figs. 4 and 5b. It can be seen from the figure that with the increase of the peak pressure, the residual compressive stress of the corner of the hole increases gradually, but when the peak pressure reaches 2.6 GPa, the residual compressive stress is basically stable. The peak value of the stress in the middle of the hole wall increases first and then decreases. When the peak pressure is 3 GPa, the stress reaches the maximum, which is 160.48 MPa. When the peak pressure is 4.5 GPa, the hole wall is all residual compressive stress, and the minimum value is 94.76 MPa. In

**Table 1**
Chemical composition of 7050-T7451 titanium alloy (wt.%).

| Composition | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Others | Al |
|---|---|---|---|---|---|---|---|---|---|---|
| Content | 0.12 | 0.15 | 2.0–2.6 | 0.10 | 1.9–2.6 | 0.04 | 5.7–6.7 | 0.06 | 0.15 | Remainder |