Laser peening of aluminum alloy 7050 with fastener holes

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The fatigue properties of laser peened aluminum alloy 7050 specimens with fastener holes were investigated. The surface profile and residual stress induced in the shock affected zone were characterized. Then, the fatigue specimens with notch were treated by laser peening (LP), and the fatigue lifes of LP-treated specimens were measured and compared with base materials without LP. The results indicated that LP improved the fatigue lifes of all tested specimens. The average fatigue lifes of specimens treated by LP before hole-drilling were 173% longer than those of untreated samples and had better effects than those specimens treated by LP after hole-drilling.

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As light alloy, the aluminum alloy 7050 is often used in airplane as skin and airframe, which is jointed by rivet or bolt with the whole body. In order to improve the fatigue properties of fastener joints in the airplane, cold-worked holes are often produced by rod extrusion before fitting. However, in rod extrusion, the rod is easy to break when the diameter of the hole and the matched rod are too small. There are parts of holes used in plane for joining skins and airframes are not more than ϕ2.5 mm. How to strengthen these small holes is a technical challenge to the engineers in the assembly line. 30 years ago, as a novel surface strengthen technology, laser peening (LP) was developed using high energy pulsed lasers. LP induces deep compressive residual stresses in the material by forming an expanding plasma shock wave at the surface of laser impact. LP also induces strain hardening in metal, which is often shown as dislocation and twin in microstructure analysis. Compared with conventional shot peening, LP produces higher magnitude and deeper compressive residual stresses and even smoother surface. At moderate power density, LP improves the fatigue life of aluminum components[1,2]. However, when laser power density is higher than 4 – 5 GW/cm^2, internal cracking could also take place within the material, which is harmful to fatigue life[3].

With the shocked zone controlled by laser spot, LP has better and flexible process control capacities. Although developed 30 years ago, LP has been used in industry for commercial applications only from the last decade. US companies such as G. E. Aviation, LSP Technologies, and Metal Improvement Company are currently using LP to strengthen turbine engine components and auto gears. Toshiba in Japan also uses LP to enhance fatigue life and corrosion properties of metal components used in nuclear power plants. In China, a lot of research works have been undertaken for years, but there are few real industrial applications at present[4−7].

Aluminum 7050 with heat-treated state of T7451 was investigated in this paper. Aluminum 7050 is mainly composed of 2.0% – 2.6% Cu, 1.9% – 2.6% Mg, 5.6% – 6.7% Zn and rest of Al as base. The specimens were cut from forged aluminum 7050 with thickness more than 100 mm. Since the material is rather thick, the mechanical property of base material varies slightly with its depth. For example, the specimens cut from the surface layer usually have slightly higher tensile strength and fatigue strength. In order to reduce possible errors resulting from the variation of materials properties, fatigue specimens were made with symmetrical, dual stress-concentration notches (holes), as shown in Fig. 1. Each specimen was made with two symmetrical narrow-necks. A notch with 2.5-mm diameter was also drilled at the center of each neck.

Two groups of specimens were tested in the experiment (see Tables 1 and 2). One group was laser-peened before the holes (notches) were drilled and the other group was processed using a reverse sequence. Fatigue tests were performed at both ends of the specimens. The end treated by LP was identified as "A" and the end without laser-peening was identified as "B".

LP experiments were performed with a Q-switched Nd:glass laser system delivering about 50 J per pulse. The full-width at half-maximum (FWHM) laser pulse is 30 ns with a beam diameter of 20 mm. During peening experiments, the laser beam was focused to about 6-mm diameter with pulse energy of about 36 – 40 J. Laser power density on target was typically about 4 GW/cm^2. The sacrificial material used to cover the target surface during peening was aluminum tape with thickness about 200 μm, and the confining material was flowing water with thickness about 2 mm, which was to retard plasma expansion and enhance the impact pressure onto target surface.

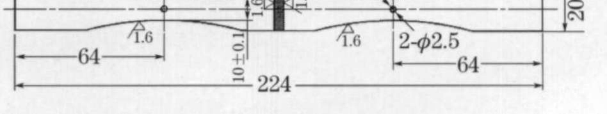

Fig. 1. Fatigue specimen with two notches (holes) used for laser shock peening (in mm).

Table 1. Comparison of Fatigue Life of Specimens (LP after Hole-Drilling Versus Base Material)

Specimen No.	Hole State	Number of Blocks	Increment of Blocks
601	A	26.743	78%
	B	14.999	
602	A	22.657	47%
	B	15.404	
604	A	17.999	11%
	B	16.285	
605	A	17.080	54%
	B	11.117	
606	A	16.375	60%
	B	10.218	
607	A	19.186	92%
	B	9.999	

Table 2. Comparison of Fatigue Life of Specimens (LP before Hole-Drilling Versus Base Material)

Specimen No.	Hole State	Number of Blocks	Increment of Blocks
611	A	52.454	204%
	B	17.275	
612	A	73.101	154%
	B	28.739	
613	A	36.873	177%
	B	13.315	
614	A	30.632	157%
	B	11.912	
615	A	40.803	231%
	B	12.317	
617	A	43.472	262%
	B	11.999	

Fatigue tests were taken under a special flight spectrum load-condition required for mid-airframe with each flight spectrum representing 150 flight hours. The maximum load in spectrum was 8.1 kN, which was equal to 270-MPa tensile stress in the minimal section crossed the center of the holes. During the fatigue life test, if the hole (notch) in one end broke down, data were recorded (in unit of spectrum blocks) as the fatigue life of this hole. The fatigue life test continued on the remaining specimen until the other end also broke down, and data were then recorded (total spectrum blocks) as the fatigue life of the later hole.

LP produces high intense (more than GPa) shock waves on the surface of the metal and alloy. When the shocked waves penetrate into the metal, elastic and plastic strain is produced at the shock affected zone, which attenuates and consumes the energy carried by the shock waves. The shock waves generated by laser are found to strengthen metal and alloy around the laser spot area when the intensities of shock waves are greater than the dynamic yield strength of target material. The size of the shock affected zone is nearly identical to the size of laser spot at impact. The surface profile and residual stress around the laser spot is shown as Fig. 2. The surface layer was examined by transmission electron microscopy (TEM) after LP. The results show that high densities of twins and dislocations are induced in the shocked zone of 7050, and the dislocations appeared to tangle each other. The twins and dislocations induced by plastic deformation lead to the improvement of both surface hardness and surface residual stress. Average value of surface residual stress along the central line of the shocked zone is about −150 MPa compared with only tens of MPa in the base material. Compressive residual stress is known to enhance the fatigue lifetime of material.

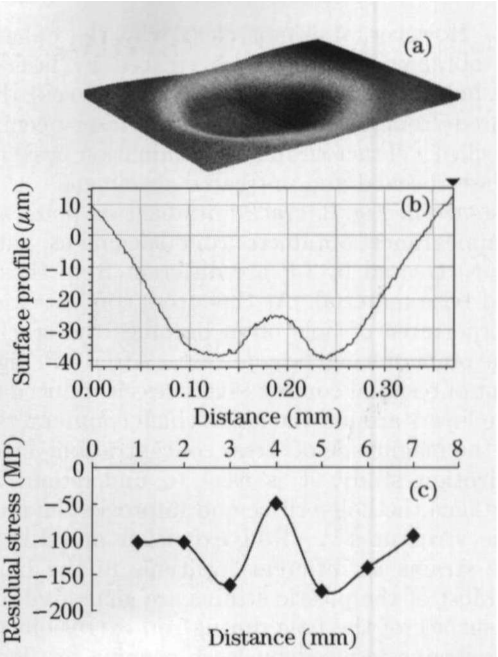

Fig. 2. (a) Effect image, (b) surface profile, and (c) residual stress in shock affected zone.

Fatigue experiments were carried out under the special flight spectrum loading condition for mid-airframe and the maximum load in spectrum was 8.1 kN. All of the untreated holes (notches) broke down before the other holes under LP. The results obtained from both sequences are displayed in Tables 1 and 2.

The experiments show that fatigue life of the end with hole treated by LP after hole-drilling was longer than that of the other end without LP. The average life is enhanced about 57%.

The results show that fatigue life of the end with hole treated by LP before hole-drilling is much longer than that of the other end without LP. The average lifetime is enhanced much greater, up to 198%, similar to the predicted increase of specimens with cold-worked holes produced by rod extrusion. As it was rather difficult to apply extrusion strengthening holes with diameter smaller than 2.5 mm, laser peening aluminum structure with small holes is a good choice to improve the fatigue properties.

LP appears to be an effective surface treatment technique to enhance the fatigue life of 7050T7451 fastener joints. However, it is not clear why the enhancement factor obtained from samples treated by laser-peening before hole-drilling is higher (nearly 4 times) than that measured from samples treated by laser-peening after hole-drilled. Fractographic examination was made to both laser-peened and untreated specimens.

As shown in Fig. 3, crack initialization point and fracture appearance obtained from specimens with holes (notches) treated by LP are different from those of untreated base material. At the stress concentration zone, the corner area of hole often becomes the crack initialization point during fatigue test. After LP, significant amount of residual compressive stress is induced onto the surface layers around the hole, which counteracts and reduces the magnitude of stress concentration. From crack initialization study, it is easy to understand how LP strengthens the hole-orifice and improves the fatigue life of hole structures[8]. Rod extrusion and LP produce plastic strains at different locations in the hole structure. Most of the plastic strains are generated along the inner surface of the hole during rod extrusion, however, plastic strains induced by laser peening are located on the top- and sub-surface of metal surrounding the hole. Although, it is able to induce residual compressive stress at depth more than 1 mm on 4-mm-thick specimens for laser peening, similar fatigue lifetime and enhancement factor are observed from specimens treated by rod extrusion. It is well known that rod extrusion produces both residual compressed stress and smooth surface along the inner side of hole. It is evident that the effects of laser peening on hole structures are very important to fatigue properties.

The fatigue life test results clearly indicate that the specimens treated by LP before drilling have longer fatigue lifetimes than those treated by LP after drilling. Figure 4 shows possible impacts of LP and drilling on the surfaces of hole-structure. Although drilling might partially release the surface residual compressive stress around the hole, the result seems to indicate that the disbenefit of drilling after laser peening is less than that of laser peening directly on the hole (just drilled) structures. When aluminum structures with small holes are treated by a high intensity laser pulse, two factors are likely to shorten the fatigue lifes of holes: (1) the absorbing layer is likely to be destroyed by the high pressure plasma, which reduces the intensity of shock waves on the target surface and heats up the inner surface of holes; (2) the plastic strains around the hole area might produce sharp-angled orifice around the lip of the hole (see Fig. 5), which could become crack initialization point during fatigue test.

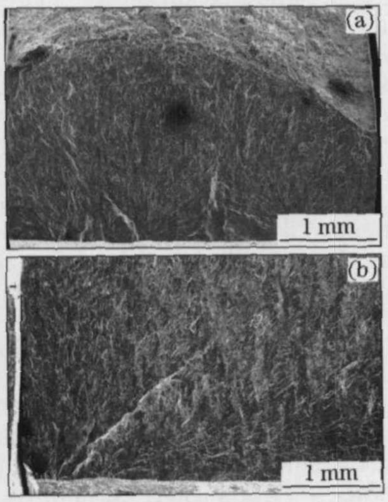

Fig. 3. Crack initialization of two holes with (a) and without (b) LP from specimen 606.

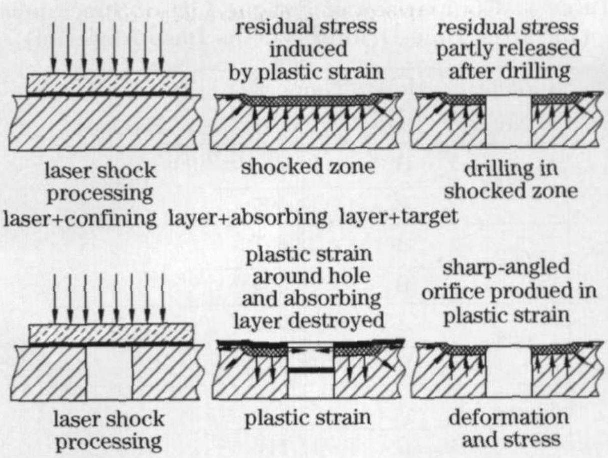

Fig. 4. Plastic strain and residual stress around the shocked zone before and after LP.

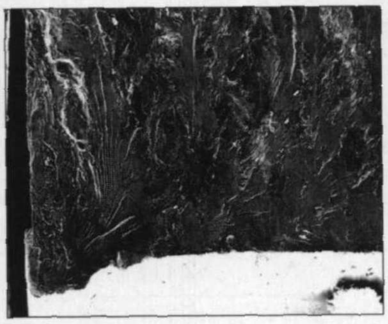

Fig. 5. Sharp-angled orifice is easy to produce fatigue crack initialization.

In conclusion, (1) LP is a potential surface enhancement technique for treating 7050T7451 components. High density of dislocations and twins, and deep residual compressive stress could be induced at the shocked zone, which are known to improve the fatigue properties of components. (2) Specimens treated by LP before drilling have better fatigue properties than those treated by LP after drilling. It is very important to avoid deformation and direct heat exposure and damage to the holes structure during LP.

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