EFFECT OF LASER PEENING ON FATIGUE PRPOERTIES FOR AIRCRAFT STRUCTURE PARTS

T. Adachi 1, H. Takehisa 1, M. Nakajima 1, Y. Sano 2

1 Fuji Heavy Industries Ltd., 1-1-11 Yonan, Utsunomiya, 320-8564, Japan
2 Toshiba Corporation, 8 Shinsugita-cho, Isogo-ku, Yokohama, 235-8523, Japan

ABSTRACT
Laser peening is expected to improve fatigue properties more than shot peening, because it is possible to induce compressive residual stresses deeper than conventional treatments. In this study, we examined the applicability of laser peening to the aircraft through investigating the effects of laser peening on fatigue properties and the formability of aircraft parts.

KEYWORDS
Laser peening, Residual stress, Fatigue, Aluminum alloy, Helicopter

INTRODUCTION

Recently, requirements from aircraft customers are shifting toward the reduction of life cycle cost (LCC) by the expansion of fatigue life as well as the safety of parts. For especially the helicopter, it is a serious problem how to reduce the maintenance cost, since the exchange frequency of numerous parts is comparatively high. Shot peening has been applied to many parts with the purpose of improvement of fatigue and stress corrosion crack resistance for the helicopter since 1970's. However, some parts, which are used under the most severe condition causes fatigue fracture even if being conducted by shot peening(1).

Laser peening is a new surface improvement technique, which can provide a higher compressive residual stress and a deeper compressive layer than shot peening. Moreover this technology, which is able to give plastic strain more deeply, is expected to be suitable for shaping the complex curvature of metal parts.

Recently, laser peening technology is rapidly advancing in conjunction with laser technology development. In the aerospace industry, this surface technology starts to be applied to the tip of fan blades inside aircraft engines with the aim of saving the fatigue failure by foreign object damage. However there are few applications to fatigue critical area of aircraft structure parts such as dynamic component of the helicopter and fastener hole areas(2).

The purpose of this study is to investigate the applicability of laser peening to fatigue life improvement and the formability of aircraft parts.

Method

(1) Laser peening process

As shown in Fig. 1, laser peening is performed in water without the protective coating such as black paint and metallic foil in Japan. The laser source is a Q-switched, frequency doubled Nd:YAG laser operating in the green wavelength range. The theory of this peening method is the following. A shock wave follows high pressure plasma caused by pulse laser irradiation on the surface of material and then a compression stress area is formed by this shock wave propagating into the material. The depth of the compressive residual stress layer built by laser peening is deeper than that of shot peening(3).

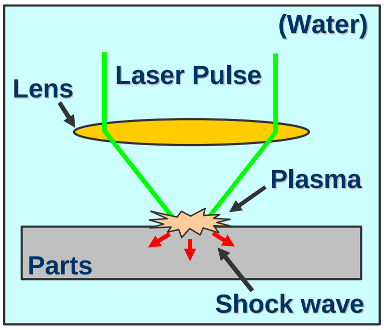


Fig.1 Schematic of laser peening

(2) Material

Some aluminum forgings have been used in numerous fatigue critical parts of aircrafts with the aim of improving the material characteristic of the parts. For this study, 7050-T7452 aluminum alloy hand forging was selected to evaluate the effects of laser peening. This alloy has both features of high strength and high resistance to stress corrosion cracking in thick section in comparison with other forging materials as shown in Table1.

Table 1 Mechanical properties of typical aluminum alloy hand forging for aircraft structures(4)

Material	Thickness (mm)	Static strength		Resistance to corrosion	
		Tensile (MPa)	Yield (MPa)	General	Stress-corrosion cracking
2014-T6	127.0-152.4	421	365	D	C
7075-T7352	127.0-152.4	421	338	C	B
7050-T7452	127.0-152.4	476	407	C	B

RESULTS

(1) Optimization of laser peening parameter

In order to optimize the process parameters for 7000 series aluminum alloy, in this study, we evaluated the residual stress profile, the surface roughness and fatigue properties after laser peening under various conditions.

Laser peening was performed under 3 conditions with combination of pulse density and pulse laser energy density as shown in Table 2. The specimen, 100 mm×100 mm plate with a thickness of 10mm, is mounted on a fast motor controlled X-Y stage inside a water tank.

Table2 Laser peening parameters

Condition No.	Pulse density (pls/mm^2)	Laser energy density (mJ/mm^2)
Condition A	6	236
Condition B	18	260
Condition C	18	88

The residual stress was measured at the center of the irradiated area by X-ray diffraction. To obtain in-depth profiles of the residual stress, surface layers of test pieces were removed by electrolytic polishing.

Figure 2 shows the result of residual stress profiles induced by laser peening. The depth of the residual stress improvement area by laser peening is about 10 times deeper than that of shot peening whose depth is approximately 0.1 - 0.2 mm. The compressive residual stress value and the depth of compressive stress area in the material tended to increase with increase in the laser energy density.

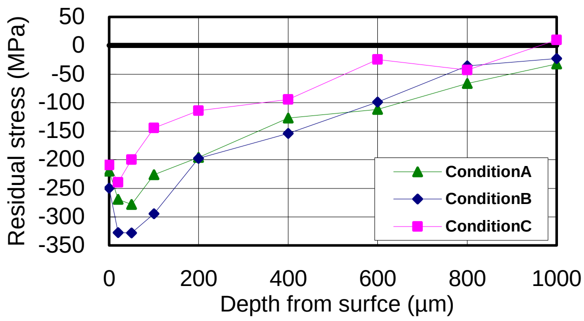


Fig. 2 Comparison of residual stress profiles in each condition

Table 3 shows the average value of surface roughness, which were measured at the peened area and the parameter Ra is the center-line average of adjacent peaks. This result indicates the surface roughness tends to be improved as the pulse density increases.

Table 3 Average surface roughness

Condition No.	Surface roughness Ra (μm)
Condition A	3.8
Condition B	2.8
Condition C	2.4
As milled (Ref.)	0.1

Table 4 Fatigue test summary

Specimen	Kt=1.0, Thickness=6.0 mm
Loading	Axial (Tension – Tension)
Frequency	10 Hz
Stress ratio	0.1
Max. stress	260 MPa (64%Fty)
Specification	ASTM E466
Test Machine	10 ton Fatigue testing machine (MTS)

A summary of fatigue test conditions is shown in Table 4. Laser peening was conducted on all four facets of the specimen except for the grip areas. As presented in Table 5, fatigue improvement by laser peening was demonstrated in Condition A and Condition B. The fatigue life of Condition B was longer than that of Condition A. However, Condition C did not show the expansion of fatigue life as compared with the non-surface treated.

In order to investigate the difference of fatigue properties among these conditions, fracture surfaces were observed by a scanning electron microscope (SEM). There were two types of crack initiation as shown in Fig. 3. On one hand, an internal fracture type was confirmed on Condition A and Condition B. The fracture nucleation was located about 1 mm inside from the surface. Such internal crack generation is known as a result of the remarkable improvement of fatigue property in the fatigue fracture of surface hardening materials and an internal area has a very slow fracture nucleation-growth through fatigue improvement of surface area by laser peening[5]. On the other hand, a surface fracture type as a typical fatigue fracture was confirmed on Non-surface treated and Condition C. This shows that fatigue improvement by compressive residual stress in surface area was not enough when specimens were laser peened on Condition C. And then, because the surface of Condition C is rougher than Non-surface treated (Table 3), it was expected that the fatigue life at Condition C was shorter than Non-surface treated. Therefore, it was confirmed that Condition B is the most suitable laser peening condition for 7000 series aluminum alloys from the view where the compressive residual stress was more important than the surface roughness on fatigue resistance.

Table 5 Results of fatigue test

LP Condition No.	Specimen No.	Fatigue life (Cycles)
Condition A	A-1	1930000
	A-2	1909000
Condition B	B-1	2968000
	B-2	2760000
Condition C	C-1	274000
	C-2	218000
Non-surface treated	N-1	477000
	N-2	460000

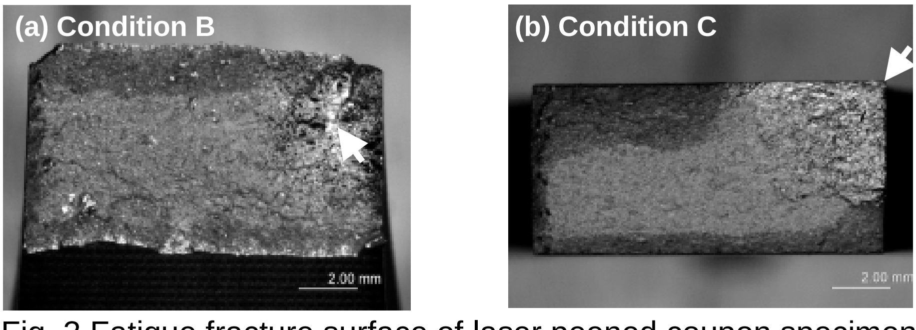


Fig. 3 Fatigue fracture surface of laser peened coupon specimens

(2) Open hole coupon tests

To demonstrate the expansion of fatigue life by laser peening with Condition B around fastener hole, tension-tension coupon fatigue tests were conducted with notched specimens. A summary of the fatigue tests is shown in Table 6. The specimen has a typical fasten-hole structure in the shape of a dog bone as shown in Fig. 4. Laser peening was conducted on both areas around a hole in the specimen. Shot peening was applied to compare the effects each other. The shot peening intensity was 0.006A, which was achieved using a cast steel shot and a coverage rate of 200%. Figure. 5 shows the result of the comparison of notched tension-tension fatigue tests of untreated, shot peened and laser peened specimens.

As shown in Fig. 5, improvements of fatigue life by laser peening tended to increase with a decrease of the maximum stress. Fatigue cycles to failure for the laser treated specimens increased more than approximately 20 times compared with the non-surface treated and about 5 times over as compared with the shot peened at the maximum stress of 140 MPa. The fatigue life improvement by laser peening on hole coupon fatigue test is greater than that of un-notched fatigue test.

Table 6 Notched fatigue test summary

Specimen	Kt=2.5
Loading	Axial (Tension – Tension)
Frequency	10 Hz
Stress ratio	0.1
Specification	ASTM E466

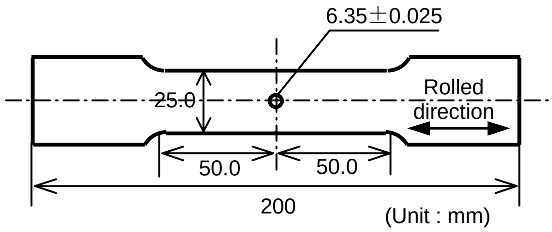


Fig. 4 Notched coupon specimen (Thickness: 6mm)

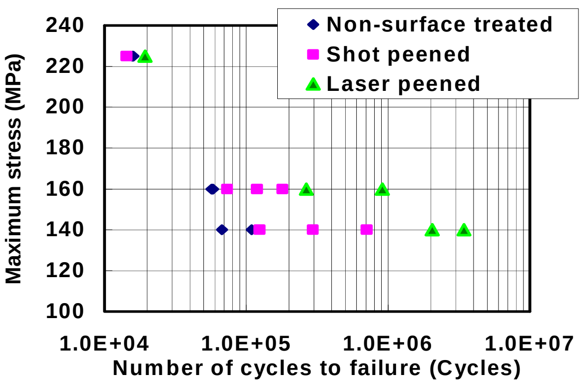


Fig. 5 Result of notched fatigue tests

(3) Component test

In order to evaluate the possibility of fatigue improvement with the component level, fatigue tests of an actual-size element, which simulate a part of the helicopter were conducted. The pitch horn, which is a part of flight control system for the main rotor of helicopters (see Fig. 6) was selected for the component test(6).

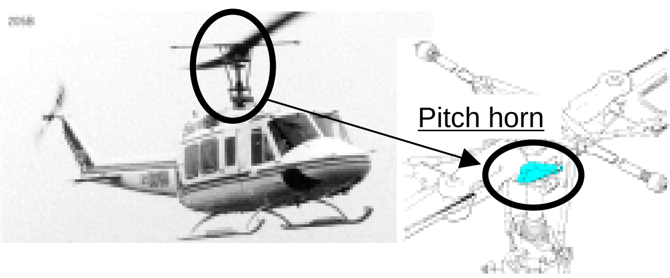


Fig. 6 Pitch horn of helicopter

The pitch horn in actual helicopters is loaded by about 5Hz high cycle fatigue load during flight. The actual-size element test was also conducted 5Hz fatigue load under the condition applying a simple sinusoidal load. The element test specimen was made of 7050-T7452 aluminum alloy as well as the coupon test. One specimen was untreated and the other specimen was treated by laser.

The test equipment and test set up are illustrated in Fig. 7. The restraint condition in the joint portion of the test specimen was simulated an actual part. The test specimen was fastened with two bolts, and the opposite side was a pinned joint. The sinusoidal test load of +/-1800 kgf was applied via a rod to the pinned joint. The rod simulated a pitch link.

The untreated specimen was tested until a failure with a visible crack due to fatigue. The crack on the untreated specimen was found at a location (1) shown in Fig. 8(a). The number of cycles to failure was about 160,000. For another specimen, laser peening was conducted at the location of A and B in Fig. 8(b). The location A and B were high stress areas predicted by the stress analysis and the preliminary strain survey. The laser peened specimen was tested until a failure and the number of cycles to failure was about 210,000. The visible crack was found at a location (2) shown in Fig. 8(b). The result of component test demonstrated that the fatigue strength of a stress concentration area was improved by laser peening. The fracture point in laser peened specimen shifted from the high stressed area to the low stressed area.

Consequently the improvement of fatigue life due to laser peening was verified through these tests. If not only high stress area but also low stress area is treated by laser peening, the expected life expansion of the element specimen would be the same as coupon test results.

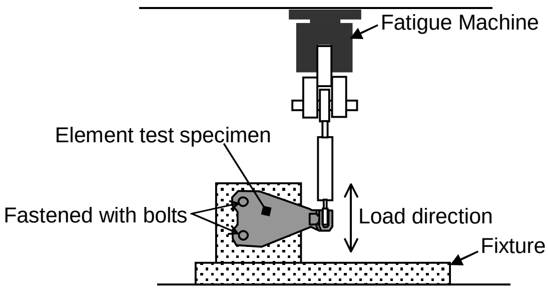
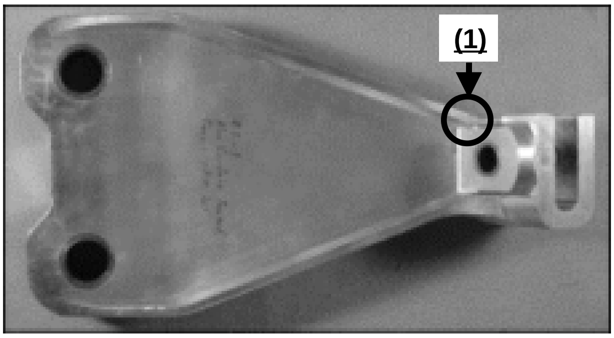
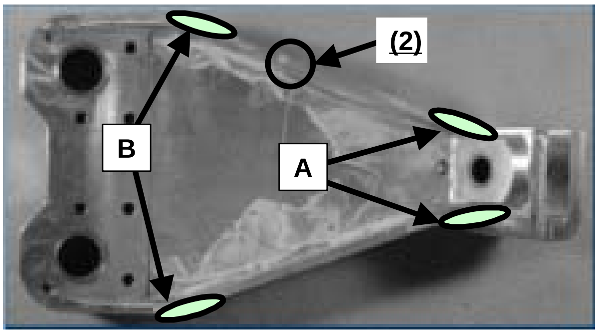


Fig. 7 Test set up



(a) Untreated test specimen



(b) Laser peened test specimen

Fig. 8 Results of component test

(4) Laser peen forming

To confirm the formability of laser peening at a coupon level, specimens of a sheet metal (7475-T761 Al alloy) were peened on some conditions and the radius of the peened specimen curvature were measured. Figure.9 shows a photo of the laser peened sheet material. All specimens were formed successfully in convex single curvature without showing buckling. As indicated in Fig.10, the radius curvature tended to decrease with increase in the number of pulses and the minimum contours' curvature is smaller than that of the wing tip area on small aircrafts such as business jets. In this test, the good formability of laser

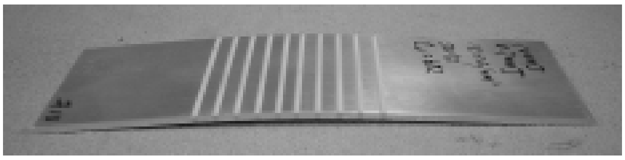


Fig.9 Laser peen formed specimen

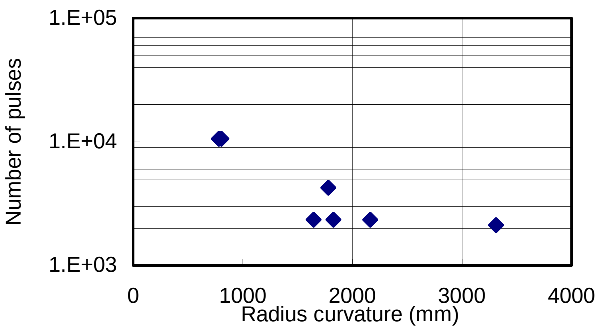


Fig.10 Laser peen formability

peen forming was verified. By the optimization of process parameters and peening patterns, this forming method is expected to become the effective method, which can form the wing skin in complex configuration and straighten some parts.

Conclusion

The optimum process parameters of laser peening for 7000 series aluminum alloys and the improvement of fatigue life by laser peening was studied and the following result were obtained:

(1) The fatigue cycles to failure for the laser treated specimens increased more than approximately 20 times compared with the non-surface treated and about 5 times over as compared with the shot peened at maximum stress of 140 MPa.
(2) The improvement of fatigue life by laser peening on the hole type fatigue test is greater than that of the un-notched fatigue test. This indicates that it is more effective for the improvement of fatigue life to apply this new surface technology to the stress concentration area such as fastener hole.
(3) The improvement of fatigue characteristics due to laser peening was demonstrated by the component fatigue test.
(4) The forming method by laser peening has a great potential to form the wing skin and straighten various parts.

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