Fatigue property enhancement by Fine Particle Shot Peening for Aircraft Aluminum Parts

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ABSTRACT

Fine Particle Shot Peening (FPSP), which has been developed in the Japanese automobile industry for steel parts, enables to improve fatigue property much more than the conventional Shot Peening (SP). The suitable FPSP process for the aluminum aircraft parts is under development. Fatigue life of conventional shot peened 7050-T7451 aluminum parts was increased by several times, while that of fine particle shot peened aluminum was increased by more than ten times compared with that of as machined. Compressive residual stress on fine particle shot peened surface which was covered with uniform dimples adequately is higher than that on shot peened surface. Fracture surface observation revealed that the fatigue crack of fine particle shot peened samples originate at the subsurface layer, which shows the high compressive residual stress at very near the surface and less roughened surface prevent crack initiation from the surface. Then FPSP can improve fatigue life farther more than SP does, which shows fatigue crack initiates from a small flaws and laps on the surface created by SP.

KEY WORDS

Fatigue enhancement, Fine Particle, High velocity, Aircraft, Smooth surface

INTRODUCTION

Fatigue improvement of aluminum parts by shot peening is an important process in aerospace industry to increase the fatigue properties with lower cost. Due to the increasing requirement for weight reduction, advanced fatigue improvement methods such as water jet peening (H.K.Tonshoff, 1998), (S.R.Daniewicz, 1999), cavitation peening (K.Enomoto, 1996), (K.Hirano,1996) and laser peening (H.Juong, In press),(O.Hatamleh, 2007) are attracted. Some of them show better fatigue properties, however, they have disadvantages on cost, processing time and so on.

Fine Particle Shot Peening (FPSP) has been developed and applied widely to steel springs and steel gears in Japanese automotive industry (H.Kubota,2007), (T.Kagaya,2003). It is a kind of shot peening process using small particles with high blowing velocity up to 200m/s and the process produces superior fatigue property compared to SP.

In this study, the fatigue enhancement mechanism by FPSP on 7050-T7451 aluminum was studied.

EXPERIMENTAL METHODS

1. Material

The fatigue specimens were prepared from aluminum alloy of 7050-T7451 101.6mm thickness plate. The specimen is an hourglass shape aluminum rod (k_t = 1.0) with a gage diameter of 6.0 mm and the longitudinal direction is LT orientation of the plate. Three different types of surface roughness, two of them are as machined with target roughness of Ra 1.6μm and 3.2μm, and the other one was polished after machining, were prepared to examine the influence of surface roughness on the fatigue property. The flat specimens with 2.4 mm thickness were used to measure the residual stress by X-ray diffraction method.

2. Shot peening

Shot media was made of ceramic compound of alumina with silica. The diameter is less than 0.06mm. The fine particle media was accelerated by air pressure through a nozzle in a suction type machine. The average Almen intensity after fine particle shot peening was between 0.085 to 0.10mmN and the coverage was more than 100%. The conventional cast steel shots S230 (0.6 mm average diameter shot size) were propelled by impellors. The actual Almen intensity and coverage were 0.10 to 0.15 mmA and 100% respectively.

Table 1 The results of Surface roughness and Residual stress

Specimen	Condition	Ra/μm	Residual Stress/MPa
Polished	Unpeened	0.2	-103
	SP	4.6	-153
	FPSP	0.9	-174
1.6 μm machined	As machined	1.2	10
	SP	4.8	-138
	FPSP	1.4	-159
3.2 μm machined	As machined	2.9	-48
	SP	5.3	-169
	FPSP	2.8	-187

3. Surface texture and fracture surface analysis

The surface texture and the fracture surfaces after fatigue testing were analyzed by a scanning electro microscopy (SEM). The surface roughness was measured by a profilometer.

4. Residual stress measurement

Residual stress of the specimens was measured by the $Sin^2\varphi$ method with a X-ray diffraction meter equipped with Chromium Kα tube.

5. Fatigue testing

The specimens were tested at constant amplitude with the stress ratio of R=0.1. All specimens were tested until failure occurs or tests were terminated at 10^7 cycles when no fracture occurred.

RESULTS

1. Surface texture

The results of surface roughness and residual stress measurement are shown in Table 1. SEM images and surface roughness measurements of 1.6μm machined are shown in Fig.1. The average surface roughness after SP was between 4.6 μm to 5.3 μm regardless of the machining conditions. The surface roughness after FPSP is almost the same. The

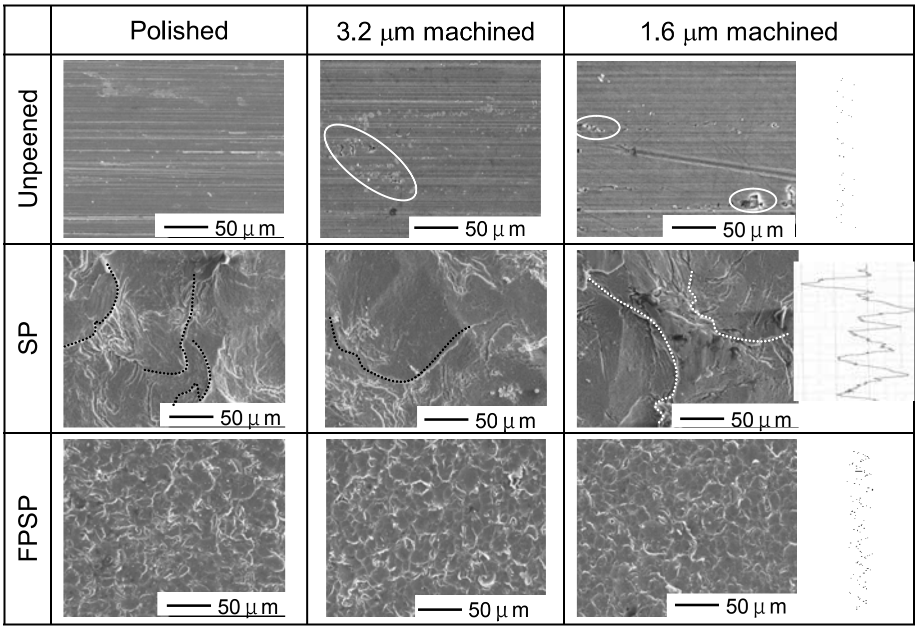

Fig.1 The SEM images of shot peened and unpeened surfaces and surface roughness profiles of 1.6 μm machined samples. (Circles in unpeened images indicate the machine scars and the dotted lines in SP images show the shape of dimples.)

surface roughness profile of FPSP in Fig. 1 indicates that small dimples are formed along the tool marks although the SEM image does not show the remained tool marks. The results of surface observation by SEM show that there exist machined scars on unpeened surface.

2. Residual stress

The compressive residual stress resulting from FPSP is higher than that from SP regardless of machined condition as shown in Table 1.

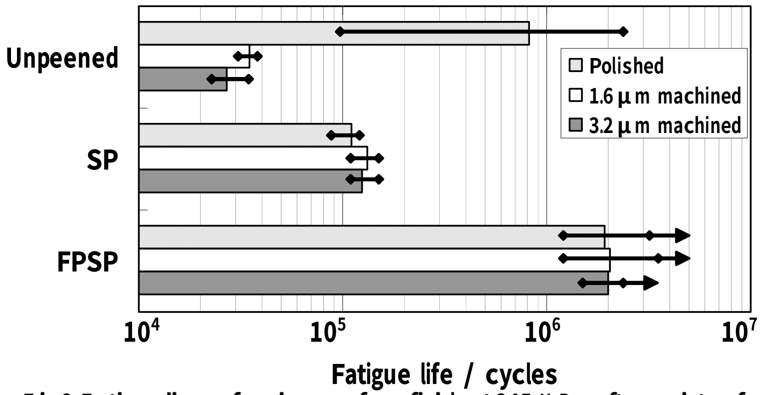

Fig.2 Fatigue lives of various surface finish at 345 MPa after variety of shot peening comparing the results of prior to peening.

3. Fatigue

The results of fatigue tests are summarized in Fig. 2. Each data shows the average of three data sets with scatter bars. All the results of fatigue life of fine particle shot peened aluminum samples are 15 to 17 times longer than that of shot peened ones, which are about 2.7 times longer than that of as machined ones. The average fatigue life of polished is the same level of SP, however, the range of scatter of polished was wide between 10^4 and 10^6.The scatter of average fatigue lives of both FPSP and SP in three different surface finishing is smaller than that of unpeened result. It indicates that the fatigue improvement effect by shot peening is constant regardless of machine finishing. The S-N curve of 1.6 μm machined is shown in Fig. 3, which indicates that the superior fatigue life by FPSP is kept at wide maximum stress range between 276 and 379 MPa.

4. Fracture surface

The SEM images of typical fracture surfaces after fatigue testing are shown in Fig. 4. It is obviously shown the crack initiation sites for each specimen are different as follows; as machined and polished at machined scars, SP at piled up boundaries between the dimples and FPSP at internal metallographic defects.

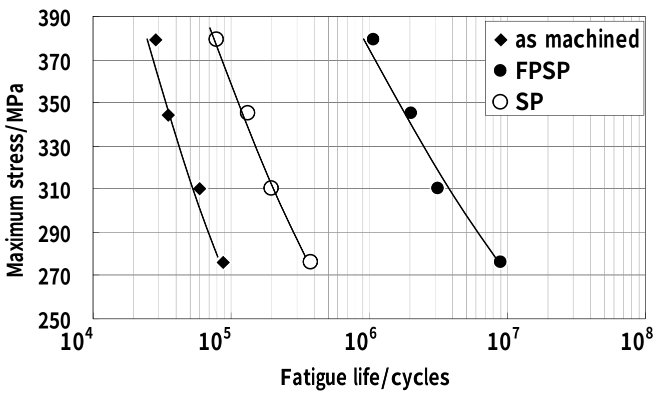

Fig. 3 S-N curve of 1.6μm machined aluminum 7050 before and after peening.

DISCUSSIONS

1. Surface texture

Surface analysis revealed that FPSP does not increase the surface roughness because of its small shot diameter. The effect of shot size on the surface roughness by shot peening can be evaluated by the depth of dimples. According to Hirai et. al.(2005), the depth of a dent "h" and piled-up height "h_p" can be expressed in the form of the following equation,

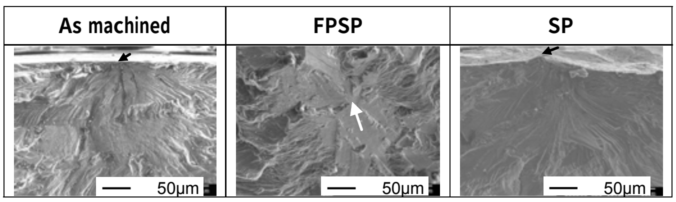

Fig.4 Fatigue fracture surface (1.6 μm machined). Crack initiation sites of each sample are pointed by arrows.

$$h = k_1 D v^{9/10} \quad [1]$$
$$h_p = k_2 D v^{5/6} \quad [2].$$

Here, k_1 and k_2 are constant, D is shot diameter and v is shot velocity.
The shot velocity of FPSP and SP are 190 m/sec (Y.Harada, 2007) and about 60 m/sec (Y. Kameyama, 2007), the FPSP shot diameter is 0.05 mm and that of SP is 0.6 mm. Therefore, depth of dent for FPSP h(FPSP) / h(SP) is 0.23, while piled-up height h_p(FPSP) / h_p(SP) is about 0.21. The ratio of the dimple height h(FPSP) / h(SP) is about 0.20, which is almost the same as the ratio of surface roughness, Ra(FPSP) / Ra(SP). Therefore the surface roughness of SP and FPSP can be expressed as a function of shot diameter.

2. Residual stress

Although collision energy of FPSP is smaller than that of SP because of the small media, the residual stress induced by FPSP is larger than that of SP. According to Wagner (L.Wagner, 1999), the maximum residual stress by SP on aluminum alloy 2024-T6 is located to the depth of between 100 to 200 μm. The X-ray penetrates 25 to 30 μm into aluminum, that is shallower than the depth to the maximum residual stress by SP. Hence the results of SP shown in Table 1 probably does not reflect the maximum residual stress. On the contrary, maximum residual stress depth of FPSP should be shallower than that of SP because of its small collision energy. Therefore, the experimental results shown in Table 1 of FPSP are considered to reflect the maximum stress. Deep residual stress distribution obtained by SP is assumed to have a role to retards crack propagation, while residua stress just below the surface induced by FPSP is expected to have a role mainly to prevent crack initiation from the surface. The depth profiles of residual stress for FPSP need to be measured to understand the superior fatigue property by FPSP.

3. Fatigue property

Figs.2 and 4 show three features. (1) the difference of surface finish varies the fatigue lives of unpeened samples, (2) the fatigue lives of SP and FPSP are hardly affected by finish conditions before peening, and (3) the fatigue life of FPSP is more than 10 times longer than that of SP, which is several times longer than that of as machined.

(1) This difference of fatigue life of unpeened samples is probably brought by the existence of machined scars and tool marks. SEM images of machined surfaces and fracture surface revealed that the rougher machined surface has more scars where can be a crack initiation site of fatigue fracture. The effect of tool marks on fatigue life can be evaluated by the value of "$\sqrt{area}$". It is defined as the equivalent surface defect size for surface roughness under the condition in which stress intensity factor for periodical surface morphology, so-called "crack", with a depth of "a" and a pitch of "2b" is equal to the maximum value of stress intensity factor along the crack front of fatigue fracture for a small surface "crack". Therefore, the "$\sqrt{area}$" value depends on "a" and "2b" of surface roughness (Y.Murakami, 1985) and the calculated result of "$\sqrt{area}$" of polished, 1.6 μm and 3.2 μm are about less than 1.8 μm, 14 μm and 37 μm, respectively. The stress intensity factor with less roughened surface is calculated using the following Murakami's formulae (Y.Murakami, 1997) for surface crack:

$$\Delta K \propto \sigma\sqrt{\pi\sqrt{(area)}} \quad [3]$$

Where σ is the stress amplitude on the surface. The reciprocal proportion of ⊿K between polished, 1.6μm machined and 3.2 μm machined are roughly 1, 0.35 and 0.22. Since it is well known that the larger the equivalent defect size "$\sqrt{area}$" is, the larger the stress intensity factor is, and the shorter the fatigue life is, it was indicated that the difference of unpeened fatigue life correspond to that of the equivalent defect size "$\sqrt{area}$" on the surface.

On the contrary, the fatigue life of SP is not affected by the prior machine condition because the surfaces are covered with uniform dimples and the induced high compressive residual stress near the surface brings almost the same fatigue life by preventing fatigue crack propagation. However, piled-up boundaries between the dimples on SP surface can be a crack initiation site to shorten the fatigue life before crack initiation.

The fatigue life of FPSP is also not affected by the prior finish condition, however, the life is more than one order of magnitude linger than that of SP. It seems that less roughened FPSP surface and the induced high compressive residual stress at very near the surface play an important role to prevent both crack initiation and propagation from the surface. Therefore FPSP can improve the fatigue life more than SP does. The study of the fatigue life improvement mechanism by FPSP considering the duplex effect of tool marks as examined above and the compressive residual stress are in progress.

CONCLUSIONS

FPSP enhances fatigue life of aluminum alloy 7050 more than one order of magnitude compared with SP due to the high compressive residual stress at very near surface along with less roughened surface. The fatigue lives of FPSP are also hardly affected by the machine finish prior to peening.

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