Effects of Ultrafine Particle Peening on Fatigue Properties of ASTM 5056 Aluminum Alloy

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Abstract
Ultrafine particle peening (Ultra-FPP) using particles (10 μm diameter) was introduced to improve the fatigue properties of ASTM 5056 aluminum alloy. Surface microstructures of the peened specimens were characterized using a micro-Vickers hardness tester, scanning electron microscope (SEM) and X-ray diffraction (XRD) to clarify the fatigue fracture mechanism. The surface hardness of the peened specimen was increased with decreasing peening time. Furthermore, the Ultra-FPP treated specimen had higher hardness than the one treated with conventional FPP using particles (50 μm diameter). Fatigue tests were performed at room temperature using cantilever-type rotating bending fatigue testing machine. It was found that the fatigue life of the Ultra-FPP treated specimen was increased with decreasing peening time due to increasing surface hardness. Especially, Ultra-FPP improved fatigue properties of aluminum alloy in the very high cycle regime for more than 10^7 cycles. Moreover, numerical calculation of particles velocity was conducted to examine the influence of shot particle size on the microstructural change of aluminum alloy.

Keywords Fatigue, fine particle peening, hardness, residual stress, aluminum alloy

Introduction

Surface modification processes are effective in terms of improving the fatigue strength of metallic materials because a fatigue crack usually initiates at the surface. A surface-hardened layer and a compressive residual stress induced by surface modification process can improve fatigue resistance. Especially, shot peening has been widely used in various fields of engineering to improve the fatigue properties of materials [1-4]. Fine particle peening (FPP) highlighted in this study is very similar to conventional shot peening method, except that shot particles used in FPP are much smaller than those used in shot peening; less than 200 μm in diameter. In the previous reports, the effects of shot particle size on the microstructural changes and fatigue properties of material were investigated [1, 5-8]. Yonekura et al. [1] has reported that fatigue strength of FPP treated ferrite-pearlite steel was higher than that of the one treated with conventional shot peening due to the generation of higher and more stable compressive residual stress at the treated surface. Moreover, FPP is very effective for creating finer crystal grains [5-8] because the particle velocity obtained with FPP is higher than that with conventional shot peening [6, 9, 10]. Based on these reports, it is expected to improve the fatigue strength by performing shot peening using finer shot particles. In this study, "ultrafine particle peening (Ultra-FPP)" using particles (10 μm diameter) was introduced to improve the fatigue properties of ASTM 5056 aluminum alloy. The purpose of this study is to examine the effects of shot particle size on the microstructure of aluminum alloy (ASTM 5056). In addition, the fatigue properties of aluminum alloy in the very high cycle regime around 10^9 cycles (giga-cycles) were experimentally investigated by performing fatigue tests in the rotating bending.

Experimental Methods

The material used in this study was ASTM 5056 aluminum alloy with the chemical composition shown in Table 1. Mechanical properties of this material are shown in Table 2. Material rods (12 mm diameter) were machined into 5 mm thick disks and fatigue specimen (Fig.1). These specimens were annealed at 473 K for 2 h to remove strain induced by machining. The Ultra-

FPP and conventional FPP were performed for the disk and fatigue specimens under the conditions given in Table 3. Figure 2 shows a scanning electron microscopy (SEM) micrograph of the shot particles ((a) 10 μm and (b) 50 μm diameter) with a Vickers hardness of 862 HV used in this study. In order to characterize the surface microstructure of the peened specimens, the hardness distributions were measured along the longitudinal section of the disk specimen using a micro-Vickers hardness tester. Residual stress was also measured at the transverse section of the smallest diameter of the fatigue test specimen using X-ray diffraction (XRD) with a Position-Sensitive Proportional Counter (PSPC) system under the conditions; CrKα radiation, (222) reflection, 2θ = 156.6 deg., K = -94.86 MPa/deg.

Table 1. Chemical composition of aluminum alloy (mass%)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Al
0.04	0.13	0.01	0.06	4.8	0.06	0.02	Bal.

Table 2. Mechanical properties of aluminum alloy

Tensile strength (MPa)	0.2% proof stress (MPa)	Elongation (%)	Vickers hardness (HV)
310	218	21	88

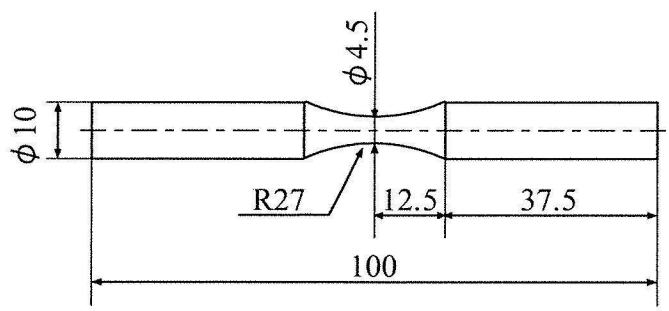


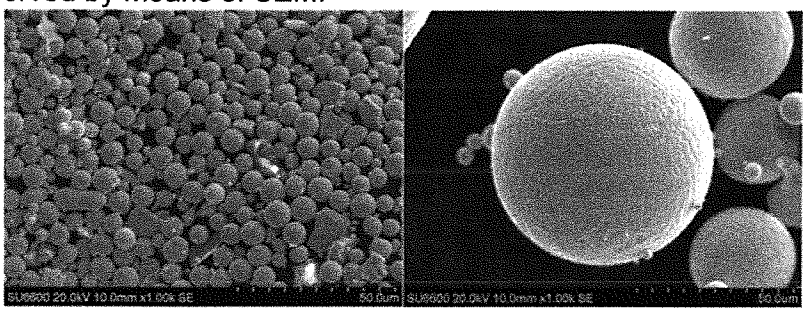
Figure 1 Specimen configuration for fatigue test

Table 3. Peening conditions

Series	Particle diameter, μm	Nozzle distance, mm	Peening pressure, MPa	Peening time, s
Ultra-FPP	10	30	0.6	3
				5
				10
				30
		50	0.2	3
				10
			0.4	3
				10
			0.6	3
				10
FPP	50	50	0.2	3
			0.4	3
			0.6	3
				10

Fatigue tests were performed using dual-spindle rotating bending fatigue testing machine. This fatigue testing machine has two spindles driven by an electric motor via V-belt and each spindle has specimen grips at both ends. Thus, this machine can perform fatigue tests for four specimens in the loading type of rotating bending, simultaneously. This type of testing machine was originally developed to perform a series of long term fatigue tests within a definite period [11]. Fatigue tests in the rotating bending were performed in room atmosphere without any controls of the temperature and the moisture at stress ratio R = -1. The rotating speed of the

spindle in the rotating bending is 52.5 Hz. After testing, the fracture surfaces of the failed specimens were observed by means of SEM.

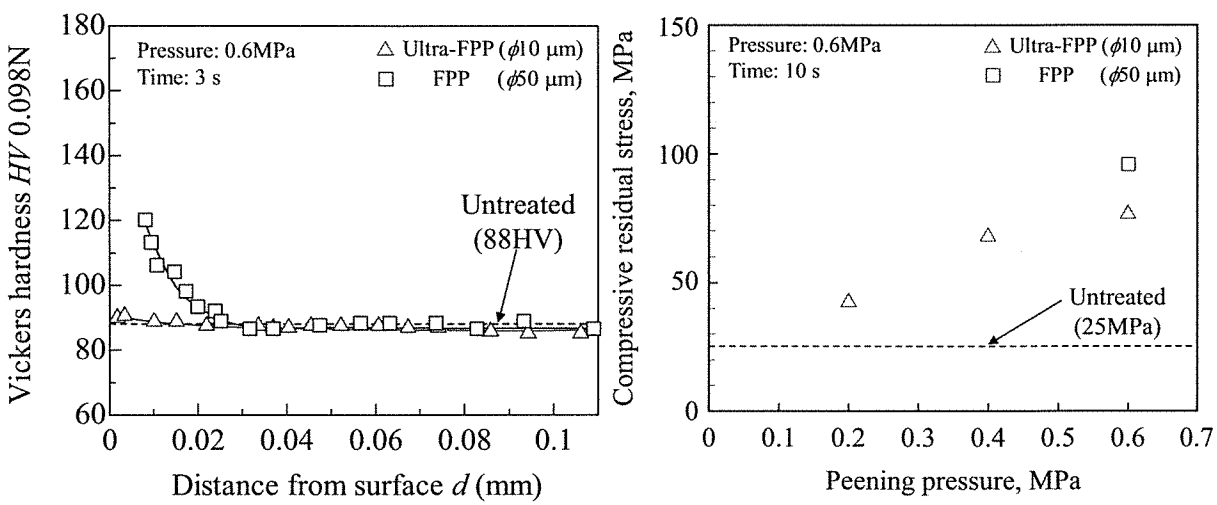


(a) ϕ10 μm (b) ϕ50 μm

Figure 2 SEM micrographs of shot particles

Experimental Results and Discussion

Effects of shot particle size on the microstructure of 5056 aluminum alloy: In this section, influences of shot particle size on the surface microstructure of aluminum alloy were examined. Figure 3 (a) and (b) show the distribution of Vickers hardness at various longitudinal-sectional depths and the residual stress at top surface for the specimens peened under the condition of 50 mm in nozzle distance, respectively. The surface hardness of the specimen was increased by the conventional FPP using particles (50 μm diameter). However, the Ultra-FPP treated specimen using particles (10 μm diameter) had almost the same hardness as the untreated specimen; represented by dashed line in this figure (a). Figure 3 (b) showed that compressive residual stress was generated at the Ultra-FPP and FPP treated surfaces. The value of compressive residual stress tended to be increased with peening pressure. However, the compressive residual stress at the Ultra-FPP treated specimens showed lower than that at the conventional FPP treated one.



(a) Vickers hardness (b) Compressive residual stress

Figure 3 Results of measuring the Vickers hardness and a compressive residual stress for the specimens peened under the condition of 50 mm in nozzle distance

In order to clarify the reason for showing lower surface hardness and compressive residual stress of Ultra-FPP treated specimen compared to the conventional FPP treated specimen, the velocity of shot particle was analyzed on the basis of the model which the authors' research group has proposed [9,10]. As results, the velocity of shot particles tended to become high with decreasing its diameter; however, the velocity of the ultrafine particles (10 μm diameter) was increased with increasing distance from the nozzle and then decreased as the velocity of compressive air was decreased. This result indicates that the velocity of ultrafine particles remarkably changes depending on that of compressive air. Consequently, the Ultra-FPP did not

remarkably modify the microstructure of aluminum alloy under the condition of 50 mm in nozzle distance due to decreasing the velocity of ultrafine particles.

Effects of peening time on the surface microstructure and fatigue properties of 5056 aluminum alloy: In the previous section, it was clarified that the velocity of ultrafine particles was decreased as velocity of compressive air was decreased with increasing distance from the nozzle. Therefore, the Ultra-FPP was performed in shorter nozzle distance (30 mm) compared to the previous sections. Figure 4 shows the distribution of Vickers hardness at various longitudinal-sectional depths for the Ultra-FPP treated specimens under the condition of 30 mm in nozzle distance. The surface hardness and thickness of hardened layer for the Ultra-FPP treated specimen tended to be increased with decreasing peening time. Moreover, the Ultra-FPP treated specimen for 3 and 10 s had higher hardness than the conventional FPP treated specimen, as shown in Figure 3 (a). This result indicates that Ultra-FPP is effective to increase surface hardness of aluminum alloy under the condition of short nozzle distance and peening time.

Figure 5 shows the results of fatigue tests for the Ultra-FPP treated specimens and untreated specimen. In the short life regime, the Ultra-FPP treated specimens showed almost the same fatigue life as the untreated specimen. On the other hand, the Ultra-FPP significantly improved fatigue properties of aluminum alloy in the very high cycle regime for more than 10^7 cycles. Especially, the fatigue life of the peened specimen was increased with decreasing peening time due to increasing surface hardness. Therefore, the Ultra-FPP treated and untreated specimens showed different type of *S-N* curve. The fatigue limit was not clearly observed for untreated specimen so that the *S-N* curve tended to decrease continuously toward the giga-cycle regime. In contrast, fatigue life of the Ultra-FPP treated specimens were divided into 2 groups; failed in short and long life regime.

In the very high cycle regime, high strength steels often reveal the duplex *S-N* property consisting of the respective fracture modes of the surface initiated fracture and the interior initiated fracture [12]. However, ASTM 5056 aluminum alloys have failed in the surface

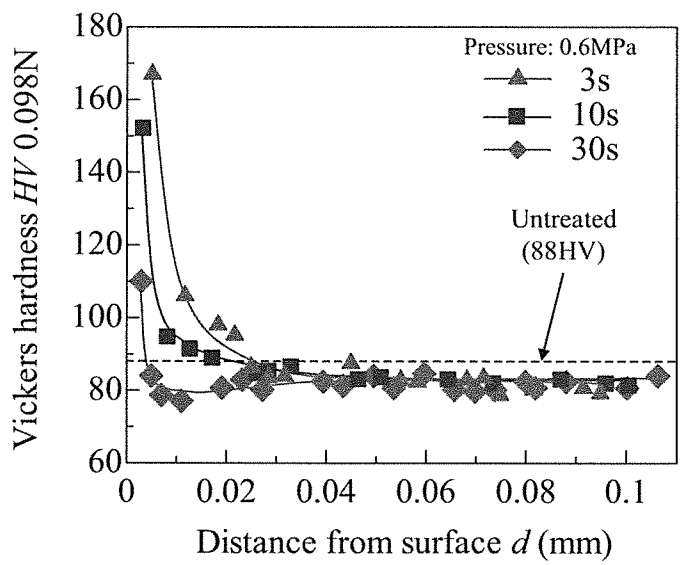


Figure 4 Distributions of Vickers hardness at longitudinal section for the specimens peened under the condition of 30 mm in nozzle distance

initiated fracture mode even in the very high cycle regime. Thus, such duplex *S-N* curves were not clearly found for this alloy.

Release behavior of compressive residual stress during fatigue tests: It is well known that residual stress is released during the fatigue tests [1,3,4]. Figure 6 shows the relationship between compressive residual stress and stress amplitude. Compressive residual stress generated on the Ultra-FPP treated specimen before fatigue tests (σ_a = 0 MPa) was higher than

that after applying cyclic loading. This result means that compressive residual stress was released during fatigue tests. In addition, another finding in Figure 6 was that compressive residual stress after fatigue tests tended to be decreased with increasing stress amplitude. This is why the Ultra-FPP does not improve the fatigue life of aluminum alloy in the low cycle regime under high stress level.

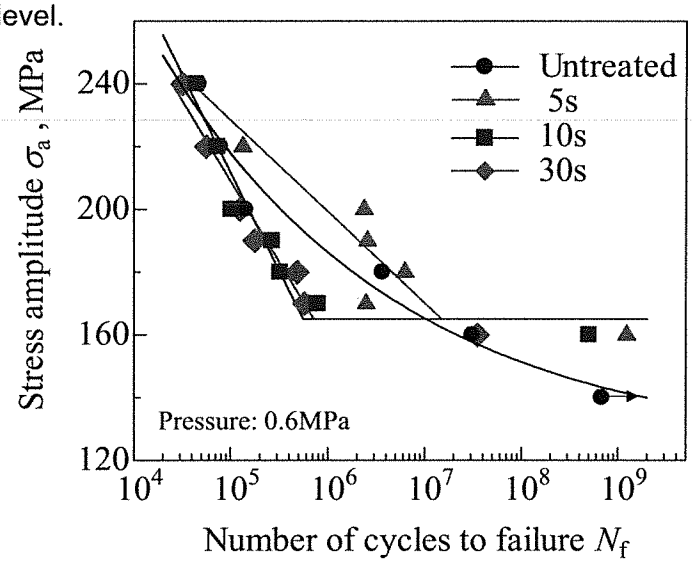


Figure 5 Results of fatigue tests for the specimens peened under the condition of 30 mm in nozzle distance

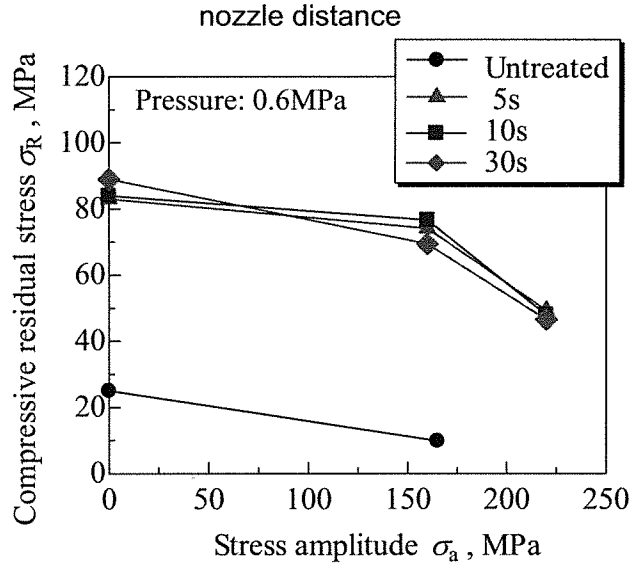


Figure 6 Relationship between applied stress amplitude and compressive residual stress generated on the specimens peened under the condition of 30 mm in nozzle distance

Conclusions

In this study, effects of shot particle size on the microstructure of ASTM 5056 aluminum alloy were investigated. Moreover, rotating bending fatigue tests were performed to examine the effects of ultrafine particle peening (Ultra-FPP) on the fatigue properties of ASTM 5056 aluminum alloy. Main conclusions obtained in this study are summarized as follows;

(1) As results of numerical calculation of particles velocity, it was clarified that the velocity of ultrafine particles remarkably changes depending on that of compressive air.

(2) The Ultra-FPP is effective to increase surface hardness of aluminum alloy under the condition of short nozzle distance and peening time.

(3) The fatigue life of the Ultra-FPP treated specimen is increased with decreasing peening time due to increasing surface hardness.

(4) The Ultra-FPP significantly improves fatigue properties of aluminum alloy in the very high cycle regime for more than 10^7 cycles. This is because the amount of releasing compressive residual stress is low during the fatigue tests under low stress level.

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