Effect of Humidity on Fatigue Properties of Shot-Peened High Strength Al Alloy

Q. Chen[1], N. Kawagoishi[2], K. Kariya[2], T. Nagano[3], Y. Kobayashi[4] and T. Tsuji[4]

1 Center for Globalization, Kumamoto University, Japan
2 Faculty of Engineering, Daiichi Institute of Technology, Japan
3 Miyakonojo National College of Technology, Japan
4 Shinto Kogio, LTD, Japan

Abstract

Fatigue properties of a shot-peened high strength Al-Cu-Mg alloy, extruded 2017-T4, was investigated in relative humidity of 25% and 85% under rotating bending. Fatigue strength was increased by shot-peening in both humidity environments. Although fatigue strength was markedly decreased by high humidity in the non-peened specimen, there is no or little influence of humidity on fatigue strength in the shot-peened one. In the non-peened specimen, the macroscopic propagation mode of a crack changed from a shear mode to a tensile one with increasing in fatigue life in high humidity which is different from the tensile mode only in low humidity. On the other hand, the propagation in the shot-peened one was a tensile mode irrespective of humidity.

Keywords : Fatigue, shot peening, high strength Al alloy, humidity, crack propagation mechanism

Introduction

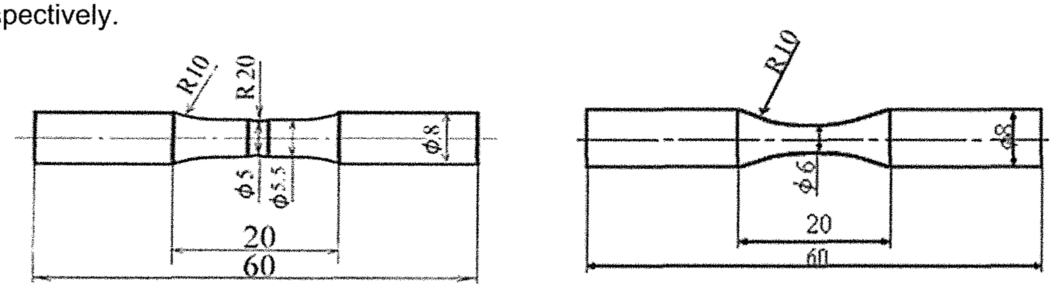
High strength Al alloys have an advantage in view point of reduction of environmental load because of their excellent properties of high specific strength, easiness for recycling, and so on. However their fatigue strengths are considerably lower than expected from their static strengths. The poor fatigue properties are caused by their high sensitivities to notch and corrosive environment. Therefore, methods for improvement of the fatigue properties of the alloys have been studied from the view points of microstructural change [1] and surface modification [2]. It is well known that shot peening is one of effective technologies to improve fatigue strength due to compressive residual stress and hardening at the surface layer induced by the treatment. Consequently, shot-peened components were widely used in machines and structures. These components are usually used in various environments including moist air which is a corrosive environment for high strength Al alloys [4]. However, it is not fully understood about the effect of humidity on the fatigue properties of shot peened Al alloys. Especially, in shot peened components, the work hardened layer with dense dislocation is apt to be affected by humidity.

In the present study, fatigue properties of shot-peened high strength Al-Cu-Mg alloy, extruded 2017-T4, and effect of humidity on the properties were investigated based on the comparison with the results of non-peened specimen [3].

Experimental Methods

Material used was an extruded bar of an age-hardened Al-Cu-Mg alloy (2017-T4). The alloy was received as age-hardened condition. The chemical composition (mass. %) of the alloy was 0.42Si, 4.06Cu, 0.3Fe, 0.73Mn, 0.58Mg, 0.05Cr, 0.02Zn, 0.05Ti, and Bal. Al. The mechanical properties were 350MPa of 0.2% proof stress, 471 MPa of tensile strength, 638 MPa of true fracture strength and 32.4% of reduction of area, respectively. The alloy had a marked texture of (111) plane at the cross section of a bar and the microstructure was elongated to the extruded direction due to its sever fabrication process. The mean grain size was about 13 μm.

Figure 1 shows shape and dimensions of specimens. After machining, parts of the specimens were shot-peened by air blasting method using ceramic particles of 0.6 mm in diameter (air pressure p=0.6 MPa), and others were paper- and electro-polished to remove the work-hardened layer caused by the machining. The electro-polished specimen was used for a successive observation of a crack initiation and propagation behavior. Therefore the specimen has a blunt and shallow circumferential notch to localize the crack initiation site and make the observation easier. Fatigue tests were carried out until 10^7 cycles using a rotating bending fatigue testing machine operated at 50 Hz in relative humidity (RH) of 25% and 85%. The deviation of humidity was RH±3%. The temperature in ambient air was not controlled but was 25±3°C. The observation of fatigue damage and the measurement of crack length were conducted under a scanning electron microscope (SEM) or under an optical microscope by using the plastic-replication technique. Crack length, ℓ, was defined as a surface length in the circumferential direction along specimen surface in both propagations of a tensile mode and a shear one. Distributions of hardness and residual stress were measured by using a micro-Vickers hardness tester and an X-ray diffraction device (Cr-Kα), respectively.



(a) Electro-polished specimen (b) Shot-peened specimen

Figure 1 Shape and dimensions of specimens.

Experimental Results

Figure 2 and figure 3 show hardness distribution and residual stress one at the surface layer

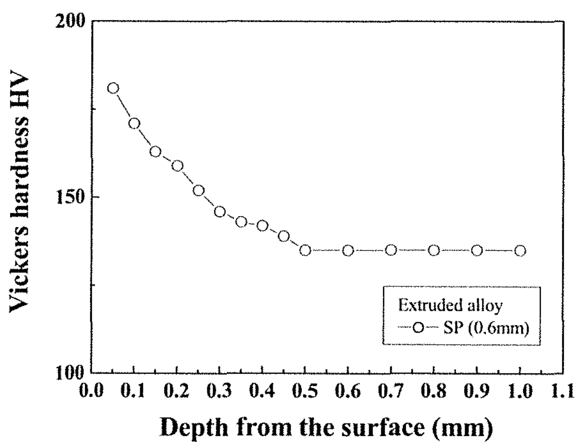


Figure 2 Hardness distribution.

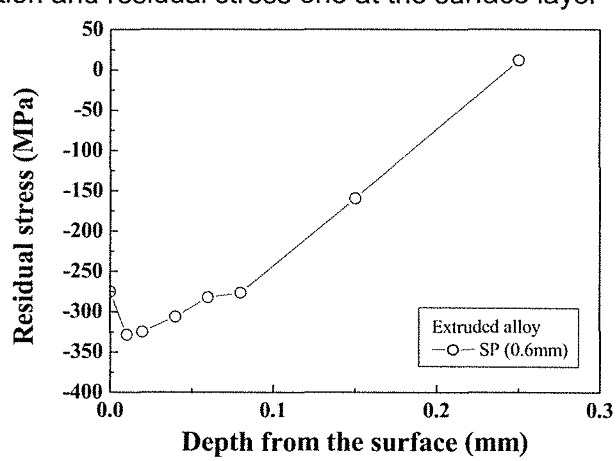


Figure 3 Distribution of residual stress.

of shot-peened specimen, respectively. By shot peening, hardening and compressive residual stress were yielded in the surface layer. The surface roughness of specimen was increased to about 30μm by shot peening in comparison with about 1μm in the electro-polished specimen.

Figure 4 shows *S-N* curves of shot-peened specimens and electro-polished ones in both humidity environments. All of fractures occurred from the specimen surface irrespective of shot peening treatment in both humidity environments. Any cracks were not observed at the surface of nonfractured specimen in low humidity, while many corroded regions were observed and a crack initiated at the region in high humidity as shown in Fig.5, as an example. Fatigue strengths are increased by shot-peening irrespective of humidity. By high humidity, fatigue strength was largely decreased in the electro-polished specimen, while the decrease is very small in the shot-peened specimen.

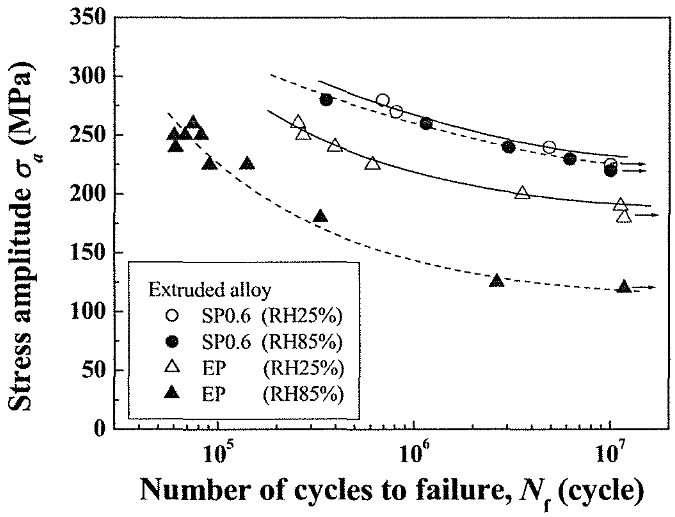


Figure 4 S-N curves showing effects of shot peening and humidity on fatigue strength.

Figure 6 shows crack propagation curves in the electro-polished specimen referred from previous paper [4]. A crack initiates at the early stage of fatigue process and most of fatigue

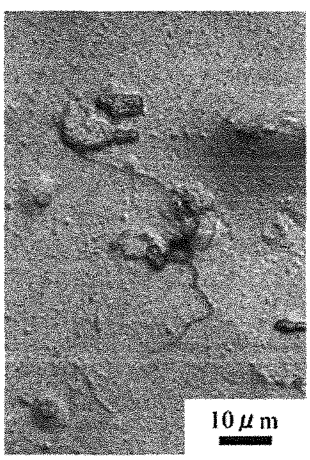


Figure 5 Crack initiated at corroded region in electro-polished specimen.

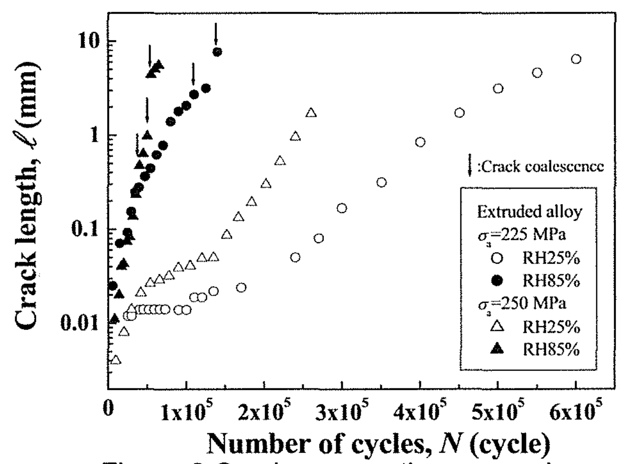
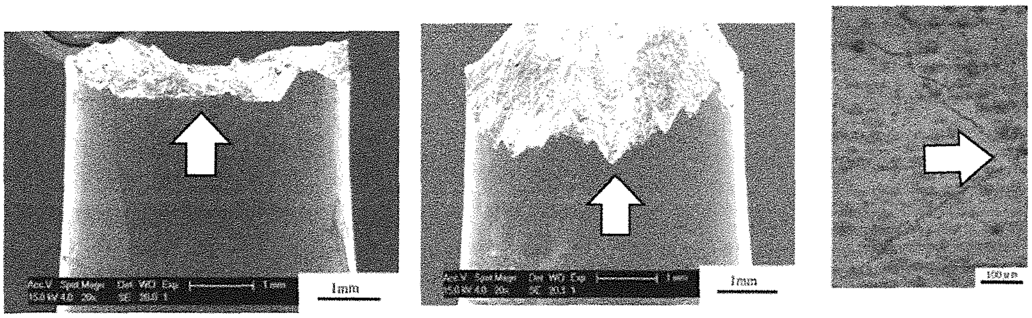


Figure 6 Crack propagation curves in electro-polished specimen.

life is occupied by the crack propagation life irrespective of humidity. Both of initiation and propagation of a crack, especially in the early propagation process, are accelerated in high humidity by corrosion as shown in Fig.5. In case of the shot peened specimen in high humidity, the further promotion of a crack initiation can be estimated easily because of the anodic dissolution due to the dense dislocation at the surface layer in addition to notch effect due to the increase in surface roughness. Therefore, the effect of shot peening on fatigue strength can be evaluated as the one on the crack propagation process.

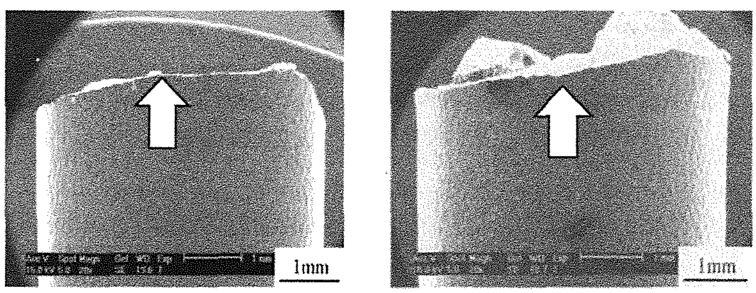
Figure 7 is SEM photos showing crack morphologies. In general, a crack initiated by slip deformation, i.e., stage I crack, propagates in a tensile mode macroscopically. It was the same at all life regions in low humidity and at the long life region in high humidity. However, the propagation at the short life region in high humidity is a shear mode in the electro-polished specimen as shown in Fig. 7 (a-2) and (a-3). By shot peening, however, the crack propagation changed to the tensile mode from the shear one regardless of fatigue life region.



←→ **Axial direction**

(a-1) RH25% (σa= 225MPa) (a-2) RH85% (σa= 225MPa) (a-3) Magnified photo of crack initiation site in (a-2)

(a) Electro-polished specimen



(b-1) RH25% (σa=240MPa) (b-2) RH85% ($σ_a$=240MPa)

(b) Shot-peened specimen

Figure 7 Crack morphologies (arrows indicate crack initiation site).

Figure 8 shows typical fracture surfaces caused by the shear mode crack in the electro-polished specimen and the tensile mode one in the shot peened specimen in RH85% shown in Fig.7. Cracks initiated by slip deformation regardless of shot-peening and humidity as shown in Fig.8 (b-1) as an example. Fracture surfaces of the electro-polished specimen were occupied by voids and flat planes like a slip planes. On the other hand, those of shot-peened specimens were mainly covered with striations regardless of humidity.

Figure 9 shows a stress dependence on the propagation direction of shear mode crack in high humidity. The propagation direction is nearly constant of 55° to the normal direction to the specimen axis.

Figure 10 shows etch pit figure on fracture surface yielded by the shear mode crack of the electro-polished specimen in RH85%. The etch pit has a pyramid shape and the direction of the base of pyramid is nearly the same as the propagation direction of crack, meaning that the shear mode crack propagated on (100) plane and to <110> direction.

Internal region (~0.3mm from specimen surface)

(b-1) Around crack initiation site

(b-2) Internal region (~0.3mm from specimen surface)

(a) Electro-polished specimen (σ_a= 225MPa) (b) Shot-peened specimen (σa= 240MPa)

Figure 8 Fracture surfaces of electro-polished specimen and shot-peened one in RH85%.

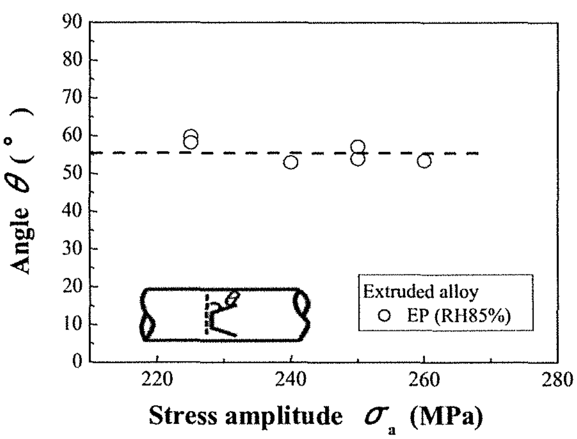


Figure 9 Propagation direction of shear mode crack of electro-polished specimen in high humidity.

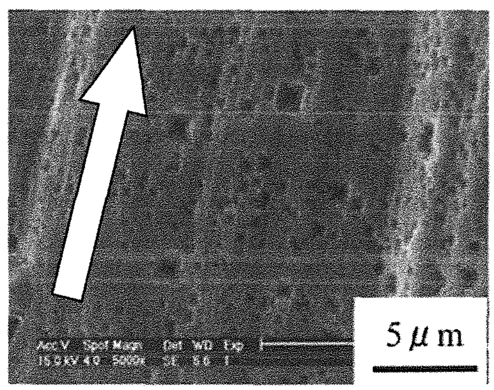


Figure 10 Etch pit figure on fracture surface yielded by shear mode crack (arrow indicates direction of crack propagation).

Discussion

As mentioned above, by shot peening, the propagation mode of crack in high humidity was changed from the shear mode to the tensile one and the decrease in fatigue strength by high humidity was largely suppressed in comparison with the results in the electro-polished specimen. These results are very important in practical application from the view point that shot peening is one of effective technologies to improve not only fatigue strength but also the sensitivity to humidity. Therefore, in the following, the reasons for these interesting results will be investigated. The extruded alloy used in this study has a marked texture of (111) plane at the cross section of specimen and shows a cyclic softening behavior. Therefore, a crack initiates by slip deformation and propagates straightly as a planar slip. On the other hand, hydrogen atoms formed by the reaction of aluminum with water vapor in high humidity can diffuse into the matrix by bulk diffusion and moving dislocation. Consequently, hydrogen atoms promote and still localize the slip deformation, inducing the acceleration of crack propagation in high humidity by hydrogen-enhanced localized plasticity (HELP) mechanism [4, 5]. In addition, the crack initiated by slip deformation propagates to a specified direction of <110> on (100) plane as a shear mode crack macroscopically. This can be also explained from that the crack propagation may be considered as nearly the same as the one in a single crystal because of the marked texture and the angle composed by planes of (100) and (111) is nearly 55°corresponded to the propagation direction of a shear mode crack. On the other hand, by shot peening, grains at the surface layer were largely deformed and the texture was changed. In addition, dense dislocations were introduced. The dense dislocation may form cell structures and induce the diffusion of many hydrogen atoms into the matrix. Consequently, dislocations may be pinned by hydrogen atoms and the deformation is suppressed. These suppression effects and the change in orientation in cell structure may induce the multiple slip and the changes in the directions of both the slip deformation and the crack propagation. By the change in the macroscopic direction of a crack propagation from the shear mode to the tensile one, the compressive residual stress acts to suppress the crack propagation effectively. These are main reasons for the change in macroscopic direction of crack propagation and the increase in fatigue strength by shot peening in high humidity.

Conclusions

By shot peening, large hardening and compressive residual stress were yielded, causing the increase in fatigue strength irrespective of humidity. Although fatigue strength was largely decreased by high humidity in the electro-polished specimen, the decrease was very small in the shot-peened one. That is, shot peening is effective to improve not only the fatigue strength but also the sensitivity to high humidity.

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