Enhancement of fatigue life of aluminum alloy affected by the density of pulsed electric current

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Abstract

We investigate the effect of pulsed electric current on fatigue-crack growth and the fatigue properties of aluminum alloy (A6061-T6) at current densities of 0–150 A/mm^2. The fatigue life of most of the treated specimens increases substantially when compared with that of untreated specimens. SEM imaging of the treated specimens shows local melting on the fracture surfaces. To clarify the effect of local melting on fatigue-crack propagation, we examine crack propagation utilizing the plastic replication method. We find that the delay of crack propagation is attributable to the crack-shielding effect arising from current-induced local melting.

Keywords: Fatigue strength; Aluminum alloys; Crack shield; Fatigue crack growth.

1. Introduction

The fatigue properties of mechanical components are of crucial research interest since fatigue fracture accounts for more than 80% of all mechanical failures [1]. In this regard, certain studies have used methods such as spot heating, shot peening, and conventional/laser-annealing to improve the fatigue strength of mechanical components [2-4]; however, these approaches are currently expensive. On the other hand, the application of pulsed electric current to mechanical components has been considered to be an alternative fatigue-improvement method. Kim *et al*. [5] have reported that the elongation of an aluminum alloy could be improved through joule heating induced by electric current. Further, Karpenko *et al*. [6] demonstrated that the low-cycle fatigue life of steel could be extended through pulsed electric current under fatigue loading. Conrad *et al*. [7] determined that the fatigue life of copper alloy could be increased through pulsed-electric-current application. Such improvement arises because the applied electric current induces slip homogenization and thus increases dislocation mobility in the alloy. Along similar lines, crack healing through pulsed electric current has recently been investigated for increasing the fatigue life of carbon and stainless steels. For example, Zou *et al.* [8] reported that pre-cracks in carbon steel could be partly healed through the application of pulsed electric current, while Hosoi *et al*. [9] healed cracks in austenite stainless steel using pulsed electric current. Despite such studies, the mechanisms underlying the relationship between fatigue life and pulsed electric current have not been fully understood.

In the present work, we studied the effect of pulsed electric current on the fatigue properties of aluminum alloy using the crack healing technique. Aluminum alloys are widely used for fabricating lightweight structural components in numerous engineering fields, particularly in the automobile industry [10, 11]. The proposed technique could be useful for prolonging the fatigue life of such mechanical components and structures made from aluminum alloy. In the study, we investigated the fatigue lives of aluminum-alloy A6061-T6 specimens via fatigue tests at electric current densities ranging from 0- to 150-A/mm^2. The fatigue crack behavior of the treated and untreated aluminum alloy specimens was also examined. Further, in order to analyze the fracture mechanism, we examined the fracture surfaces with scanning electron microscopy (SEM), and we quantitatively evaluated fatigue crack propagation using the plastic replication method.

2. Material and Methods

2.1 *Material and specimen configuration*

Rolled sheet of aluminum alloy (A6061-T6) was used as the experimental material. Tables 1 and 2 list the mechanical properties and chemical composition of A6061-T6, respectively. The fatigue specimens were machined to a shallow notched-dumbbell shape (Fig. 1) with thickness and width of 4.5 and 8 mm, respectively. The surface of the specimens was polished with emery paper and buffed with alumina powder to obtain a mirror plane.

2.2 *Experimental conditions and procedure*

The fatigue tests were conducted with the use of an electrohydraulic fatigue testing machine (Shimazu EHF-F1) operating at room temperature with a stress ratio (R) of −1 and frequency of 15 Hz under controlled load conditions. To investigate the effect of pulsed electric current on fatigue cracks, after the fatigue life reached 70%, electric currents were applied to the specimens at each 10% increased fatigue life ratio until failure. The fatigue life ratio is defined as

$$\text{Fatigue life ratio (\%)} = \frac{\text{Number of cycles } (N)}{\text{Nunber of cycles to failure } (N_\mathrm{f})} \times 100 \qquad (1)$$

Here, the specimens' fatigue life ratio was considered with reference to the fatigue life of an untreated specimen, and each pulsed electric current was applied to each specimen at the regular fatigue life corresponding to the calculated fatigue life ratio based on the untreated specimen. Electric currents of 60-150 A/mm^2 with a pulsing duration of 0.5 ms were supplied via a transistor-type power source (Miyachi MDA-8000B). The application conditions of electric current are shown in Table 3 in detail. Hereafter, the treated specimens are designated according to the supplied electric current as 60-, 90-, 120-, and 150-A/mm^2 specimens, and the specimen without electric current treatment is referred to as the untreated specimen.

Fig. 2 shows the schematic of the fatigue test process for treated specimens. The process is as follows: a) fatigue tests were carried out with the use of a computer controller until the 70% fatigue life ratio was reached; b) direct electric currents (DC) were applied to the specimens; c) fatigue tests were carried out again, and electric currents were applied at 10% step increases of the fatigue life ratio until failure. After the fatigue tests, in order to analyze the fracture mechanism, we carried out SEM observations of the crack initiation site on the fracture and top surfaces at a stress level of 160 MPa. Fatigue crack propagation was examined with the use of the plastic replication method from 7×10^4 fatigue life cycles onward. The stress amplitude at which the fatigue life is approximately 1×10^5 cycles (i.e., a stress level of 160 MPa) was used as the stress level for the crack growth tests. Fatigue crack propagation (i.e., crack growth rate) was assessed as a function of the maximum stress-intensity factor (K_{max}), which in turn was calculated with the use of the Newman-Raju solution for a semi-elliptical crack [12, 13]. The aspect ratio was assumed as $a/c = 1$, where a represents the crack depth and $2c$ the crack length. Factor K_{max} is calculated as:

$$K_{max} = \sigma_{max}\sqrt{\pi a} \cdot \frac{1}{E(k)} \cdot F_s \quad (2)$$

Here, σ_{max} represents the maximum applied stress, a the crack depth, $E(k)$ the aspect ratio factor, and F_s the boundary correction factor.

3. Experimental results

3.1 *Fatigue properties*

Fig. 3 illustrates the relationship between alternating stress amplitude, σ and the number of cycles to failure, N_f, where the error bars indicate that the measurement results were obtained from two or three different samples. It is noted that for treated specimens, the fatigue life increases up to a current density of 90-A/mm^2 and slightly decreases thereafter. The increased fatigue life of the 90-A/mm^2 specimen is 55% higher than that of the untreated specimen, whereas for the 150-A/mm^2 specimen, the fatigue life is less than that of the untreated specimen. This reduction in fatigue life at overly high current densities is attributed to current-induced thermal damage.

3.2 *Fractographic studies*

Figs. 4-8 present the SEM images of the crack initiation sites at the fracture surface and top surface of the untreated and treated specimens. In the untreated specimen, crack initiation occurred through cyclic slip deformation at the specimen surface (Fig. 4). In contrast, local melting sites were observed in the treated specimens, and the area of the local melting zone increased with increasing current density (Figs. 5-8). In addition, in the SEM images of 150-A/mm^2 specimen (Fig. 8), electrical-stimulation-induced damages (i.e., small dimples) were observed. Fig. 9 shows SEM images of fracture surface observation for the specimens untreated and treated by 150-A/mm^2. The cracks can be regarded as semi-elliptical ones approximately and the crack depth can be assumed to be equal to the half of crack length.

3.3 *Behavior of fatigue crack propagation*

Fig. 10 depicts the relationship between the surface crack length and the number of cycles, wherein the arrows indicate the cycle at which the specimen was subjected to pulsed electric current. Only one specimen was measured for each current condition since the scatter is significantly small. Fatigue cracks were initiated on the surface of the specimens and propagated horizontally perpendicular to the direction of the applied load. In the 60- and 90-A/mm^2 specimens, fatigue crack growth was delayed after the application of pulsed electric current. This effect is clear when the crack length is less than those at 10×10^4 and 11×10^4 fatigue life cycles, respectively, for the 60- and 90-A/mm^2 specimens, and the effect decreases substantially when the cycle number is larger than the above values. We speculate that pulsed electric current has strong delaying effect on crack growth when the crack is in the initiation stage (for e.g., $2c < 45$ μm for the 90-A/mm^2 specimen). This effect clearly reduces when the crack propagates away from the initiation area. In contrast, in the 150-A/mm^2 specimen, the fatigue crack grew rapidly after the application of pulsed electric current. This result indicates that at overly high current densities, crack growth in the treated specimen is faster than that in the untreated specimen.

Fig. 11 depicts the crack propagation rate as a function of the maximum stress-intensity factor, K_{max}. From the figure, it is noted that for the 60-A/mm^2 specimen, the crack growth rates are slower than that in the untreated specimen, and for the 90-A/mm^2 specimen, the delaying effect of crack propagation is stronger than that for the 60-A/mm^2 specimen. On the other hand, it is observed that the delaying effect is stronger for low K_{max} values due to the relatively high density of the electric current formed at the crack tip. In contrast, for the 150-A/mm^2 specimen, the crack propagation rate is higher than that of the untreated specimen due to the current-induced thermal damage.

4. Discussion

The experimental results demonstrate that pulsed electric current influences the fatigue life of aluminum alloys (Fig. 2). Fig. 12 shows the relationship between the increased fatigue life, calculated using Eq. 3, and the applied current density obtained at the stage level of 140 MPa.

$$\text{Maximum increased fatigue life (\%)} = \frac{N_f\ \text{(Treated specimens)} - N_f\ \text{(Untreated specimen)}}{N_f\ \text{(Untreated specimen)}} \times 100 \qquad (3)$$

We observed that the fatigue life of most treated specimens was higher than that of the untreated specimen. The maximum increases in the fatigue life for the 60-, 90-, and 120-A/mm^2 specimens were 24%, 55%, and 38%, respectively. However, for the 150-A/mm^2 specimen, fatigue life decreases by 10% when compared with that of the untreated specimen because of the relatively fast crack propagation. The application of electric current with different densities leads to delay or acceleration of the crack growth rate (Fig. 11), thereby increasing or decreasing fatigue life, respectively. Here, crack propagation is considered to be affected by local melting, as illustrated in Fig. 13. Electric current concentrates [14, 15] around the fatigue crack tip (Fig. 13(a)) and thus induces joule heating [16], which induces local melting, which can either increase or reduce fatigue life. It is also considered that thermal compressive stress was induced around the crack tip, because the heated area is constrained by the surrounding unheated area [9]. This compressive stress could close the crack and obstruct the propagation of the crack. Local melting and the thermal compressive stress can form a crack shield [17, 18] (i.e., crack closure), and thus, the fatigue crack does not propagate after the application of electric current (Fig. 13(b)), thereby improving fatigue life. On the other hand, overly high current density can induce dimples around the crack tip (i.e., thermal damage) [19] (Fig. 13(c)), thereby reducing fatigue life. Our results are consistent with the behaviors reported in the literature, and we speculate that the effect of electric current is mostly effective when the crack is in the initiation stage. Our SEM images (Section 3.2) clearly show that local melting occurs at the crack initiation region. Further, fatigue crack growth is delayed significantly when the crack is in the initiation state. From these results, we speculate that crack shield or thermal damage due to local melting affects fatigue crack propagation strongly at the initiation stage. Consequently, the effect of delaying or accelerating on fatigue crack propagation leads to change in the fatigue life.

5. Conclusion

The effect of high-density pulsed electric-current on the fatigue life of aluminum alloy was examined. Especially, the mechanism to prolong fatigue life was investigated in detail based on the evaluation of crack growth and propagation rate. The results are summarized as follows:

1) Fatigue life of aluminum alloy can be prolonged by the treatment of pulsed electric current and with the optimum current density of 90- A/mm^2, the increase of fatigue life reached up to 55%.

2) It has been clarified that the pulsed electric current has the effect to delay the growth and propagation of fatigue cracks at their initiation stage and this delay effect is the key factor to prolong the fatigue life of aluminum alloy.

3) It was found that local melting occurred on the crack surface at the crack initiation zone due to joule heating induced by high-density pulsed electric-current plays an important

role to obstruct the propagation of a fatigue crack. Besides that, thermal compressive stress induced by pulsed electric current also has the effort to decrease the propagation rate of the crack.

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Figure captions

Fig. 1. Schematic of fatigue specimen.

Fig. 2. Schematic of the fatigue test process.

Fig. 3. Relationship between stress amplitude and number of cycles to failure.

Fig. 4. Scanning electron microscopy (SEM) images of the crack initiation site for the untreated specimen: (a) fracture surface, (b) top surface.

Fig. 5. Scanning electron microscopy (SEM) images of the crack initiation site for the 60-A/mm2 specimen: (a) fracture surface, (b) top surface. Arrows indicate the local melting sites.

Fig. 6. Scanning electron microscopy (SEM) images of the crack initiation site for the 90-A/mm2 specimen: (a) fracture surface, (b) top surface. Arrows indicate the local melting sites.

Fig. 7. Scanning electron microscopy (SEM) images of the crack initiation site for the 120-A/mm2 specimen: (a) fracture surface, (b) top surface. Arrows indicate the local melting sites.

Fig. 8. Scanning electron microscopy (SEM) images of the crack initiation site for the 150-A/mm2 specimen: (a) fracture surface, (b) top surface. Arrows indicate the local melting sites.

Fig. 9. Scanning electron microscopy (SEM) images of fracture surfaces: (a) untreated specimen (b) 150-A/mm^2 specimen.

.Fig. 10. Relationship between surface crack length and number of cycles.

Fig. 11. Crack propagation rate as a function of maximum stress-intensity factor.

Fig. 12. Increased fatigue life of treated specimens as function of applied electric current (σ = 140 MPa).

Fig. 13. Schematics depicting the influence of electric current on crack tip at the initiation stage

of fatigue cracks: (a) concentration of electric current; (b) crack shield under optimal current densities; (c) thermal damage under overly high current densities.

Table captions

Table 1 Mechanical properties of A6061-T6.

Table 2 Chemical composition of A6061-T6 (wt%).

Table 3 Application conditions of electric current.