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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.

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, Zhou 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

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Table 1
Mechanical properties of A6061-T6.

0.2% proof stress $\sigma_{0.2}$ (MPa)	Tensile strength σ_B (MPa)	Elongation δ (%)	Vickers hardness *HV*
292	325	12	102

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

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.66	0.30	0.30	0.06	1.00	0.17	0.02	0.021	Bal.

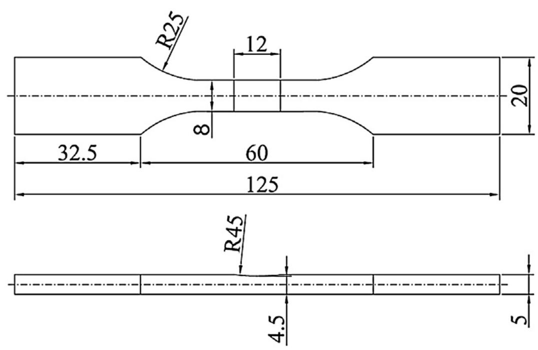

Fig. 1. Schematic of fatigue specimen.

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

$$\text{Fatigue life ratio } (\%) = \frac{\text{Number of cycles } (N)}{\text{Number of cycles to failure } (N_f)} \times 100 \quad (1)$$

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:

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

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

Table 3
Application conditions of electric current.

	Group A	Group B	Group C	Group D	Group E
Current density (A/mm^2)	None	60	90	120	150
Pulse duration (ms)		0.5	0.5	0.5	0.5
Electric energy density (kJ/mm^2)		0.5	1.1	1.9	2.9