Low-cycle fatigue properties of ultrafine-grained zinc–22 wt.% aluminum alloy during
room-temperature superplastic flow

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Abstract

Low-cycle fatigue behavior during room-temperature superplastic flow was investigated for ultrafine-grained Zn–22 wt.% Al alloy. This alloy exhibited a longer fatigue life and a lower crack propagation rate than other materials at high strain amplitudes above $\pm 5\%$. In addition, many cavities and secondary cracks were observed near the tips of cracks. These are probably responsible for the apparent reduction in the crack propagation rate and the long fatigue lifetime of this alloy.

Keywords: Low cycle fatigue; Superplasticity; J-integral; Crack propagation rate; Zn–22Al alloy

Isolators and seismic dampers have received considerable attention because of their ability to ensure a secure and safe living space during earthquakes [1,2]. A seismic damper absorbs the energy of an earthquake by undergoing plastic deformation and thus protects the main structure of a construction during a tremor. Such dampers are exposed to compression–tension deformation with a strain amplitude of at least $\pm 3\%$ and a strain rate of the order of $>10^{-3} \text{ s}^{-1}$ during earthquake shaking. In general, low-yield-point steel has been used as a damping material because of its low yield stress of about 100 MPa and its relative high ductility of about 50% [3]. However, it is necessary to perform maintenance on seismic dampers following every major earthquake, because the rise in yield stress caused by work hardening, as shown in Ref. [3], increases the resistance of the damper to deformation under the originally designed load. The yield stress of low-yield-point steel is expected to increase from 125 to 180 MPa after a large earthquake. For this reason, we examined the characteristics of superplastic Zn–22 wt.% Al alloy, which exhibits almost the same yield stress as low-yield-stress steel at a strain rate of $1.0 \times 10^{-2} \text{ s}^{-1}$ (100 MPa), has a high ductility of more than 60% and shows no work hardening

[3]. We recently reported that ultrafine-grained Zn–22 wt.% Al alloy produced by an equal-channel angular extrusion (ECAE) process exhibits a high elongation of about 250%, even at room temperature, and a high strain rate of 10^{-2} s^{-1} [4,5]. These values suggest that the alloy could be used in seismic dampers [3,6–8]. Because of its sufficient ductility, a seismic damper made of Zn–22 wt.% Al alloy would not fail as a result of tensile stress during initial cyclic deformation, but would, instead, fail as a result of low-cycle fatigue (LCF) due to repeated plastic strain. Although the LCF properties of this alloy need to be assessed in order to improve its reliability, there were no reports of such an assessment having been made. In a previous report [9], we describe our investigations of the fatigue lifetime and a fracture appearance of Zn–22 wt.% Al alloy. However, the fatigue crack-propagation behavior of this alloy, which is an important characteristic in terms of LCF, has not been investigated in detail. We have therefore investigated fatigue crack-propagation properties for ultrafine-grained Zn–22 wt.% Al alloy during LCF in the superplastic region.

The material used in the present study was an extruded Zn–22 wt.% Al alloy. Because reducing the grain size increases the superplastic strain rate and/or decreases the superplastic temperature [10,11], the Zn–22 wt.% Al alloy was subjected to ECAE to impart room-temperature superplasticity. ECAE was carried out at 333 K for up to eight passes with a

90° angled channel using route Bc. The specimen was removed from the die and then rotated by +90° in a constant direction between each pass [12]. After eight passes, an almost equiaxial microstructure consisting of Zn-rich and Al-rich phases was established, and the average grain size was approximately 0.5 μm . LCF tests for this study had to be carried out in the superplastic region. Figure 1 shows the deformation mechanism map for Zn–22 wt.% Al alloy at 303 K: the deformation conditions at a strain rate of $1.0 \times 10^{-3} \text{ s}^{-1}$ are within the superplastic region. We therefore conducted our LCF tests at a strain rate of $1.0 \times 10^{-3} \text{ s}^{-1}$.

Figure 1. Deformation mechanism map for Zn–22 wt.% Al alloy at 303 K.

LCF tests were performed by means of an automatically controlled tensile-testing machine.

The specimens used in the LCF tests were cylindrical, with a diameter of 6 mm and a length of

6 mm in the gage section, in common with previous work [9]. To avoid local deformation and stress concentration induced at the contact points between extensometer probes and surface of the specimen, a noncontact displacement measurement system was used in these strain-controlled fatigue tests. The strain amplitude was measured from the length between the shoulders of the specimen by using a light-emitting diode/charge-coupled device optical micrometer (LS-7030 produced by Keyence Corporation). Because the alloy is intended for use as a seismic damper, LCF tests at high strain amplitudes of ± 5 and $\pm 10\%$ were carried out at room temperature. The fatigue life was defined as the number of cycles corresponding to a 25% reduction in the maximum tensile load.

Strain amplitudes at which previously reported tests on LCF have been conducted were below about $\pm 4\%$ [13–16]. In this study, however, it was possible to conduct cyclic tests at high strain amplitudes above $\pm 5\%$, where no LCF behavior has been previously reported. According to the earlier reports [17,18], the relationship between plastic strain range and the number of cycles to failure follows the Coffin–Manson equation:

$$\Delta \varepsilon_p N_f^m = \theta \quad (1)$$

where $\Delta \varepsilon_p$ is the plastic strain range, N_f is the fatigue life, m is the fatigue ductility exponent and θ is the fatigue ductility coefficient. The relationship between the plastic strain range and the

number of cycles to failure for this alloy is represented in Figure 2. The Zn–22 wt.% Al alloy exhibited a sufficiently long LCF lifetime of more than 100 cycles, even at high strain amplitudes of about $\pm 5\%$. For comparison, data for carbon steel [15], high-strength steel [15] and Ti alloy [15] are also included in the graph in Figure 2. The data for high-strength steel and Ti alloy deviate from linearity. It is known that the apparent fatigue lifetime is reduced because the local true strain near a surface crack is larger than the macroscopic strain as a result of significant localization of plastic deformation in the short strain range [19]. Because of the absence of experimental data, it is impossible to provide a direct comparison between Zn–22 wt.% Al alloy and steels, but it is likely that the Zn–22 wt.% Al alloy tested in the superplastic region has a much longer fatigue life than the other materials.

Figure 2. Relationship between plastic strain range and number of cycles to failure.

In a previous report [9], it was shown that specimens fracture through propagation of surface cracks formed during cyclic deformation. Since propagation of a crack severely affects the fatigue lifetime, fatigue crack-propagation characteristics were investigated for Zn–22 wt.% Al alloy during superplastic flow. In LCF, the crack propagation rate of a surface small crack, da/dn , is generally analyzed in terms of the cyclic J -integral range, ΔJ . In this study, ΔJ was estimated by reference to the values given by Dowling [20], Raju and Newman [21] and Hatanaka et al. [22,23]. For uniaxial loading of smooth specimens with small, semicircular surface cracks, Dowling [20] calculated ΔJ as the sum of the elastic component, ΔJ_e , and the plastic component, ΔJ_p :

$$\Delta J = \Delta J_e + \Delta J_p \quad (2)$$

ΔJ_e and ΔJ_p were expressed as follows [22]:

$$\Delta J_e = 2\pi\Delta W_e a \left(\frac{M_k}{\phi(\lambda)} \right)^2 \quad (3)$$

$$\Delta J_p = 2\pi f(n)\Delta W_p a \left(\frac{M_k}{\phi(\lambda)} \right)^2 \quad (4)$$

where a is the crack length, M_k is the modification coefficient given by the Raju–Newman analysis [21], λ is the aspect ratio of semicircular cracks and n is the work-hardening exponent obtained from cyclic stress–strain hysteresis loops. In addition, the elastic strain energy density, ΔW_e , the plastic strain energy density, ΔW_p , the complete elliptic integral of the second kind, $\phi(\lambda)$, and $f(n)$ were represented as follows [22]:

$$\Delta W_e = 2^{1-2n} \frac{B}{E} (\Delta \varepsilon_p)^{2n} \quad (5)$$

$$\Delta W_p = 2^{1-2n} \frac{B}{1+n} (\Delta \varepsilon_p)^{1+n} \quad (6)$$

$$\phi(\lambda) = \int_0^{\frac{\pi}{2}} (\cos^2 \xi + \lambda^2 \sin^2 \xi)^{\frac{1}{2}} d\xi \quad (7)$$

$$f(n) = \frac{(n+1)}{2\pi} \left\{ \frac{3.85(1-n)}{\sqrt{n}} + \pi n \right\} \quad (8)$$

where B is the material constant obtained from a cyclic stress–strain curve according to the following equation [22]:

$$\Delta \sigma = 2B \left(\frac{\Delta \varepsilon_p}{2} \right)^n \quad (9)$$

where $\Delta \sigma$ is the stress amplitude. From Eqs. (2)–(9), ΔJ in this study was calculated by using the values of B , n and λ obtained from the experimental data. Figure 3 shows the relationship between the crack propagation rate and ΔJ , where the crack length is assumed to equal the depth

of the largest surface crack observed by a color laser microscope (VK-9500, Keyence Corporation). For comparison, data for carbon steel [15], high-strength steel [15] and Ti alloy [15], calculated by the same method, are included in the plot. Figure 3 suggests that the fatigue crack propagation rate for this alloy was almost same as that of the other alloys in the relatively low J-integral range of about 2.0×10^{-2} MPa m, whereas it was considerably reduced in the high J-integral range of about 5.0×10^{-1} MPa m, i.e. the fatigue crack-propagation exponent for this alloy is lower than that of the other alloys. The fatigue crack-propagation line for Zn-22 wt.% Al alloy during superplastic flow can be represented by the following equation:

$$da/dN = 5.5 \times 10^{-5} (\Delta J)^{1.0} \quad (10)$$

Although the lower fatigue crack-propagation exponent of 1.0 is probably a result of the longer fatigue lifetime of this alloy, as shown in Figure 2, the crack propagation exponent is lower than that generally suggested in earlier reports [14,15]. The reduction in the crack propagation exponent may be to the result of a particular characteristic of superplasticity. To check this, the area adjacent to a crack tip of a deformed specimen was examined by scanning electron microscopy. Figure 4 is a micrograph taken near a crack tip. Many small cavities and crack branches can be seen near the crack tip. In addition, the presence of cavity formation and the linkage of cavities aligned perpendicular to the cyclic direction were verified from the surface

appearance. In a previous report [24], we describe our investigations of the cavity-nucleation mechanism for Zn–22 wt.% Al alloy during superplastic deformation by using the analyses of Chokshi et al. [25], Raj et al. [26] and Chan et al. [27]. The analytical results under the conditions that were used in that study showed that cavities could be nucleated at the grain boundary/ledge junction when $\beta > 0.2 \mu\text{m}$ and $h > 4.5 \text{ nm}$, where β is the inter-ledge separation distance and h is the height of the ledges. Because the initial grain size of $0.5 \mu\text{m}$ is larger than the calculated values of β and h , evidence of cavity formation (Fig. 4) was also demonstrated theoretically. In general, we consider that during superplastic flow, a stress concentration generated by grain-boundary sliding is actively relaxed by diffusional flow and dislocation annihilation in order to continue the plastic deformation; therefore, many cavities are initiated when the relaxation process is inadequate [28–31]. In brief, a stress that cannot be relaxed by the relaxation process appears to be relaxed by cavity formation. Likewise, in the discipline of fracture, Fu et al. [32] and Evans et al. [33] have reported that a crack tip stress is relaxed by a microcracked process zone (the shielding effect), resulting in an enhancement of fracture toughness. In addition, Hatanaka et al. [34] and Ogawa et al. [35] have investigated fatigue crack-propagation characteristics for Ti–6Al–4V alloy, and have reported that secondary cracks lead to a reduction in the propagation rate of fatigue cracks. According to Ogawa et al. [35], the

crack-propagation rate for a specimen with secondary cracks is lower than for a specimen with no secondary cracks in the ΔK range above about $30 \text{ MPa}\sqrt{\text{m}}$. By substituting the ΔK value into the equation given by Ref. [36], the corresponding ΔJ was found to be about $8.0 \times 10^{-3} \text{ MPa m}$. This value agreed with the critical ΔJ value seen in Figure 3, where the critical ΔJ value is defined to be equal to the ΔJ value for both previous reports and in this study. Consequently, we suggest that during LCF in the superplastic region, crack branching and many cavities formed around a crack tip relax the crack-tip stress field, leading to a reduction in the propagation rate of fatigue cracks. In addition, this phenomenon appears to make possible cyclic deformation at high strain amplitude, and results in the longer fatigue lifetime, as shown in Figure 2. However, the effect of stress relaxation by cavity formation and/or crack branching on the propagation rates of fatigue cracks cannot be discussed quantitatively on the basis of the current study, and more experimental work is needed to clarify this important point.

In conclusion, the crack-propagation properties for ultrafine-grained Zn–22 wt.% Al alloy during LCF in superplastic region were investigated and compared with the corresponding results for several other materials. With the Zn–22 wt.% Al alloy, it was possible to conduct LCF tests even at high strain amplitudes of more than $\pm 5\%$, and the alloy appeared to exhibit a longer LCF lifetime than the other materials examined. The rate of fatigue crack propagation in

this alloy was lower than that in other materials in the high J-integral range. In addition, the formation of cavities and crack branching were observed around a crack tip. We therefore conclude that the formation of cavities and secondary cracks as a result of the relaxation of stress concentration around the crack tip results in a reduction in the rate of fatigue crack propagation and results in a longer fatigue lifetime.

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Figure 3. The relationship between the crack propagation rate and ΔJ .

Figure 4. Micrograph of the region adjacent to the crack tip of a Zn–22 wt.% Al alloy sample tested in the superplastic region.

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