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Effect of initial twins on the stress-controlled fatigue behavior of rolled magnesium alloy

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ABSTRACT

The effect of initial twins on the fatigue behavior of rolled AZ31 alloy was investigated by introducing {10–12} twins into the alloy through pre-deformation and then conducting fully reversed stress-controlled fatigue tests along the rolling direction (RD) and the direction normal to the rolling plane (ND). It was found that the fatigue life of the alloy is higher under RD loading than under ND loading, but when initial twins exist, the fatigue resistance along the RD decreases, whereas the ND fatigue resistance increases, eventually reversing the fatigue resistance behavior under the ND and RD loading conditions. The tensile mean strain generated under ND loading is also changed to compressive strain by initial twins, whereas the reverse is true under RD loading. The fatigue strength of samples with and without twins is inversely proportional to the logarithm of their plastic strain energy density, which corresponds to the inner area of the hysteresis loop at half-life, irrespective of the loading direction.

1. Introduction

Magnesium alloys have recently received attention in the electronics and transportation industries owing to their low density and high specific strength. To improve the weight loss effect, the application of wrought Mg alloys, which have much higher mechanical properties than cast Mg alloys, is being gradually extended, particularly in the automotive, train, and aircraft industries. As most structural parts and vehicle components are subjected to repeated loading or vibration under service conditions [1], it is necessary to evaluate and understand the fatigue properties of wrought Mg alloys before they are used as structural components.

The fatigue behavior of rolled Mg alloys under strain-controlled [2–5] and stress-controlled [6–8] fatigue test conditions has been widely investigated, and twinning has been found to play an important role in the cyclic stress–strain responses and fatigue properties. As rolled Mg alloys usually have a strong basal texture, with most of the basal planes of the crystal grains aligned parallel to the rolling plane, their plastic deformation behavior under tension and compression exhibits significant anisotropy due to a difference in the dominant deformation mechanisms (i.e., slip and twinning) [9,10]. This in turn leads to asymmetric hysteresis loops during cyclic deformation that are distorted in the twinning-induced region. In addition, the directional nature of deformation twinning results in anisotropic fatigue resistance depending on the loading direction relative to the crystallographic orientation of rolled Mg alloys [5–8]. Fully reversed strain-controlled fatigue tests of rolled AZ31 alloy revealed that when specimens are loaded parallel to the rolling direction (RD), {10–12} twinning is easily activated in compression, whereas when they are loaded normal to the rolled plane (ND), twinning causes them to yield easily in tension [5,11]. This loading-direction-dependent anisotropy causes superior fatigue resistance in ND specimens by introducing beneficial compressive mean stress, in contrast to the detrimental tensile mean stress in the RD specimen. On the other hand, under fully reversed stress-controlled fatigue test conditions, the fatigue resistance is higher in the RD specimen than in the ND specimen because the twinning stress in tension of the ND specimen is lower than that in compression of the RD specimen, and this increases the fatigue damage due to the larger plastic strain in the ND specimen [8].

Initial {10–12} extension twins are also known to strongly affect the cyclic deformation behavior and fatigue properties of rolled Mg alloys by modifying the {10–12} twinning–detwinning characteristics during cyclic deformation [12–15]. Initial {10–12} twins formed in an RD specimen cause variation in the active plastic deformation mechanisms during cyclic deformation and thus reduce the developed mean stress, which ultimately results in improved fatigue resistance [13,14]. In contrast, initial twins introduced into ND specimens lead to a significant decrease in compressive flow stress during cyclic loading, causing an increase in the mean stress and eventually degrading the fatigue resistance [15]. However, all of these studies showing the influence of initial {10–12} twins focus on the fatigue properties under strain-controlled fatigue tests. Strain-controlled fatigue tests are gen-

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erally conducted to analyze fatigue behavior in a low-cycle region (number of cycles N 10^4) [16]. However, most vehicle components are subjected to cyclic loading for quite long periods of more than 10 years, so it is necessary to evaluate and understand their high-cycle fatigue properties ($N > 10^4$) and fatigue strength (or fatigue limit), which are typically measured using stress-controlled fatigue tests. Although the high-cycle fatigue characteristics of various rolled Mg alloys have been extensively studied [7,8,17,18], the effect of initial twins on the high-cycle fatigue properties has not been investigated despite the fact that {10–12} twins can easily occur during the manufacturing processes of rolled materials (rolling, leveling, coiling, etc.) or the sheet-forming processes for making final products (deep drawing, stretching, bending, etc.). Furthermore, given that the fatigue behavior of rolled Mg alloys is obviously different in low- and high-cycle fatigue test modes [5,8], the influence of initially existing twins on the high-cycle fatigue properties and its loading direction dependence should be investigated to understand the fatigue characteristics of rolled Mg alloy products that will be used under multiaxial or complex stress state conditions for a long period of time. This study therefore investigates the effects of initial {10–12} twins on the cyclic stress–strain response and fatigue strength of rolled AZ31 Mg alloy by introducing twins into ND and RD specimens through pre-deformation and then conducting fully reversed stress-controlled uniaxial tension–compression fatigue tests.

2. Experimental procedures

The material used in this study was a commercial hot-rolled AZ31 alloy plate with a thickness of 50 mm and a chemical composition of 3.6Al–1.0Zn–0.5Mn (wt%), which was homogenized at 400 °C for 4 h. This homogenized alloy had a twin-free equiaxed grain structure with an average grain size of ~30 µm (Fig. 1a). Two types of specimens with cylindrical axes oriented parallel to the ND or the RD were used and are hereafter denoted as ND and RD, respectively (Fig. 1a). To introduce {10–12} twins into the samples, relatively large dog-bone-shaped specimens (gauge section: ⌀12 mm×23 mm) were first machined from the homogenized plate (Fig. 1b), and then 5% tension and 5% compression were applied to the ND and RD specimens, respectively. These pre-deformed samples are hereafter denoted as pre-tensioned ND (or ND with twins) and pre-compressed RD (or RD with twins), respectively. To examine the textural evolution by twinning, the X-ray diffraction method was applied to the cross-sectional area of the undeformed and pre-deformed ND and RD specimens.

The pre-deformed ND and RD specimens were remachined to tensile specimens (gauge section: ⌀6 mm×25 mm) and fatigue specimens with a continuous radius between the grip ends and a minimum diameter at the center of 5 mm (Fig. 1b). Tensile tests were conducted at room temperature using an INSTRON 8501 universal testing machine at a strain rate of 10^{-3} s^{-1}. Stress-controlled fatigue tests were performed in air at room temperature using a servo-hydraulic axial testing machine (INSTRON 8801) with a 25 Hz sine wave and a stress ratio of −1 (i.e., a fully reversed axial tension–compression fatigue test). At stress amplitudes with a finite fatigue life, two or three samples were tested for each condition, and three samples were tested under stress amplitude conditions with a fatigue limit. The fatigue strength (i.e., fatigue limit) was defined as the stress amplitude at which the specimen does not fail in a range of 2×10^6–1.5×10^7 cycles. Before the tests, the fatigue specimens were mechanically polished using progressively finer grades of emery papers and then buff-finished to obtain a smooth surface. Additional stress-controlled fatigue tests were also conducted at a frequency of 1 Hz and stress amplitude of 95 MPa with an extensometer attached to each specimen in order to measure the stress–strain response during cyclic loading.

3. Results and discussion

The cross-sectional microstructures of the pre-deformed ND and RD samples (Fig. 2) clearly show that a considerable quantity of twins is formed in both samples. It is well known that {10–12} twinning, which is the primary twin system in Mg, can be active under two loading conditions: tension parallel to the *c*-axis of the hexagonal close-packed lattice and compression perpendicular to the *c*-axis [19]. As rolled Mg alloys generally have a strong basal texture in which most of the basal planes are aligned parallel to the rolling plane, {10–12} twins can be easily generated under both tension along the ND and compression along the RD [20], as shown in Fig. 2. The twin morphology, however, differs considerably; in the pre-compressed RD sample, twins developed in a grain are almost parallel to each other (bright bands in a grain, Fig. 2b), whereas the twin morphology in the pre-tensioned ND sample (dark bands in a grain, Fig. 2a) is more complicated, showing different orientations and intersections between twins. This is attributed to activation of different twin variants depending on the loading conditions [20,21]. For compression along the RD, generally one twin variant or a twin variant pair with the highest Schmid factor is active in a grain, causing a parallel twin structure. For tension along the ND, on the other hand, all six twin variants have nearly equal possibilities of activation, leading to an intersection between twin bands. In addition, the area fraction of the twinned region is smaller in the pre-tensioned ND sample (31.1%) than in the pre-compressed RD sample (55.1%) because growth of twins is suppressed by their intersection [22].

The (0002) pole figures obtained from cross-sections of the samples show that the *c*-axes of the grains are oriented parallel to the loading

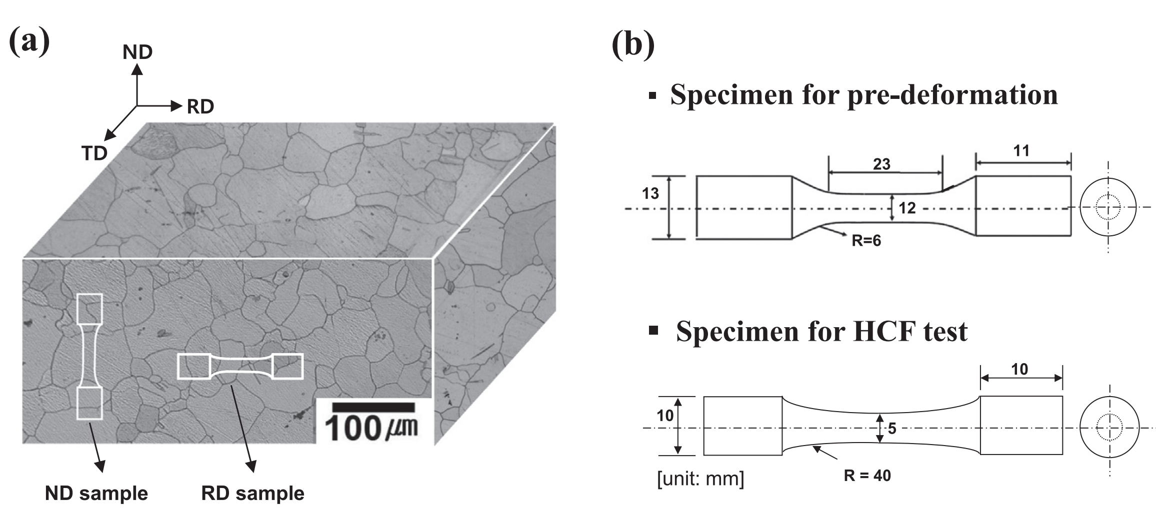

Fig. 1. (a) Three-dimensional microstructure of rolled AZ31 Mg alloy and (b) dimensions of samples used for pre-deformation and fatigue tests.