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Influence of loading direction on the anisotropic fatigue properties of rolled magnesium alloy

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ABSTRACT

The influence of loading direction on the fatigue behavior of rolled AZ31 alloy was investigated by conducting fully reversed stress-controlled fatigue tests along the rolling direction and normal to the rolling plane. Alternating twinning and detwinning behavior during initial cycling was found to cause asymmetric hysteresis loops, resulting in a compressive strain in the rolling direction and a tensile strain normal to the rolling plane. A transition in the dominant deformation mechanism from twinning–detwinning to slip occurs at around five cycles under both conditions due to cyclic hardening, thus making their loops symmetric. The lower twinning stress in tension along the normal direction leads to an increase in fatigue damage by plastic strain, resulting in a lower fatigue resistance than along the rolling direction.

1. Introduction

Environmental concerns over global warming and CO_2 emissions have seen an increase in the popularity of using magnesium in the automotive industry, as the low density and high specific strength of these alloys provide a means of reducing weight and fuel consumption in automobiles. Wrought alloys subjected to forming processes such as extrusion, rolling and forging generally provide superior mechanical properties to cast alloys [1], which has recently led to an increase in their use in exterior automotive components such as roofs and wheels, as well as interior parts such as door inner panels and luggage retainers. As all vehicle components are usually subjected to cyclic loading or vibration under service conditions, their fatigue properties need to be systematically investigated for safety reasons [2].

It is widely known that wrought Mg alloys prepared by conventional processing methods (e.g., extrusion and rolling) without the addition of texture-modifying alloying elements (e.g., Ce, Gd and Ca) usually have a strong basal texture, with most basal planes being aligned parallel to the rolling plane or extrusion direction. The directional nature of deformation twinning in such alloys gives them outstanding anisotropic deformation behavior under monotonic tension and compression at room temperature, which in turn results in strong asymmetrical hysteresis loops that are distorted in the twinning-induced region during cyclic deformation [3–5]. It has also been recently reported that wrought Mg alloys exhibit anisotropic fatigue resistance depending on the direction of loading relative to their crystallographic orientation [6–10]. Sajuri et al. [6] have investigated the stress-controlled fatigue properties of an extruded AZ61 alloy plate by subjecting it to cyclic loading along the extrusion direction (ED), transverse direction (TD), and 45° to the ED (45), through which it was found that the fatigue strength is highest along the ED. Meanwhile, Lv et al. [7,8] have reported that the fatigue life of a rolled AZ31 alloy sheet along the TD is greater than that along the rolling direction (RD) under both stress- and strain-controlled cyclic loading. Through strain-controlled fatigue tests of extruded AM30 alloy, Jordon et al. [9] have also demonstrated that loading along the ED results in a reduced low-cycle fatigue life, but a higher high-cycle fatigue life, when compared to loading along the TD.

This past research has tended to focus on the in-plane anisotropy of fatigue behavior in wrought Mg alloys; i.e., all of the applied loading directions were parallel to the processing plane. They have therefore overlooked the fact that deformation behavior along the normal direction (ND) to the processing plane is significantly different to that along the RD (or ED), and that this in turn can give rise to anisotropic fatigue behavior between the ND and

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RD. Indeed, there have been only a very limited number of studies into the difference in fatigue properties between the out-of-plane direction (i.e., ND) and in-plane directions (i.e., ED, RD, TD and 45) of wrought Mg alloys [11–13]. Hong et al. [11] carried out strain-controlled fatigue tests using rolled AZ31 alloy plate and found that fatigue resistance along the ND is superior to that along the RD under uniaxial tension–compression deformation, but the fatigue behavior under stress-controlled conditions was not examined. Meanwhile, Ishihara et al. [12] conducted stress-controlled fatigue tests using an extruded AZ31 alloy plate and reported that the fatigue life along the ND at high stress amplitudes is shorter than that along the ED and TD, but found the fatigue strength to be almost identical under rotating bending fatigue test conditions.

Automobiles on roads, trains on railroads, aircraft in the sky, and ships at sea are all typically subjected to repeated multiaxial loading and are therefore in danger of fatigue failure. For fail-safe fatigue design of components subject to complex stress states in use, it is essential to understand the fatigue properties of materials under uniaxial stress conditions with different loading directions. This is particularly crucial in the case of wrought Mg alloys with an intense texture and anisotropic deformation characteristics. Despite this, there has been no investigation into the anisotropy of fatigue deformation behavior between ND and RD under stress-controlled uniaxial tension–compression conditions. Given the limitations of previous studies, stress-controlled fatigue tests were conducted along the ND and RD of a rolled AZ31 Mg alloy plate under uniaxial tension–compression modes to investigate the anisotropy in its fatigue properties. The cyclic stress–strain response is herein discussed in relation to active plastic deformation mechanisms such as $\{10\bar{1}2\}$ twinning, detwinning, and the evolution of slip with an increasing number of cycles.

2. Experimental procedure

The material used in this study was a 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. As described in a previous report [14], this homogenized alloy had a twin-free equiaxed grain structure with an average grain size of ~30 μm, and exhibited an intense basal texture in which most basal planes were aligned parallel to the rolling plane.

In order to investigate the loading direction dependency, two kinds of specimens were machined from the homogenized plate with cylindrical axes oriented parallel to the ND and RD, which are hereafter denoted as ND and RD, respectively (Fig. 1a). From the (0002) pole figures obtained from cross-sections of both samples using X-ray diffraction, it can be seen that the *c*-axes of the grains are oriented parallel to the loading direction in the ND sample, but are perpendicularly aligned in the RD sample (Fig. 1b).

Tensile and compressive tests were conducted at room temperature using an INSTRON 8501 universal testing machine with a strain rate of $10^{-3}\,s^{-1}$. Dog-bone-shaped (gauge section: ∅6 mm × 25 mm) and cylindrical (∅10 mm × 12 mm) specimens were used for tension and compression, respectively. All tensile test specimens were prepared according to ASTM E-8 standard.

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) in a stress amplitude range of 75–120 MPa. Fatigue specimens with a continuous radius between the grip ends and minimum diameter at the center of 5 mm were used (Fig. 1a). Prior to the testing, these were progressively polished using abrasive papers with mesh of #800, #1500, and #2400, and then buff-finished to obtain a smooth surface. Additional fatigue tests were also conducted at a frequency of 1 Hz and stress amplitude of 95 MPa with an extensometer attached to each specimen to measure the stress–strain response during cyclic loading. The similar fatigue lives at 1 and 25 Hz confirm that a difference in frequency has a negligible effect on the fatigue properties.

3. Results and discussion

3.1. Deformation behavior

The tensile and compressive stress–strain curves in Fig. 2 (and associated data in Table 1) show that the tensile yield strength is much lower than the compressive yield strength in the case of the ND sample, but the reverse is true of the RD sample. This asymmetric feature has been previously attributed to a difference in deformation mechanism with varying sample orientation (i.e., ND or RD) and whether the loading is in tension or compression [15,16]. It is also well known that $\{10\bar{1}2\}$ extrusion twins, which along with basal slip are a dominant room temperature deformation mechanism in Mg alloys, can be activated when tensile stress is applied parallel to the *c*-axis of the hexagonal close-packed unit cell, or if compressive stress is applied perpendicular to the *c*-axis [17]. As a result, $\{10\bar{1}2\}$ twinning is easily activated under tension of a ND sample and compression of a RD sample, resulting in a low yield strength and strain hardening during the early stage of deformation, which is a typical feature of twinning-dominated deformation [14,15]. In contrast, the compressive curve of the ND sample and tensile curve of the RD sample exhibits high yield strength and a subsequent low strain hardening until fracture due to deformation by slip.

3.2. Fatigue behavior

The stress life curves in Fig. 3 reveal that the fatigue strength of the RD and ND samples at 2×10^6 cycles are 90 and 75 MPa, respectively, with the fatigue life of the RD sample also greater than that of the ND sample in the low-cycle regime. This indicates that rolled Mg alloy exhibits anisotropic fatigue properties depending on its loading direction, and that its fatigue resistance is improved when cyclic loading is applied along the RD rather than ND. It is also notable that all the stress amplitudes range from 75 to 120 MPa, including the fatigue strengths, and are higher than the yield strengths caused by twinning presented in Table 1 (56 MPa tensile yield strength (TYS) and 66 MPa compressive yield strength (CYS) for the ND and RD samples, respectively). This means that $\{10\bar{1}2\}$ twinning is activated in all cyclic loading conditions of both samples, and that plastic deformation by twinning generates even under loading conditions that are around the fatigue strength. From this, it can be expected that twinning behavior during cyclic deformation plays an important role in determining the cyclic stress–strain responses and resultant fatigue properties of both samples. In order to better understand this twinning-related deformation and its relationship to fatigue life, the stress–strain evolution at a stress amplitude of 95 MPa (i.e., immediately above the 90 MPa fatigue strength of the RD sample) was investigated in both sample types.

Fig. 4a and b shows the hysteresis loops obtained with a stress amplitude of 95 MPa up until the initial 1 and 5/4 cycles with the ND and RD samples, respectively. Note that in the case of the ND sample, a relatively large plastic deformation (a strain of ~2.9%, Fig. 4a) is generated during the first tensile loading by $\{10\bar{1}2\}$ twinning due to its low critical resolved shear stress causing a low yield point and strain hardening. Once the tensile stress reaches 95 MPa, however, the load is reversed to compression and deformation is predominantly caused by detwinning. As a