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Effects of pre-tension on fatigue behavior of rolled magnesium alloy

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ABSTRACT

The effects of pre-tension on the fatigue properties of a rolled Mg-3Al-1Zn (AZ31) alloy were investigated by imposing 2%, 5%, and 10% tensile strains along the rolling direction before low-cycle fatigue tests. The investigation showed that the applied pre-tension increased the dislocation density and introduced a small number of twins into the material. Although the as-rolled sample and all the pre-tensioned samples exhibited asymmetric hysteresis loops owing to the alternation of twinning and detwinning during each cycle, the tensile and compressive peak stresses increased with an increase in the amount of pre-tension during the first cycle. With an increase in the number of cycles, however, the flow stress, mean stress, plastic strain energy density, and hysteresis loop of the samples became similar irrespective of the amount of pre-tension, which is attributed to cyclic strain softening or hardening behavior depending on the initial dislocation density. Despite the relatively large pre-deformation, the pre-tensioned samples exhibited a fatigue life equivalent to that of the as-rolled sample because of an early extinction of the difference in the cyclic stress-strain response caused by pre-tension. This result demonstrates that the pre-tension process can improve the yield strength of rolled Mg alloys without a loss of their low-cycle fatigue resistance.

1. Introduction

Rolled Mg alloys have recently gained considerable attention from the transportation industry because their density is lower than that of other structural metals (e.g., steels and aluminum alloys) and strength is higher than that of cast Mg alloys with casting defects (e.g., inclusions and porosities). Normal rolled Mg alloys, which are fabricated without both the addition of rare earth elements and application of severe plastic deformation processes, generally possess a strong basal texture with most of the basal planes of the crystal grains aligned parallel to the rolling plane. As there are only two independent slip systems for basal slip in Mg alloys when deformed at room temperature, deformation twinning plays an important role in the deformation of Mg alloys by helping to satisfy the von Mises criterion [1], which requires five independent deformation systems for achieving homogeneous deformation. The combination of the preferred crystallographic orientation of the material and the polar nature of the twinning mechanism induces anisotropic deformation behavior in rolled Mg alloys not only under monotonic plastic deformation such as tension and compression but also under cyclic fatigue deformation [2,3]. The fatigue behavior of rolled Mg alloys has been widely investigated from various viewpoints such as the influence of the loading direction (i.e., the sample orientation or texture) [3–6], fatigue test conditions (e.g., the strain- or stress-controlled mode and applied strain/stress amplitude ranges) [6–8], and initial {10–12} twins [9–11].

It has recently been reported that pre-deformation can significantly affect the cyclic stress-strain response and fatigue resistance of rolled Mg alloys. In a rolled Mg alloy with an intense basal texture, {10–12} twins can be easily generated under compression along the rolling direction (RD) or tension along the normal direction (ND) to the rolling plane, because primary {10–12} twinning is activated when the c-axis of the hexagonal close-packed (HCP) lattice is extended [12,13]. Accordingly, pre-compression along the RD and pre-tension along the ND cause the introduction of {10–12} twins into the material. In addition, unlike steels and aluminum alloys, in which dislocation slip is the main deformation mechanism under both tension and compression, rolled Mg alloys have a non-zero mean stress during cyclic loading owing to the activation of both twinning and slip [3,14,15]. Previous

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studies [9,10] have revealed that the pre-compression of rolled AZ31 alloy along the RD prior to fatigue tests reduces the tensile mean stress generated during cyclic deformation along the RD by accommodating the tensile deformation through detwinning of initial {10–12} twins. Since the tensile mean stress degrades the fatigue resistance by accelerating the crack opening and increasing the accumulation of fatigue damage, the decreased mean stress consequently improves the fatigue resistance of the rolled alloy under strain-controlled fatigue tests. Conversely, a pre-tension along the ND shortens the out-of-plane fatigue life of the material by increasing the mean stress [11]. Although these studies demonstrate the outstanding influence of plastic deformation (carried out prior to fatigue tests) on the fatigue properties of rolled alloys, they focused on the role of {10–12} twins formed by pre-deformation on the cyclic twinning–detwinning behavior and resultant fatigue life of the alloy. Despite the fact that the stress-strain behavior can vary significantly with numerous dislocations generated by pre-deformation, the effect of pre-deformation on fatigue properties with respect to the increased dislocation density has not yet been investigated. In addition, since rolled sheets can be easily subjected to pre-tension along the in-plane directions during the manufacturing or post-forming processes such as coiling and press forming, the effect of pre-tension along the directions parallel to the rolling plane on fatigue properties should be investigated for determining the reliability of the final products. In this study, therefore, pre-tension was applied to a rolled Mg alloy along the RD in order to induce strain hardening by dislocation slip, and then, the evolution of the cyclic stress-strain response and fatigue life at different amounts of pre-tension were investigated under fully reversed strain-controlled fatigue tests along the RD.

2. Experimental procedure

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%). The alloy plate was homogenized at 400 °C for 4 h. This homogenized alloy had an equiaxed grain structure with an average grain size of ~30 µm (Fig. 1a). To impose pre-tension on the samples, relatively large dog-bone-shaped specimens (gauge section: ϕ12 mm×30 mm) were first machined from the homogenized plate (Fig. 1b). The cylindrical axis of these specimens was parallel to the RD. Once these specimens were pre-tensioned to the strain values of 2%, 5%, and 10%, they were remachined to cylindrical compressive (ϕ6 mm×9 mm) and dog-bone-shaped fatigue specimens (gauge section: ϕ5 mm×10 mm) (Fig. 1b). The as-rolled and 2%, 5%, and 10% pre-tensioned samples will be hereafter referred to as AR, 2PT, 5PT, and 10PT samples, respectively.

The microstructural characteristics of the AR and 10PT samples were analyzed using an electron backscatter diffraction (EBSD) instrument installed on an SU-6600 field emission scanning electron microscope. For the EBSD examination, the sample surface was ground on 2400 grit silicon carbide paper and polished using a 1 µm diamond paste, which was followed by a final polish with colloidal silica for 40 min. The EBSD data were analyzed using Tex-SEM Laboratories orientation imaging microscopy (TSL OIM) analysis software; the data with a confidence index greater than 0.1 were used for the twin, texture, and grain orientation spread (GOS) analyses.

Compression tests were conducted at room temperature by using an Instron 8501 universal testing machine at a strain rate of 10^{-3} s^{-1}. Low-cycle fatigue tests were performed in air at room temperature by using a servo-hydraulic axial testing machine (Instron 8801) at the total strain amplitudes of 0.5% and 1% and a frequency of 1 Hz under a fully reversed condition (i.e., at a strain ratio of −1). Before the tests, the fatigue samples were mechanically polished using progressively finer grades of emery paper and then buff-finished to obtain a smooth surface. Additional fatigue tests were also carried out on 3%, 6%, and 8% pre-tensioned samples at a total strain amplitude of 1% in order to clearly investigate the effect of pre-tension on the fatigue life of the material.

3. Results and discussion

3.1. Microstructural characteristics of pre-tensioned material

The EBSD analysis results of the AR (pre-tension of 0%) and 10PT (pre-tension of 10%) samples are shown in Fig. 2; the results show that the AR sample had a twin-free structure with a strong basal texture (Figs. 2a, b, and d), whereas the 10PT sample contained three types of twins: the {10–12} extension twin, {10–11} contraction twin, and {10–11}-{10–12} double twin (Figs. 2e and f). Although most grains are favorably oriented for {10–11} contraction twinning under a tension along the RD, the {10–11} twins are generally activated in later stages of deformation with high stress levels owing to the high critical resolved shear stress of the {10–11} twinning system [16]. In addition, since a {10–11} twinning dislocation is less mobile than a {10–12} twinning dislocation because of the narrower core width [2], the {10–11} twins are typically thin and straight in shape owing to the restriction of the twin boundary motion, and they thus occupy a small volume fraction. Further, {10–12} twinning can occur inside the {10–11} twins because the crystallographic orientation of the {10–11} twins is favorable for {10–12} twinning. As a result, most of the {10–11} twins are partially or completely changed to the {10–11}-{10–12} double twins, as shown in Fig. 2f. Moreover, it can be seen that a few

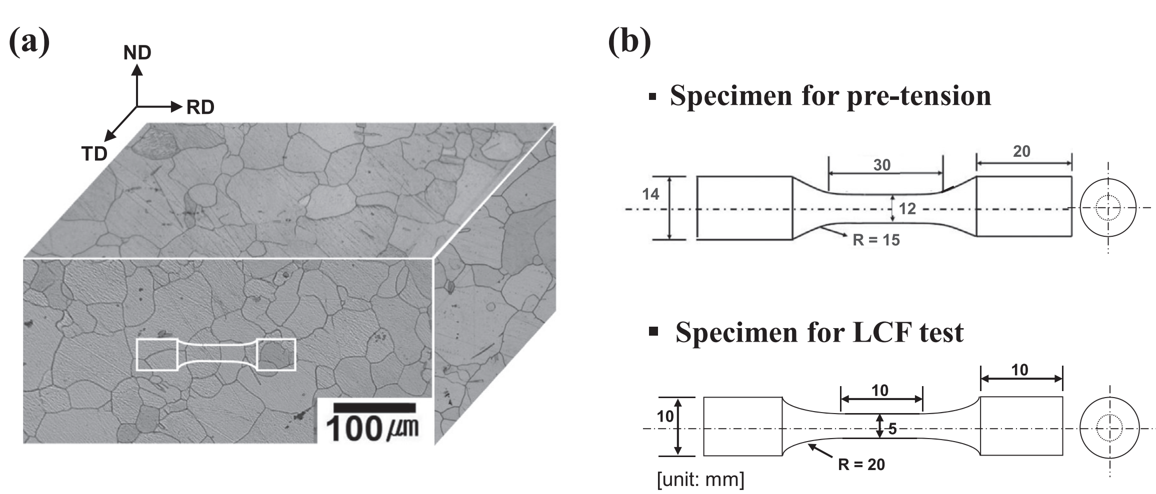

Fig. 1. (a) Three-dimensional microstructure of rolled AZ31 Mg alloy and (b) dimensions of samples used for pre-tension and fatigue tests.