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Multiaxial behaviour of wrought magnesium alloys – A review and suitability of energy-based fatigue life model

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ABSTRACT

Different wrought magnesium alloys from AM, AZ, and ZK family in the form of extrusion, rolled sheet and rolled plate have been selected for this study. Monotonic and cyclic behaviours are presented and compared. In particular, multi axial behaviours under proportional and non-proportional loadings are discussed. Despite the differences between the investigated alloys, it has been found that these alloys exhibit similar monotonic and cyclic characteristics. The similarity is attributed to the limited slip system in HCP magnesium, and the dominant role of deformation twinning in causing yield and hardening asymmetry. With strain energy density merit as a suitable fatigue parameter, it is therefore hypothesized that a simple two-parameter energy-based fatigue model is capable of correlating fatigue life of wrought magnesium alloys irrespective of material process, loading conditions and loading orientations. The hypothesis is then tested over a large number of fatigue results (354 tests). It is shown that fatigue lives predicted using the energy-life model are in good agreement with experimental results. Such simple model may prove to be useful in the early design stages lightweight components out of magnesium alloys.

1. Introduction

Energy crises and environmental concerns have led to strict transportation laws asking for aggressive reduction in fuel consumption and pollutant gas emission. The demand on fuel-economic vehicles has forced transportation industry to boost light-weighting research and seriously consider its applications. Owing to its high specific strength and excellent machinability, magnesium alloys have recently been in the front and center of structural lightweight research. Cyclic loading is the prime loading of vehicles structural body and suspension parts. In particular these loads have a multiaxial nature and hence study of multiaxial behaviour of Mg alloys is of significant importance.

The predominant manufacturing method for magnesium is casting. Many researchers have studied fatigue of cast magnesium alloys, mainly AZ91 and AM60. Research focused on high cycle fatigue behaviour of these alloys has demonstrated that fatigue cracks initiate at porosities [1–3], and that crack initiation life is primarily controlled by pore size [2,4]. Lu et al. [3] and Horstemeyer et al. [4] reported that fatigue crack initiation occurs below the surface. The fatigue crack propagation path in AM60B depends on the local microstructure and casting defects. Fatigue cracks grow through α-magnesium dendrites under low porosity conditions, and through interdendritic regions under high porosity conditions [3]. El Kadiri et al. [5] investigated crack propagation mechanisms in AM50 cast alloy and found that fatigue cracks initially propagate along the interface of α-magnesium dendrites and at the aluminum-rich boundary. Cracks then coalesce into a small, main fatigue crack that advances interdendritically. In the long crack regime, the crack advances in a mixed transdendritic–interdendritic mode.

However, due to their low strength and ductility, cast alloys are not yet good candidates for load-bearing structural components. Wrought alloys have shown superior strength and ductility when compared to cast alloys [6,7]. Extrusion, rolled sheet and plates, and warm-forge are the material processes producing wrought alloys [8]. Fatigue behaviour of these alloys has in the past decade been of interested of many research centers. The focus of research, among others, has been on fatigue crack initiation, crack propagation, process induced anisotropy and asymmetry, uniaxial cyclic behaviour under push–pull and shear strains, and multiaxial loading.

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AZ31B is the most common wrought magnesium alloy in the industry. The AZ31B magnesium sheet, similar to other wrought magnesium alloys, has a strong texture [9,10], which results in different modes of deformation under in-plane tension and compression. Cyclic in-plane loading causes twinning and de-twinning deformation in the two consecutive reversals. Twin deformation accumulated during compressive loading is not fully recovered in subsequent tension reversals [11]. Therefore, the AZ31B sheet exhibits cyclic hardening during compression, and cyclic softening during the tension reversal [11,12]. An unusual asymmetric shape of the hysteresis loop is the key feature of the cyclic behaviour of wrought magnesium alloys, which is more pronounced at high strain amplitudes. The strain-life curve shows a kink at the strain amplitude above which hardening behaviour is asymmetric in tension and compression reversals [13,14]. AZ31B has superior fatigue strength in the transverse direction, as compared with the rolling direction, under both stress- and strain-control conditions [12]. Fatigue crack initiation occurs in the transgranular mode, while crack growth occurs in the intergranular mode [15].

Although hardening behaviour of AZ31B for strain-controlled cyclic axial loading tests is asymmetric, stress-control loading produces symmetric hysteresis [16]. Refining grain size in extruded AZ31 alloys makes the asymmetry less pronounced under monotonic and cyclic axial loading [17,18]. Grain size refinement also improves fatigue strength, especially in the high cycle regime [19]. Extruded AZ31B exhibits cyclic hardening behaviour due to residual twins accumulated during cycling [20]. Unlike cast magnesium alloys, Masing behaviour is not observed in extruded magnesium alloys due to the strong tension–compression asymmetry [21]. The S–N curve for extruded AZ31B has a sharp bend [19,22,23]. Twin bands are the preferable locations for the initiation of fatigue cracks in extruded AZ31 [24]. Ishihara et al. [25] reported that fatigue crack initiation life is negligible compared to the total life, and fatigue life can be reasonably estimated by a fracture mechanics approach. Twinning is the predominant mechanism of plastic deformation at high plastic strain amplitude whereas slip prevails at low plastic strain amplitude [7]. Lin and Chen [26] reported that the Bauschinger effect in extruded AZ31 is more pronounced at high strain amplitudes.

There have been few comprehensive multiaxial studies of wrought magnesium alloys. The study on AZ31B extrusion by Albinmousa et al. [27–29] and on AZ61A extrusion by Zhang et al. [30] that discusses the effect of multi-axiality on fatigue behaviour of wrought alloys are among the most comprehensive multiaxial studies. In this paper, the results of these works are compared with other multiaxial work on Mg alloys. First, the asymmetry possess by wrought alloys is reviewed and causes are discussed. Then multiaxial loading behaviour is reviewed and results for different wrought alloys are compared. A two-parameter energy-based fatigue model is then proposed. It is shown that a large number of fatigue results for Mg wrought alloys can be correlated through the proposed model.

2. Microstructure

Three types of wrought magnesium are considered in this review: extrusion, sheet and rolled plate. Chemical compositions and microstructural characteristics of the considered alloys are listed in Tables 1 and 2. It is seen from Table 2 that grain size varies depending on the manufacturing process. The effect of grain size on the mechanical behaviour of magnesium alloys have been investigated by many researchers. Koike et al. [31] did monotonic tensile tests on fine-grained AZ31B extrusion with an average grain size of 6.5 ± 0.4 μm and found substantial non-basal slip activities at 2% strain. Uematsu et al. [19] studied the effect of extrusion conditions on grain refinement and fatigue behaviour of several magnesium extrusions. For AZ31B, experiments by Uematsu et al. showed that grain size decreases with decreasing working temperature. They were able to achieve grain size of 2.1 μm at extrusion rates of 67 and outlet temperatures of 625°K. Fatigue strength improvement was found to be associated with smaller grain size, especially in the high cycle regime. The fatigue strengths at 10^7 cycles for the samples with grain sizes of 7.2 and 2.1 μm were 90 and 130 MPa, respectively. Like Uematsu et al. [19], Chino et al. [32] observed the same relation between extrusion temperature and grain size. In addition, they found that monotonic tension–compression anisotropy became less pronounced with fine-grained samples compared to other samples with larger grain sizes. Zhu et al. [18] performed cyclic tension–compression tests on ultrafine-grained AZ31 extrusion with an average grain size of 5.6 μm and compared it with a conventional one that had an average grain size of 30 μm. Comparisons of the cyclic behaviour showed that, while conventional extrusion exhibits stress–strain asymmetry and cyclic hardening, the ultrafine-grained extrusion exhibits symmetric stress–strain behaviour and cyclic softening.

3. Monotonic behaviour

Monotonic tension, compression and torsion stress–strain curves are compared for several alloys, including, AZ31 [33], AZ31B [28,34], AM30 [35], AM60 [36], AZ61A [30] and ZK60 [37]. Stress–strain curves for different orientations are presented. Definition of orientations is shown in Fig. 1.

Monotonic axial behaviours, tension and compression, of different magnesium extrusion at different orientations are compared in Fig. 2. Considering the tensile curves for extrusion direction in Fig. 2a it can be seen that the post-yielding behaviour of AM30 [35], AM60 [36], AZ31B [34], AZ61A [30] and ZK60 [37] appears to be of a power-law nature. The post-yielding behaviour of AZ31 [33] and AZ31B [28] is plateau. Conversely, the tensile behaviour for AZ31B along normal direction [28] is distinctly different compared to other tensile as it shows concave upward post-yielding behaviour. It should be noted that 45° specimens [28] were machined in the ED-ND plane.

Monotonic compressive stress–strain curves of AZ31B [28,34,38], AZ61A [30] and ZK60 [37] are compared in Fig. 2b. It is seen from this figure the three alloys exhibit concave upward post-yielding behaviour when loaded along the extrusion or transverse directions. Such unusual behaviour is commonly attributed to twinning deformation activated due to loading orientation with respect to the texture. The compressive responses for AZ31B along the 45° and normal directions show different behaviours compared to other curves. Their post-yielding behaviour is concave downward.

Monotonic tensile and compressive behaviours for AZ31 [33] and AZ31B [39,40] magnesium rolling at different orientations are compared in Fig. 3a and b. Stress–strain curves were plotted in two graphs to better show the difference.

Fig. 3a shows that the post-yielding behaviour of the tensile curves is of a power-law nature while the compressive curves exhibit sigmoidal-type behaviour with concave upward characteristics due to deformation twinning. On the other hand, the tensile and compressive behaviours for both transverse and normal directions are different as shown in Fig. 3b. This figure shows that tensile loading along the normal direction results in sigmoidal-type behaviour similar to that observed in compression. In contrast, compressive loading along the normal direction results in usual concave downward behaviour. Similarly, tensile loading along the transverse direction results in concave downward behaviour.