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Rate and temperature dependent deformation behavior of as-cast WE43 magnesium-rare earth alloy manufactured by direct-chill casting

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ABSTRACT

In this work, we study the deformation behavior of a direct chill cast WE43 Mg alloy. This material initially has equiaxed grains approximately 40 µm in diameter and a random texture. The room temperature, quasi-static response exhibits little plastic anisotropy when evaluated parallel to and normal to the solidification direction and no initial yield tension-compression asymmetry. The deformation at room temperature is accompanied by significant basal texture development and formation of three types of deformation twins: $\{10\bar{1}2\}\langle\bar{1}011\rangle$, $\{10\bar{1}1\}\langle10\bar{1}\bar{2}\rangle$, and $\{11\bar{2}1\}\langle\bar{1}\bar{1}26\rangle$ as well as double twins $\{10\bar{1}1\}\langle10\bar{1}\bar{2}\rangle$-$\{10\bar{1}2\}\langle\bar{1}011\rangle$, although each in small amounts < 10% up to failure. We find that in the elevated 250 °C ± 20 °C regime, the material exhibits a negative strain rate sensitivity, with a decreasing flow stress as the strain rate increases. In most of the high-temperature, 250 °C to 350 °C, and high-strain-rate, 0.01/s to 10/s, tests, the material failed at moderate compression strains, 0.35–0.45. Subsequent fracture analyses find that the material fractures transgranularly by a typical shear fracture, often with the presence of additional arrested cracks. At elevated temperatures and under strain rates sufficiently low (i.e., 275 °C and 0.01/s, 300 °C and 0.1/s, 350 °C and 1/s, 375 °C and 10/s) or at a temperature of 400 °C deformation conditions, the material exhibited pseudo-super plastic behavior, experiencing relatively high deformation strains (> 1.0 true strain) without fracturing.

1. Introduction

WE43 is a magnesium alloy that has shown an attractive set of properties, including high strength, creep resistance, corrosion resistance, and ignition and flame resistance [1–5]. Along with its intrinsic lightweightness, this alloy has potential for use as medical implants and body armor [1,2]. Properties, such as strength, toughness, and formability (ability to shape into parts without cracking) depend critically on its underlying microstructure, such as grain size and texture. A better understanding of the relationship of these properties to its microstructure would help to increase the use of this alloy in a broader set of structural applications.

WE43 has a hexagonal close packed (hcp) structure [6–8]. For most metals with an hcp structure, such as Ti [9,10], Be [11], Zr [12], and other low-symmetry structures [13–19] structural properties are anisotropic, that is, they depend on the directionality of the applied stress or strain, including the sense of loading (tension versus compression) relative to the material microstructure [20–25]. Generally low anisotropy is desired for formability and product design [26–32]. Unlike many Mg alloys that have been studied, WE43 is known for its low plastic anisotropy and tension-compression (T-C) asymmetry for a given loading direction [6–8]. This desirable behavior has been attributed to similar critical resistances to slip among the three main hcp slip modes in Mg alloys, basal < **a** >, prismatic < **a** >, and pyramidal < **c** + **a** > slip, and a low propensity to deformation twin [26,33]. As a matter of reference, for pure Mg at room temperature, basal slip is the easiest followed by prismatic slip, which is usually several times harder than basal slip and pyramidal slip several times harder than prismatic slip [34,35]. Pure Mg also deforms readily by $\{10\bar{1}2\}\langle\bar{1}011\rangle$ (**c**-axis) extension twinning and $\{10\bar{1}1\}$ $\langle10\bar{1}\bar{2}\rangle$ (**c**-axis) contraction twinning and $\{10\bar{1}1\}\langle10\bar{1}\bar{2}\rangle$-$\{10\bar{1}2\}\langle\bar{1}011\rangle$ double twinning in suitably oriented grains [36–41]. At the same time, pure Mg exhibits outstandingly high plastic anisotropy and T-C asymmetry, making it difficult to form without cracking at room temperature. Other Mg alloys exhibit similar traits, such as AZ31 and ZK60 and Mg-4Li [42–48]. Consequently, WE43, with its reduced plastic anisotropy and other attributes, such as corrosion

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resistance and low flammability, compared to Mg and other Mg alloys, has become one of the more promising lightweight Mg alloys for structural applications [1,2].

The outstanding WE43 properties studied to date are typically not of the as-cast material and derive from samples that have undergone a particular mechanical and thermal processing history [3,49,50]. Many key microstructural features of the material that govern material strength, such as grain size, grain shape, precipitates, and initial texture, can depend on the details of the pre-processing steps prior to mechanical testing. These include mechanical deformation and/or thermal treatment. The former mechanical step, such as rolling, helps to refine the grain size and homogenize the as-cast microstructure. Rolling causes the grains to reorient crystallographically, altering the initial texture of the material to a typical rolling texture. For WE43, like many other Mg alloys, the rolling texture orients the **c**-axes of most grains near the normal direction (ND) of the rolled plate [51,52]. The deformation process can also elongate the grains in the rolling direction (RD) and increase the stored dislocation density [53–57].

The latter thermal treatment step is also particularly critical as WE43 is an age-hardenable alloy [6–8,58]. The alloying elements Y and Gd,with aging treatment, can form precipitates in the Mg grain interiors and grain boundaries [58,59]. These precipitates can strengthen the material by acting as obstacles to dislocation motion [59,60]. Generally two types of precipitates form, globular and plate-like, and both contribute to strengthening the material [58,61,62]. Most common heat treatments, after pre-deformation, are the T5 and T6 conditions; the T5 condition refers to a heat treatment for 48 h at 205 °C and the T6 condition usually to a solution-treatment at 536 °C for 24 h and then aging step at 205 °C for 48 h [58]. The T5 temper leaves the material with a small amount of RE-rich precipitates [61,62]. For the rolled, and T5 temper WE43 material studied in [6], precipitates came in two forms, globular and plate-like, and in 0.2–0.9% and 0.2% volume fraction respectively. Polycrystal modeling has suggested that the latter precipitates are particularly important in increasing the strains to failure of WE43, since they tend to hinder basal slip more so than prismatic slip, and thereby help reduce the differences in their slip resistances relative to pure Mg [6,59].

The casting process can play a role in the distribution of the alloying elements prior to the aging step, and thus, can affect the size, shape, and number density of the precipitates for the same aging treatment. Most casting processes used are sand casting, permanent mode cast, and gravity casting. Recently direct-chill (CD) casting method was reported, which uses a faster cooling rate than these previous techniques [58]. As a result, the hcp Mg matrix becomes supersaturated with a higher solubility of Nd and Y elements than via other casting methods.

The DC provides a different microstructure from other casting methods, one that is higher quality and promises direct machinability of parts. The DC produces a fine-grained structure without the need for a pre-deformation step and subsequent heat treatment. Recently, Jiang et al. [58] studied via SEM and TEM the grain microstructure and precipitate content of DC as-cast WE43, prior to any thermal treatment has been analyzed. They report that the DC WE43 material is comprised of hcp Mg with intermetallic face-centered cubic (fcc) $Mg_{14}Nd_2$ phases lying within the grains and at the grain boundaries. In addition, they performed a few mechanical tests. The room temperature tensile yield varied from 132 MPa to 150 MPa as the grain size ranged from 80 µm to 60 µm from the center to the edge of the 500 mm diameter ingot. The elongation to failure increased as well with strength, from ~ 4% to 6%. Deformation in other directions and in compression, temperatures and strain rates, and their connection with the evolving texture and twinning were not analyzed in this work.

The tensile results for as-cast DC WE43 are lower than those reported recently for the DC WE43 material that had been subsequently rolled and T5-tempered, which are 180 MPa in the RD and 195 MPa in the TD [8]. The differences in grain structure, initial texture, and precipitate arrangements possessed by the DC WE43 and the same material

Table 1
Tested samples of DC WE43 under simple compression along the SD. The "dashed" symbol means the test was not carried out. Every test was repeated at least three times and the results were within 3% difference. We use * in the case of the room temperature tests at quasi static rates (RT, 0.001/s) to indicate that other samples directions were tested in compression (PSD and NSD) and also in tension. "To fracture" means that the test was carried out to sample failure and "not to fracture" means that the test was interrupted prior to sample failure, because it did not fail and the deformation went beyond a strain of 1.0.

	0.001/s	0.01/s	0.1/s	1/s	10/s
RT	to fracture*	–	–	–	–
250 °C	–	to fracture	to fracture	to fracture	to fracture
275 °C	–	not to fracture	to fracture	to fracture	–
300 °C	–	not to fracture	not to fracture	to fracture	to fracture
325 °C	–	–	–	to fracture	–
350 °C	–	not to fracture	not to fracture	not to fracture	to fracture
375 °C	–	–	–	–	not to fracture
400 °C	–	not to fracture	not to fracture	not to fracture	not to fracture

with a heat treatment could lead to a distinctly different deformation response. Less plastic anisotropy can be expected than prior WE43 material with an initial texture. The larger grain size may give way to more twinning. The lack of plate-like prismatic plane precipitates could likely lead to different amounts of basal, prismatic, and pyramidal slip activated. Considering its high microstructural quality and its potential to be directly machined into parts without need of subsequent processing, the plastic anisotropy, any T-C asymmetry, and twinnability of the DC WE43 would be of interest.

In this work, we assess the mechanical properties of DC WE43 at a range of elevated temperatures (up to 400 °C) and moderately high strain rates (up to 10/s). We evaluate the initial microstructure and assess its plastic anisotropy and T-C asymmetry in the solidification direction and normal to it. It bears a notably homogenized microstructure, in texture and grain size, and equiaxed grain shapes. This leads to a low T-C asymmetry. For any given strain rate, as the deformation temperature increased from room temperature to 400 °C, the material strength reduced. Despite this, the material does deform by two types of extension twins and a compression twin at room temperature, more so than reported by other WE43 microstructures with the T5 temper tested before, each in small amounts less than 10% volume fraction and altogether less than 20% twin boundary fraction at high strain levels. The material exhibited a strong sensitivity to strain rate and temperature, most interestingly exhibiting a window of elevated temperature and strain rate in which the material deformed plastically in compression to very large strains, exceeding 1.0. Because of its stark contrast in microstructure of the DC WE43 with the same DC WE43 but in the rolled and T5 condition, we discuss the possible reasons for differences in their mechanical behavior.

2. Material and experiments

2.1. Material

The material studied here is direct chill (DC) cast WE43 in the as-cast condition. All mechanical test samples evaluated in this work originated from the same DC WE43 ingot. As mentioned, the WE43-T5 material studied in prior work [8] started with this same WE43-DC material but had a subsequent hot rolling step followed by a thermal treatment corresponding to the T5 condition.