Materials Science & Engineering A 726 (2018) 194–207

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Deformation and fracture mechanisms in WE43 magnesium-rare earth alloy fabricated by direct-chill casting and rolling

Mohammad Jahedi[a], Brandon A. McWilliams[b], Marko Knezevic[a,*]

[a] Department of Mechanical Engineering, University of New Hampshire, 33 Academic Way, Kingsbury Hall, W119, Durham, NH 03824, USA
[b] Weapons and Materials Research Directorate, US Army Research Laboratory, Aberdeen Proving Ground, MD 21005, USA

ARTICLE INFO

Keywords:
Rare earth magnesium alloys
Microstructure
Crystallographic texture
Fractography

ABSTRACT

This paper examines deformation behavior of WE43 alloy in direct-chill as-cast (as-cast-WE43) and rolled heat-treated T6 (WE43-T6) conditions with an emphasis on fracture mechanisms. Unlike many Mg allows, as-cast-WE43 and WE43-T6 exhibit no tension/compression asymmetry in their yield stress. WE43-T6 material shows more anisotropy in yield stress than as-cast-WE43, which is attributed to their respected initial crystallographic textures. Both WE43-T6 and as-cast-WE43 exhibit some anisotropy in strain hardening due to texture evolution and deformation twinning. Both materials show a small elongation to fracture of approximately 6% in tension. In contrast, strain to fracture in compression is large. Crystallographic texture evolves substantially in compression, where crystals are slowly reorienting their crystallographic **c**-axis parallel to the loading direction with plastic strain. Both materials fracture by a typical shear fracture in compression. Fractographic analysis of fractured surfaces in compression for WE43-T6 reveals evidence of transgranular facets that are much larger than grain size with minor content of microvoid coalescence. Although elongation to fracture in tension is small with no necking, detailed analysis of fracture surfaces reveals evidence of ductile microvoid coalescence. However, the intergranular fracture character, especially in the central high stress triaxiality region of the samples, limits the ductility of the material.

1. Introduction

As the lightest metallic materials, magnesium alloys have been receiving increasing attention because of potential for their use in automotive and aerospace applications [1–3]. To accelerate the adoption of magnesium alloys as structural materials allowing for the weight reduction of products, properties of these alloys are being enhanced by improving their alloy composition. WE series of alloys is recognized as very successful due to remarkable age hardening characteristics and retention of strength at elevated temperatures [4,5]. Amongst the WE series alloys, WE43 alloys exhibits good castability, strength, creep resistance, corrosion resistance, and ignition and flame resistance [6–10].

Poor ductility of Mg alloys at room temperature is attributed to difficulties in activating slip systems on multiple crystallographic planes such as basal, prismatic, and pyramidal for accommodating an arbitrary imposed plastic strain. Stress necessary to move a dislocation at room temperature for these various slip planes can differ significantly for Mg alloys and as a result prefered texture induces significant plastic anisotropy [11–15]. Moreover, Mg alloys deform by multiple twinning modes. Hexagonal close-packed (HCP) structure of Mg has a c/a ratio of 1.624 [16]. Resistance to slip on basal planes $\{0001\}\langle\bar{1}\bar{1}20\rangle$ is low in its magnitude [17]. Resistance to slip on prismatic planes is higher $\{\bar{1}100\}\langle\bar{1}\bar{1}20\rangle$, while pyramidal slip $\{\bar{1}101\}\langle\bar{1}\bar{1}20\rangle$ is hard in Mg [11,18–20]. The latter slip mode occurs in combination of the 1st $\{10\bar{1}1\}\langle11\bar{2}\bar{3}\rangle$ or type I and the 2nd $\{\bar{1}\bar{1}22\}\langle11\bar{2}3\rangle$ or type II pyramidal slip [21–25]. A **c**-axis extension $\{10\bar{1}2\}\langle\bar{1}011\rangle$ twin and a **c**-axis contraction $\{10\bar{1}1\}\langle10\bar{1}\bar{2}\rangle$ twin are commonly observed in Mg. Additionally, extension twins form within the contraction twin lamella leading to double-twins [26,27]. Specific to WE43, another **c**-axis extension $\{11\bar{2}1\}\langle\bar{1}\bar{1}26\rangle$ twin often activates [28].

These twins play an important role in deformation and failure behavior of Mg alloys especially at room temperature. For example, the very high strain hardening rates in many Mg alloys like AZ31 result from abundant extension twinning, which reorient crystal orientation to be suitable for the activation of the hard pyramidal slip modes [29–31]. In many studies [32–34], the formation of double twins has been correlated to void and crack formation and flow localization in the vicinity of its boundaries. This correlation has been rationalized to arise due to substantial crystal reorientations associated with the double-

* Corresponding author.
E-mail address: marko.knezevic@unh.edu (M. Knezevic).

https://doi.org/10.1016/j.msea.2018.04.090
Received 1 March 2018; Received in revised form 21 April 2018; Accepted 21 April 2018
Available online 24 April 2018

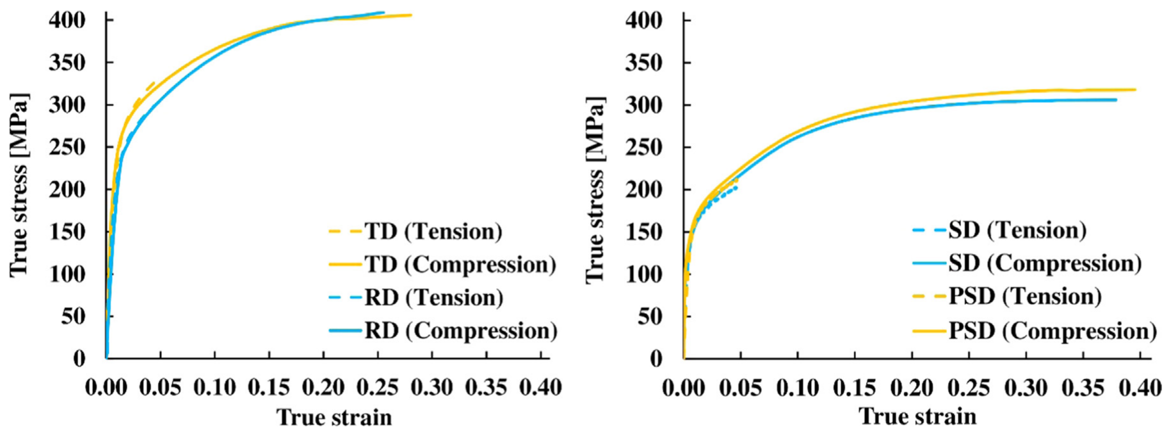

Fig. 1. True stress-true strain response in tension and compression as a function of loading direction for WE43-T6 and as-cast-WE43.

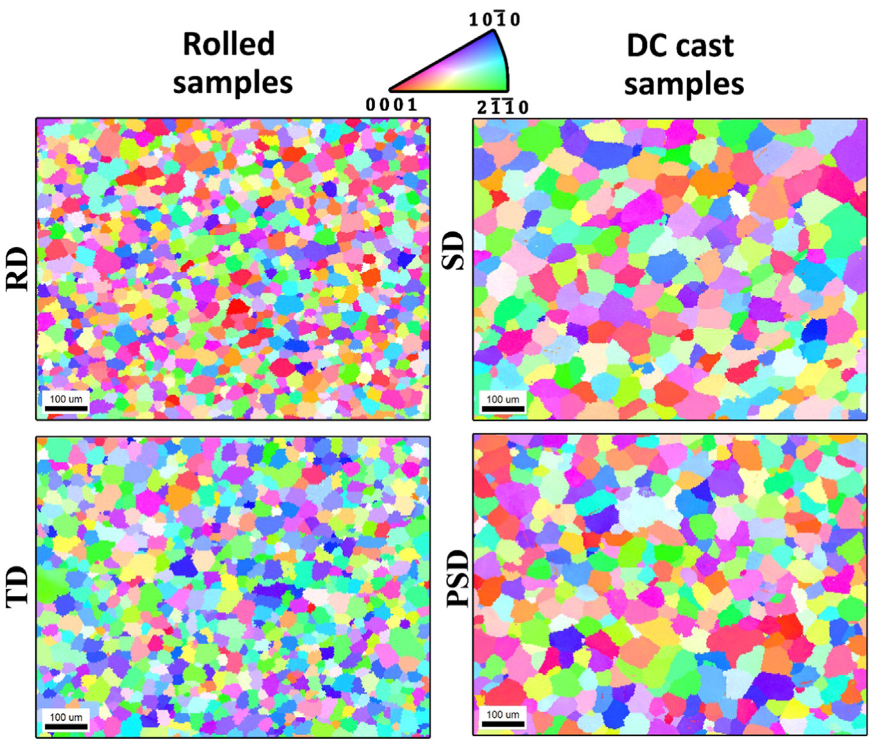

Fig. 2. Inverse pole figure maps showing initial microstructure in WE43-T6 and as-cast-WE43 samples. The sample direction perpendicular to the maps is indicated on the left of the maps: rolling direction (RD), transverse direction (TD), solidification direction (SD), and perpendicular to the solidification direction (PSD). The colors in the maps represent the orientation of the indicated sample axis with respect to the local crystal lattice frame according to the IPF triangle. The scale-bar shown in the maps is 100 µm.

twinned region and underlying shifts in active crystallographic slip modes. The twinned region of a contraction twin is much more favorably oriented for easy basal slip than the original parent crystal [35]. The intense basal slip activity that results within the thin lamella region of the double twin produces a localized shear that cannot be accommodated across the primary twin interface and ultimately leads to void formation. The effect of texture on fracture toughness of AZ31 was investigated and found that a sample with a pre-crack normal to the basal plane had a higher value of fracture toughness than a sample with a pre-crack parallel to the basal plane [36]. In addition to texture, precipitates play a significant role in fracture behavior of Mg alloys. For example, discontinuously precipitated $Mg_{17}Al_{12}$ phases decorating grain boundaries provide easy intergranular fracture sites in AZ alloys [37,38].

Rare earth (RE) containing Mg alloys have been created to increase ductility and strength while reducing the anisotropy and tension/compression asymmetry in comparison to typically used Mg alloys like AZ31 [39–42]. The underlying mechanisms responsible for these improvements are reduced rations in the activation stress for basal, prismatic, and pyramidal slip modes, reduced twinning activity, and formation of moderately strong texture. These alloys also show higher resistance to creep and corrosion [9,10,43]. WE43 containing 3.7–4.3 wt% Y, 2.4–4.4 wt% Nd, and at least 0.4 wt% Zr is an example of such alloys. The alloy is also a biodegradable material [44–46]. Moreover, it is considered as a material for armors, particularly because it has been certified as non-flammable [39]. Finally, it shows reasonably good high temperature properties retaining its strength to a temperature of 300 °C. In addition to solid solution [47,48], the strength of the alloy is achieved by precipitates formed during aging treatment, where the shape and orientation of the precipitates formed on prismatic planes effectively block basal dislocations [6–8]. The alloying elements like Y, with aging treatment, form precipitates inside grains and along grain boundaries [48,49] strengthening the material by acting as obstacles to dislocations [48,50]. Generally two types of *β'* precipitates form, globular and plate-like shapes, and both significantly contribute to strengthening the material [49,51,52]. A small addition of Zn like 0.2 wt% was found to improve elongation to fracture of the standard WE43 alloy because of the formation of an additional block-like Zn–Zr secondary phase [53]. Most common heat treatments, after hot rolling, are the T5 and T6 conditions; the T5 condition refers to a heat