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Triggering rare earth texture modification in magnesium alloys by addition of zinc and zirconium

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Abstract

Two Mg alloys, Mg–1Zn–1Ce–0.6Zr and Mg–1Zn–1Gd–0.6Zr (wt.%), were subjected to large strain hot rolling treatment, followed by annealing at different temperatures. Nucleation of recrystallization initiated inside shear bands and in the vicinity of particles, resulting in a panorama of orientations with varying stored energies. Recrystallization resulted in the evolution of new, softer orientations, in terms of slip, accompanied by significant texture weakening. On comparison with their respective binary counterparts, the quaternaries established the significant role played by the additional presence of non-rare earth (non-RE) elements (Zn, Zr) in augmenting the RE texture modification effect. Contrary to Mg–1Ce, deformation/recrystallization texture modification in Mg–1Zn–0.6Zr–1Ce was governed by a complex interplay between precipitate redissolution and segregation events. Moreover, compared to Mg–1Gd, the Mg–1Zn–0.6Zr–1Gd alloy revealed deformation/recrystallization texture transition at lower annealing temperature. Such a behavior was attributed to an increased tendency of RE–non-RE solute-pairing/clustering in the latter, thereby amplifying solute drag and magnifying selective growth events. Tensile tests conducted post-annealing revealed remarkable ductility improvement in the quaternary alloys over their binary equivalents.

Keywords: Recrystallization; Enhanced ductility; Shear banding; Rare earth elements; Texture

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1. Introduction

The improvement in the mechanical response of magnesium alloys by texture modification has been attracting researchers lately due to an unexplored potential for designing optimal textures. The deterministic factors defining a material's texture usually depend on the processing method, the initial texture and the alloy's chemistry. It should be noted here that processing encompasses the effects of crystallographic deformation mechanisms, recrystallization, grain growth and phase transformation. Although, a wide range of wrought magnesium alloy compositions and processing schemes have been explored over the years, no significant variation in the textures of conventional wrought magnesium alloys has been reported. It is imaginable that, through the use of unusual processing techniques, texture variations can be anticipated. However, in some cases, a careful choice of deformation parameters can generate more random textures in conventional Mg alloys, such as AZ31 or AM50, with positive implications for subsequent forming at ambient temperature [1].

Modifying the chemical composition of magnesium alloys with special emphasis on rare earth (RE) elements has shown numerous indications of improved properties of this class of alloys, such as grain refinement, better formability at low temperatures, and enhanced strength and creep resistance at elevated temperatures [2]. In recent years, wrought Mg–RE alloys have attracted much scientific attention since their textures have been found to be much weaker and less common than those typically observed for conventional Mg alloy sheets or extrusions. To date, texture modification in RE-containing Mg

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alloys has been associated primarily with changes in the recrystallization texture, as opposed to changes in the deformation texture [1,3–5]. The following part of the introduction will thus focus squarely on understanding the distinctions in the recrystallization mechanisms that could lead to texture modification.

In Mg alloys, the following mechanisms of recrystallization have been proposed:

(i) *Grain boundary nucleation:* Locally activated non-basal slip mechanisms in grain mantle regions near the grain boundaries (sites of intense lattice rotation) accommodate a significant amount of plastic strain, subsequently leading to nucleation of new fine grains adjacent to the original grain boundaries [6].

(ii) *Subgrain boundary migration:* The formation of recrystallization nuclei by means of subgrain boundary motion through a deformation zone is associated with the accumulation of misorientation or coalescence of subgrains, leading to the formation of high-angle boundaries [7]. Like the grain boundary nucleation mechanism, this mechanism can also be described as a “rotation” recrystallization mechanism. It requires heterogeneous deformation for the necessary orientation gradients to develop, and the new grains are considered rotated portions of the parent grains.

(iii) *Shear band nucleation (SBN):* There are a variety of shear band types that have been proposed as nucleation sites for recrystallization in magnesium. The relevant ones include kink bands, formed by basal slip in poorly oriented grains [6], and twinning-related shear banding, which takes place in regions undergoing $\{10\bar{1}1\}$ twinning [8] or $\{10\bar{1}1\}$–$\{10\bar{1}2\}$ double twinning [9]. Shear band microstructures are generally very heterogeneous and show large internal orientation spreads that can account for nucleation of grains with a wide spectrum of orientations, some of which are distinct from the typical deformation texture. SBN of recrystallization has received particular attention in Mg–RE alloys [4,5,10].

(iv) *Deformation twinning nucleation (DTN):* Acting as nucleation sites for recrystallization, deformation twins have a significant potential to modify the recrystallization texture owing to the fact that the different variants of primary and secondary twinning induce a large number of rotations associated with new orientations, relative to the deformed matrix orientation. Numerous studies have in fact documented this type of recrystallization as occurring within deformation twins and at twin–twin or twin–grain intersections [11–16]. According to some studies (e.g. [12,13]), the potency of recrystallization nucleation within twins, and thus the contribution to texture, depends largely on the twin type (extension or compression) and twin generation (primary or secondary).

(v) *Particle-stimulated nucleation (PSN):* While high densities of very small particles can pin boundaries and retard recrystallization, second phase particles larger than ~1 μm in size can actually act as nucleation sites for recrystallization [17]. PSN has been frequently reported in magnesium alloys to provide more randomly oriented nuclei, which gives rise to weaker recrystallization textures [18,19]. PSN in magnesium is always in competition with other recrystallization mechanisms. Even though its contribution to the recrystallized microstructure (in terms of volume fraction) is generally small, there can be cases where the growth of PSN grains dominates the microstructure and greatly affects the overall bulk texture, as shown in Ref. [20].

The impact of the above mechanisms on the texture in magnesium is quite different. While the first two mechanisms do not usually cause any significant alteration of the original deformation texture through the recrystallization process (nucleated grains assume the orientation of the host grain), the other listed mechanisms, (iii)–(v), are commonly associated with appreciable texture modification. More specifically, DTN and SBN can give rise to unique, new orientations of recrystallized grains that are distinct from the deformation orientation [4,14,21]. PSN, on the other hand, does not give rise to well-defined orientations. Instead, it generates new random orientations that weaken the overall texture intensity and increase the texture scatter. In contrast to Mg–RE alloys, recrystallization textures in pure Mg and its common alloys are quantitatively slightly weaker than deformation textures, though qualitatively quite similar [22,23]. The reason behind such behavior can arise due to little contribution from recrystallization mechanisms (iii)–(v), SBN in particular.

In a previous experimental study [10], the annealing textures of highly deformed binary Mg–RE alloys were investigated. It was found that the addition of RE elements is not always sufficient to impart texture changes during deformation and recrystallization, and the level of recrystallization texture modification depends strongly on the choice of the rare earth element and the annealing temperature. A significant texture change through annealing at temperatures above 300 °C was depicted by Mg–1 wt.% Gd alloy, whereas Mg–1 wt.% Ce showed negligible qualitative texture changes, thereby retaining the deformation texture with the moderate drop in texture intensity seen above 300 °C. SBN of recrystallization was found to play a critical role in generating a wide spectrum of recrystallization nuclei that displayed a selective growth behavior, giving rise to the formation of new annealing textures, as mentioned above.

Later investigations (presented in this study) revealed that the addition of non-RE elements, like Zn and Zr, can in fact impart qualitative texture changes in Mg–1 wt.% Ce alloy, rendering Ce an effective RE texture modifier. Furthermore, for the Mg–1 wt.% Gd alloy, which was