Unlocking the Strengthening Potential of Magnesium Alloys Using Deformation-Induced Clustering and Precipitation

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Keywords

Clustering • Precipitation • Deformation • ECAE •
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Extended Abstract

Light metals of Aluminum (Al) and Magnesium (Mg) hold great promise in many structural applications [1–6]. However, the overall progress in strengthening these metals has been remarkably different. While significant improvement has been achieved in developing high strength Al alloys, the anisotropic hexagonal crystal system and complex plasticity mechanisms have made the design of high strength Mg alloys a challenging exercise [7–9].

In particular, the hardness increment obtained during conventional aging is dramatically lower in Mg alloys than in Al alloys. This is due to insufficient quenched vacancies and unfavorable nucleation events in Mg alloys leading to widely spaced and elongated precipitates that offer little resistance to dislocation or twin motion [7, 10]. A closer look at several custom and commercial Mg alloys shows that while rare-earth alloys offer some promise for precipitation hardening, they remain an expensive solution with limited availability in many countries. However, redesigning stronger Mg alloys is beginning to benefit from fundamental studies on clustering and phase transformations in model binary alloys.

Our recent studies have examined two binary Mg chemistries, mainly the Mg-Al and Mg-Zn systems [11–14]. These rare-earth-free alloys offer a chance to conduct fundamental studies of precipitation mechanisms and processing pathways that can help alter the nucleation events leading to precipitate formation. We demonstrate that careful control of atomic-scale defects such as dislocations and vacancies can significantly alter the nucleation barrier, promote solute clustering far from and along dislocation lines, along twin boundaries, within twins, and along grain boundaries [13, 15, 16].

In Mg-Al alloys, there is strong evidence to show that extensive deformation using equal channel angular extrusion (ECAE) at low to moderate temperatures results in a high density of nanoscale precipitates with far lower aspect ratios than the much larger and more elongated precipitate plates produced during conventional aging [13, 15, 17, 18]. When compared with large precipitates often seen during conventional peak aging, these nanoscale precipitates with basal habit planes boost strength by offering more resistance to dislocation and/or twin motion. Nanoindentation studies showed a hardness jump from 0.76 GPa (for peak aged sample) to 1.26 GPa (for deformed sample), a 65.8% increase in an Mg-6Al (wt%) alloy. In the same study, the author reported a nanoindentation hardness jump from 0.96 GPa (for peak aged sample) to 1.48 GPa (for deformed sample), a 54.2% increase in an Mg-9Al (wt%) alloy [15]. A significant advantage here is that the processing time for deformed samples took effectively 8 h while the peak aging

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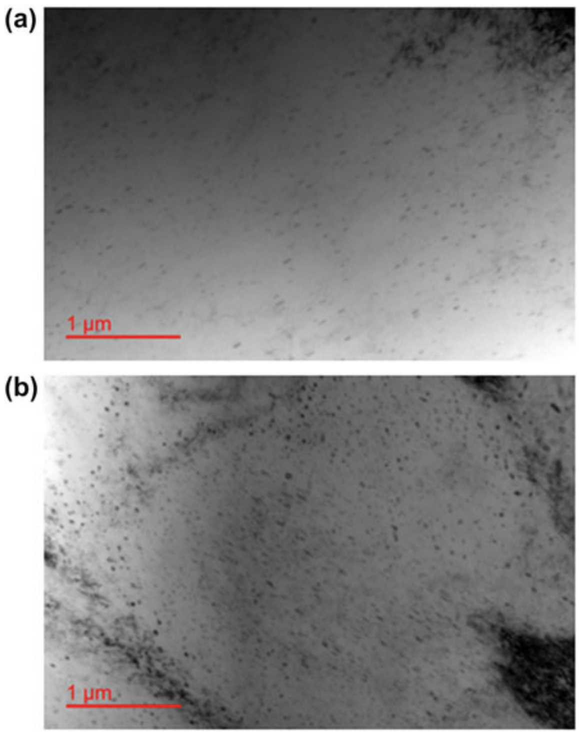

Fig. 1 **a** TEM micrograph of Mg-9Al (wt%) alloy subjected to 6 h of annealing at 150 °C followed by one pass of ECAE at 150 °C. **b** TEM micrograph of Mg-9Al (wt%) alloy subjected to one pass of ECAE at 150 °C followed by 6 h of annealing at 150 °C

for the Mg-6Al (wt%) alloy was nearly 480 h, and for the Mg-9Al (wt%) alloy was 163 h.

One part of our recent studies has further demonstrated the critical role of deformation in driving solute clustering and precipitation. An Mg-9Al (wt%) alloy was processed along two paths. In the first path, the alloy was subjected to 6 h of annealing at 150 °C followed by one pass of ECAE at 150 °C (Fig. 1a). In the second processing path, the alloy was subjected to one pass of ECAE at 150 °C followed by 6 h of annealing at 150 °C (Fig. 1b). From transmission electron microscopy (TEM) studies, the areal precipitate number density was calculated as 3e13m^{-2} for the first path (Fig. 1a) and 2.12e14m^{-2} for the second path (Fig. 1b). It is thus clear that deformation followed by annealing (processing path 2) induces more precipitates. Deformation as a first step ensures sufficient nucleation sites (vacancies, dislocations, etc.) which are artificially injected. Further annealing only helps to grow the solute clusters and precipitates. In processing path 1, the initial annealing does little to inject any defects or aid in solute clustering and is thus an inefficient route.

The precipitation process can be enhanced even more in alloy systems where the precipitate habit plane is along the c-axis, such as in Mg-Zn alloys. In Mg-Zn alloys, the ECAE process has been shown to produce very fine precipitates [14]. However, close examination of microstructures in these alloy systems using TEM and atom probe tomography (APT) reveals extensive solute clustering and suggests that vacancy-based mechanisms are active during the nucleation process. We have employed molecular dynamics simulations and Monte Carlo methods (Fig. 2) to understand how vacancies generated by extensive deformation impact solute diffusion and induce solute clustering and precipitation [20–22].

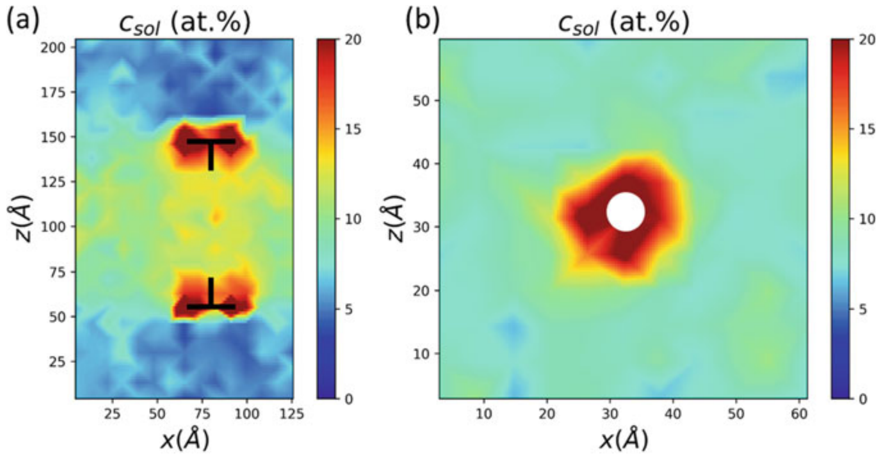

Fig. 2 Monte Carlo simulation results of equilibrium solute segregation near defects in Mg-9Al (wt.%) alloy at 150 °C. Semi-empirical potential by Kim et al. was used [19]. **a** Defect present is a basal- <a> edge dislocation dipole. The segregation occurs at the ends of the wide stacking faults. **b** The defect is a vacancy cluster containing 13 vacancies. Color bars represent the solute (Al) concentration near the defects (Color figure online)

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Competing Interests The authors declare no competing interests.

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