Deformation Driven Precipitation in Binary Magnesium Alloys

Chapter · January 2020

DOI: 10.1007/978-3-030-36647-6_26

2 authors:

Suhas Eswarappa Prameela
Johns Hopkins University

Tim Weihs
Johns Hopkins University

Deformation Driven Precipitation in Binary Magnesium Alloys

Suhas Eswarappa Prameela and Timothy P. Weihs

Abstract

Unlike Aluminum (Al) alloys, precipitation strengthening of Magnesium (Mg) alloys has proven challenging. Precipitate density is typically too low, and precipitate size is often too large and elongated to enhance the resistance to plastic deformation significantly. Mimicking recent work in Al alloys, we are exploring how low-temperature plastic deformation can enhance the density, size, and morphology of common intermetallic particles and thereby lead to significant hardening in Mg alloys. The low temperatures tend to favor nucleation overgrowth, while the deformation provides vacancies and dislocations that can assist nucleation. Using equal channel angular extrusion, and moderate temperatures, we explore the processing and thermodynamic factors controlling nucleation and growth of precipitates in Mg–Al and Mg–Zn binary alloys.

Keywords

Dynamic precipitation • Nucleation • Magnesium alloys • Nano precipitates • Strengthening

Magnesium alloys continue to receive significant interest from the broader scientific community, particularly from those interested in low-density structural materials [1, 2]. These lightweight alloys offer great potential for use in defense, transportation, electronics, and biomedical applications. There are now several research efforts focused on understanding the fundamental issues that control alloy processing and design. One of these efforts is driven to understand the role of initial microstructure and the controlling mechanisms during thermo-mechanical processing of Mg alloys, to create useful final microstructures. Possible attributes of such microstructures may include rich solute clusters, fine precipitates, small grain sizes, and random textures that help to tailor strength and anisotropy [3–7]. However, despite these efforts, our abilities to design and fabricate magnesium alloys with all of these microstructural attributes are still limited.

One overarching idea for improving the microstructure of Mg alloys is to follow the approaches that have proven successful in developing Al alloys [8, 9]. For example, precipitate hardening in Al alloys has been very effective. Micro-alloying, conventional aging (T6 treatment), double stretch aging, and dynamic strain aging are a few examples of how one can create very useful microstructures with fine precipitates in Al alloys. Mimicking these techniques to precipitation harden Mg alloys has resulted in varying degrees of success. Some of the core challenges limiting success include our narrow understanding of the roles that vacancies, solute atoms, and dislocations play during thermo-mechanical processing in Mg alloys. Conventional wisdom suggests that when extensive deformation and the climb of the edge dislocations generate excess vacancies [10], the rate of atomic diffusion rises, leading to enhanced nucleation and growth. However, by limiting the duration of deformation and by relying on the annihilate of vacancies once deformation ceases, one can effectively use the mechanical generation of vacancies as a switch to enhance nucleation with a limited impact on coarsening through growth. One simply stops the deformation following nucleation to limit coarsening. Dislocations can also play a dominant role in precipitation through their local stress states. The hydrostatic stress fields around edge dislocations can reduce the nucleation barrier for the formation of intermetallics simply due to changes in density upon precipitate formation. Further still, these dislocations promote the formation of solute clusters that lower the barriers for nucleation even further and can thereby lead to a higher number of fine precipitates. Studies have focused on manipulating solute clusters, mobile dislocations, and forest dislocations to aid nucleation processes. The type of solute atoms present in the microstructure also plays a significant

S. Eswarappa Prameela · T. P. Weihs (✉)
Department of Materials Science and Engineering, Hopkins Extreme Materials Institute, Johns Hopkins University, Baltimore, MD, USA
e-mail: weihs@jhu.edu

J. B. Jordon et al. (eds.), *Magnesium Technology 2020*, The Minerals, Metals & Materials Series, https://doi.org/10.1007/978-3-030-36647-6_26

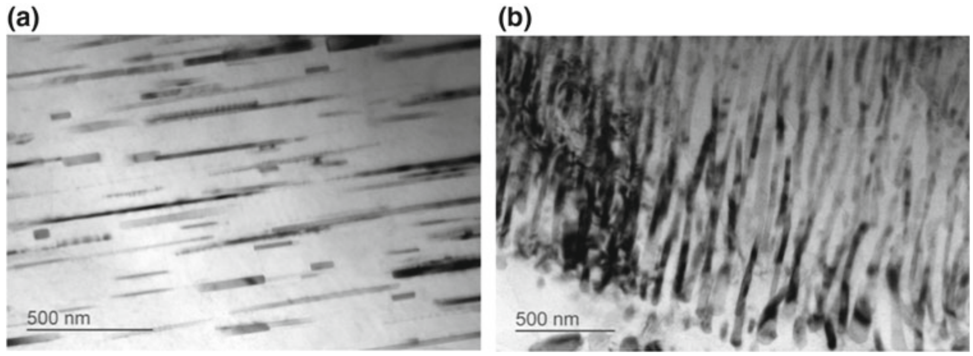

Fig. 1 Mg-9Al (wt%) after ECAE 4Bc processing at 150°C **a** Continuous precipitates within the grain interior. **b** Discontinuous precipitates near the grain boundary

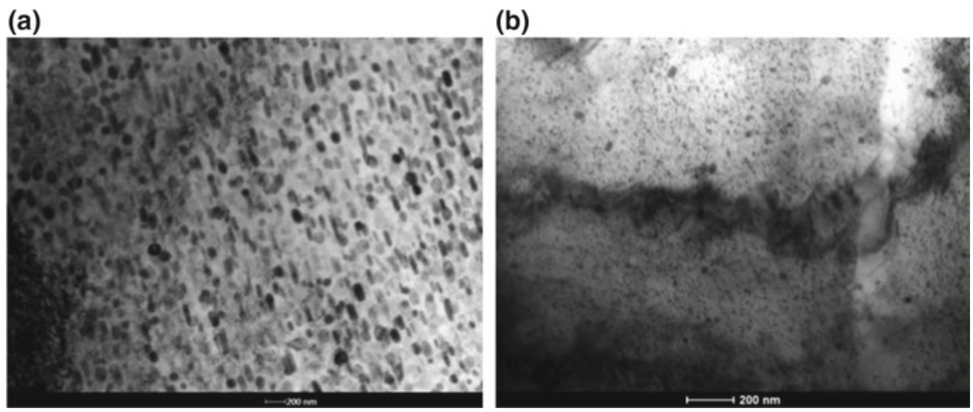

Fig. 2 **a** Fine nano precipitates in Mg–9Al (wt%) alloy. **b** Fine nano precipitates in Mg–3Zn (wt%) alloy

role as it can directly influence the formation of GP (Guinier–Preston) zones and other metastable phases [11, 12].

In our studies, we consider two binary magnesium alloys (Mg–Zn and Mg–Al) without micro-alloying elements and attempt to manipulate the nucleation and growth of precipitates by controlling deformation. We do so at low temperatures to aid nucleation of fine precipitates while limiting intermetallic coarsening.

The phase transformation sequence in Mg–Al and Mg–Zn alloys is as follows [13]:

$$\mathrm{Mg{-}Al: Solid\ solution} \ \rightarrow \underset{(0001)_{\alpha}\mathrm{habit\ plane}}{\beta(\mathrm{Mg_{17}Al_{12}})}$$

$$\mathrm{Mg{-}Zn: Solid\ solution} \ \rightarrow \mathrm{GP\ zones} \rightarrow \underset{[0001]_{\alpha}\mathrm{rod}}{\beta_1'(\mathrm{Mg_4Zn_7})} \rightarrow \beta_2''(\mathrm{MgZn_2}) \rightarrow \beta(\mathrm{MgZn})$$

Conventional peaking aging of these alloys often results in large aspect ratio precipitates that are not favorable for strengthening [14]. For example, the T6 treatment of Mg–9Al (wt%) alloy creates continuous precipitates in the grain interiors and divorced eutectic type precipitates called discontinuous precipitates [15] along the grain boundaries as shown in Fig. 1a and b, respectively.

In our work, binary magnesium alloys (Mg–9Al (wt%) and Mg–3Zn (wt%)) were dynamically aged by equal channel angular extrusion (ECAE). The extrusion was carried out at a rate of 0.15 mm/min at 150 °C and along the 4Bc route. Transmission electron micrographs show fine precipitates in Fig. 2a, b for both of these alloy systems after four passes.

We hypothesize that the severe plastic deformation (ECAE) injects a high density of dislocations during processing leading to an increased density of sites for nucleation [16, 17]. The hydrostatic stress states around edge dislocations attract solute clusters and ease precipitation by dramatically lowering the barrier for nucleation of intermetallics. This leads to a very high number density of fine precipitates, as shown above in Fig. 2. The very tight spacings and high number densities can result in significant Orowon strengthening and substantial increments in yield strengths [1, 18, 19]. Our work focuses on characterizing the impact of dislocations, as well as excess vacancies on this enhancement of precipitation in Mg alloys.

References

1. X.L. Ma, S. Eswarappa Prameela, P. Yi, M. Fernandez, N.M. Krywopusk, L.J. Kecskes, T. Sano, M.L. Falk, T.P. Weihs, Acta Mater. 172 (2019) 185–199.
2. S.R. Agnew, J.F. Nie, Scr. Mater. 63 (2010) 671–673.
3. J. Robson, Metall. Mater. Trans. A 45 (2014) 5226–5235.
4. J.D. Robson, N. Stanford, M.R. Barnett, Scr. Mater. 63 (2010) 823–826.
5. N. Stanford, J. Geng, Y.B. Chun, C.H.J. Davies, J.F. Nie, M.R. Barnett, Acta Mater. 60 (2012) 218–228.
6. J.F. Nie, B.C. Muddle, H.I. Aaronson, S.P. Ringer, J.P. Hirth, Metall. Mater. Trans. A 33 (2002) 1649–1658.
7. S. Eswarappa Prameela, P. Yi, V. Liu, B. Medeiros, L.J. Kecskes, M.L. Falk, and T.P. Weihs, Effect of Second Phase Particle Size on the Recrystallized Microstructure of Mg–Al Alloys Following ECAE Processing, Magnesium Technology 2020. https://doi.org/10.1007/978-3-030-36647-6_27
8. J.F. Nie, B.C. Muddle, Mater. Sci. Eng. A 319–321 (2001) 448–451.
9. W. Sun, Y. Zhu, R. Marceau, L. Wang, Q. Zhang, X. Gao, C. Hutchinson, Science 363 (2019) 972–975.
10. P. Yi, R.C. Cammarata, M.L. Falk, Model. Simul. Mater. Sci. Eng. 25 (2017) 085001.
11. J.F. Nie, B.C. Muddle, Acta Mater. 48 (2000) 1691–1703.
12. X. Gao, J.F. Nie, Scr. Mater. 58 (2008) 619–622.
13. J.-F. Nie, Metall. Mater. Trans. A 43 (2012) 3891–3939.
14. D. Mallick, S. Eswarappa-Prameela, V. Kannan, M. Zhao, J. Lloyd, T. Weihs, KT Ramesh, On the Role of Texture and Precipitate Orientation in Spall Failure of a Rolled Magnesium Alloy, in Bulletin of the American Physical Society, 2019, vol. Volume 64, Number 8. (http://meetings.aps.org/Meeting/SHOCK19/Session/1C.2)
15. J.B. Clark, Acta Metall. 16 (1968) 141–152.
16. Prameela, S. Eswarappa and Yi, Peng and Mediros, Beatriz and Liu, Vance and Keckes, Laszlo J. and Falk, Michael L. and Weihs, Timothy P., Deformation Assisted Nucleation of Continuous Nanoprecipitates in Mg-Al Alloys (11 11, 2019). Available at SSRN: https://ssrn.com/abstract=3484667
17. Ma, X., Eswarappa-Prameela, S., Krywopusk, N., Kecskes, L. J., Sano, T., & Weihs, T. P. (2018). Dynamic Precipitation in a Binary Mg-Al Alloy During Equal Channel Angular Extrusion (ECAE). Microscopy and Microanalysis, 24(S1), 2222–2223
18. J.F. Nie, Acta Mater. 56 (2008) 3169–3176.
19. J.F. Nie, Scr. Mater. 48 (2003) 1009–1015.