G Model
JMST-1182; No. of Pages 6

ARTICLE IN PRESS

Journal of Materials Science & Technology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Journal of Materials Science & Technology

journal homepage: www.jmst.org

Insight from *in situ* microscopy into which precipitate morphology can enable high strength in magnesium alloys

Bo-Yu Liu [a,1], Nan Yang [a,1], Jian Wang [b], Matthew Barnett [c], Yun-Chang Xin [d], Di Wu [e], Ren-Long Xin [d], Bin Li [f], R. Lakshmi Narayan [a,g], Jian-Feng Nie [h], Ju Li [a,i], Evan Ma [a,j,*], Zhi-Wei Shan [a,*]

[a] *Center for Advancing Materials Performance from the Nanoscale (CAMP-Nano) & Hysitron Applied Research Center in China (HARCC), State Key Laboratory for Mechanical Behavior of Materials, Xi'an Jiaotong University, Xi'an 710049, People's Republic of China*
[b] *Mechanical and Materials Engineering, University of Nebraska-Lincoln, Lincoln, NE 68588, USA*
[c] *Institute for Frontier Materials, Deakin University, Geelong, Victoria 3216, Australia*
[d] *College of Materials Science and Engineering, Chongqing University, Chongqing 400045, People's Republic of China*
[e] *Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, People's Republic of China*
[f] *Department of Chemical and Materials Engineering, University of Nevada, Reno, USA*
[g] *Department of Materials Science and Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA*
[h] *Department of Materials Science and Engineering, Monash University, Melbourne, Victoria 3800, Australia*
[i] *Department of Nuclear Science and Engineering and Department of Materials Science and Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA*
[j] *Department of Materials Science and Engineering, Johns Hopkins University, Baltimore, MD 21218, USA*

ARTICLE INFO

Article history:
Available online xxx

Keywords:
Precipitate selection criterion
In-situ TEM
Mg alloy
Mechanical property
Deformation twinning

ABSTRACT

Magnesium alloys, while boasting light weight, suffer from a major drawback in their relatively low strength. Identifying the microstructural features that are most effective in strengthening is therefore a pressing challenge. Deformation twinning often mediates plastic yielding in magnesium alloys. Unfortunately, due to the complexity involved in the twinning mechanism and twin-precipitate interactions, the optimal precipitate morphology that can best impede twinning has yet to be singled out. Based on the understanding of twinning mechanism in magnesium alloys, here we propose that the lamellar precipitates or the network of plate-shaped precipitates are most effective in suppressing deformation twinning. This has been verified through quantitative *in situ* tests inside a transmission electron microscope on a series of magnesium alloys containing precipitates with different morphology. The insight gained is expected to have general implications for strengthening strategies and alloy design.

1. Introduction

Lightweight magnesium (Mg) alloys are being actively pursued for their energy saving potential in fuel intensive transport [1,2]. However, the low strength of Mg alloys seriously hampers their broad applications. The idea of age hardening, inspired by success with Al alloys [3], has been widely applied to Mg alloys by introducing precipitates to enhance the strength. However, the strengthening effect is unsatisfactory [4] (Fig. S1). Different from Al alloys whose plasticity is governed exclusively by dislocation slips, yielding of Mg is usually subsidized by both dislocation slips on basal plane and deformation twinning (DT) on $\left\{10\bar{1}2\right\}$ plane (Fig. S2) [5]. The suppression of both basal slip and $\left\{10\bar{1}2\right\}$ DT is necessary in strengthening Mg alloys. For basal slips, the resistance from precipitates can be well quantified by Orowan model [6–8] and the strengthening effect is reliable [8–13]. However, from the experimental point of view, a consensus has yet to be reached whether the $\left\{10\bar{1}2\right\}$ DT can be effectively suppressed by precipitates [9–15] (Table S1). Although a few microscopy studies suggested that twin

* Corresponding authors at: Center for Advancing Materials Performance from the Nanoscale (CAMP-Nano) & Hysitron Applied Research Center in China (HARCC), State Key Laboratory for Mechanical Behavior of Materials, Xi'an Jiaotong University, Xi'an 710049, People's Republic of China.
E-mail addresses: ema.mse.jhu@gmail.com (E. Ma), zwshan@xjtu.edu.cn (Z.-W. Shan).
[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.jmst.2018.01.017
1005-0302/© 2018 Published by Elsevier Ltd on behalf of The editorial office of Journal of Materials Science & Technology.

can be arrested by precipitates [16–19], they could not tell if twin can move again to pass through those precipitates, and how much stress increase would be needed for that to occur. The theoretically predicted best precipitates for blocking DT are prismatic plates [4,20], but DT can not be reduced by such precipitates in some experiments [10,14]. With readily activated $\{10\bar{1}2\}$ DT, Mg alloys still suffer from low strength [21]. Therefore, an effective precipitate morphology that can impede $\{10\bar{1}2\}$ DT to a great degree is pressingly needed for developing high strength Mg alloys.

The present work was inspired by an atomistic understanding of twinning mechanism in Mg. $\{10\bar{1}2\}$ DT can grow through the migration of basal-prismatic interfaces (BP) [22–25] and the twin is then not restricted on the $\{10\bar{1}2\}$ plane [26–28]. This facilitates the growth of $\{10\bar{1}2\}$ twin in a flexible manner (with liquid-like characteristics): when a part of the twin is pinned by precipitates, the other parts can still migrate via BP migration. A hint of this phenomenon is that the twin boundary is always curved when it intersects with precipitates [7,16–19,29,30]. As such, we hypothesize that if the precipitate entails a high aspect ratio (like a wall), or the precipitates connect with each other to form a three-dimensional network, the expanding twin would have a hard time bypassing or engulfing such an obstacle. When twinning becomes difficult, non-basal dislocation slips that originally do not come into play would necessarily become activated (Fig. S3). Fig. 1 outlines this proposed strategy for the selection of precipitate morphology in Mg alloys.

2. Material and methods

It is however difficult to validate the strategy as proposed in Fig. 1, using conventional experimental methods. This is because in bulk samples there are multiple obscuring factors that would make the result ambiguous, including the simultaneous activation of multiple deformation modes that interact (DT, basal and non-basal slips) [31], varying grain size and crystal orientations of different proportions, non-uniform spatial distribution of precipitates, as well as the frequent occurrence of detwinning. In order to pinpoint the obstructing effect of each type of precipitate morphology on $\{10\bar{1}2\}$ DT, we tested inside a transmission electron microscope (TEM) a series of Mg alloys, each being a microscale sample containing only a specific morphology. Since it is difficult to obtain all morphologies for a specific precipitate phase at one alloy composition, we used several alloys, including Mg-Al (AZ31), Mg-Zn (ZK60 and Z6), Mg-Y-Nd (WE54) and Mg-Gd-Y-Zn (GWZ931), to cover the whole range of shape of precipitates, such as particles, rods, plates and lamellar precipitates (Fig. 2). In order to exclude the effect of different solute species, precipitate phase/composition and lattice constant (e.g. c/a ratio), whenever possible we directly compared the twinning behavior and mechanical data from a same alloy system. To avoid the interference from basal slips, the compression loading axis for all the tested samples is aligned in parallel with the basal plane to ensure the dominancy of $\{10\bar{1}2\}$ DT.

3. Results and discussion

3.1. Microscopy observations

As shown in Fig. 2(a) and (b), and (Supplementary Materials) S4-S6, DT in pillars with dispersed particles, rods or nano plates behaved similarly to that in pure Mg pillars: a twin formed at the top of the pillar and finally engulfed almost the entire pillar. The densely distributed precipitates neither blocked twin growth, nor divided the twin into smaller pieces. The DT behavior was quite different when the precipitates were connected to each other. Fig. 2(c) shows a WE54 pillar where the precipitate formed a network: no twin could be detected. During compressive loading, the pillar underwent obvious plastic deformation, but the latter must be mediated by non-basal dislocation slip (see Fig. S3 for possible slip systems). This is in stark contrast to the test on another pillar containing two isolated plates fabricated from the same WE54 sample. In such a pillar, when applied stress reached a critical level, twin was nucleated and expanded towards the root part of the pillar (Fig. S7). Similar suppression of DT could also be achieved in GWZ931 pillars containing long-period-stacking-order (LPSO) lamellae (Fig. 2(d)). After this pillar was shortened along the axial direction by ~7%, only two small volumes were twinned. In contrast, in the test on another pillar containing less LPSO lamellae that was fabricated from the same GWZ931 sample, twinning still dominated the plastic deformation (Fig. S8). With the increasing volume fraction of

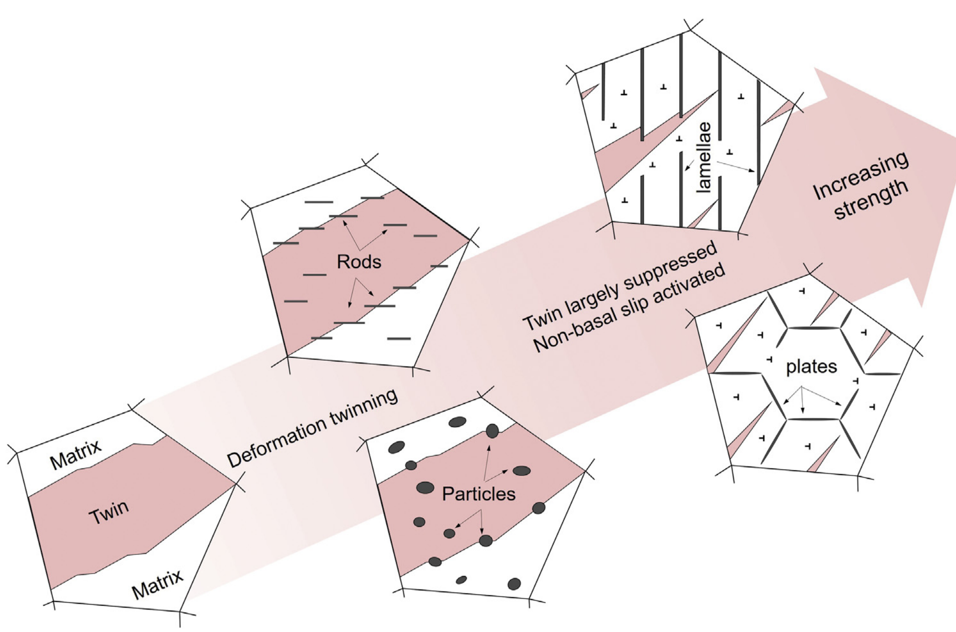

Fig 1. Criteria for precipitate morphology selection in the design of high-strength Mg alloys.