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Combined effects of source hardening and activation of new slip systems on simultaneous enhancement of strength and ductility in fine-grained Mg-3Gd alloy

X. Luo[1], Guilin Wu[1], Zongqiang Feng[1], Junqian Luo[1], Tianbo Yu[2], Tianlin Huang[1], Niels Hansen[1,3], Xiaoxu Huang[1,2]

[1] International Joint Laboratory for Light Alloys (MOE), College of Materials Science and Engineering, Chongqing University, Chongqing 400044, China
[2] Department of Mechanical Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark
[3] Risø Campus, Technical University of Denmark, DK-4000 Roskilde, Denmark

E-mail: xihu@mek.dtu.dk; xiaoxuhuang@cqu.edu.cn

Abstract. Yield point phenomenon often occurs in fine-grained and ultrafine-grained fcc and bcc metals, which causes a sharp increase in yield stress by source hardening but a rapid decrease in ductility due to the limited work hardening capacity. Here we report that an occurrence of yield point phenomenon in a fine-grained Mg-3Gd alloy can increase the yield stress to a level that facilities the activation of <c+a> type dislocations and their interactions with <a> type dislocations. As a result, not only the yield stress but also the tensile ductility are improved that suggests a new strategy overcoming the conventional strength-ductility trade-off.

1. Introduction

Yield point phenomenon associated with Lüders banding has commonly been observed in fine-grained and ultrafine-grained (UFG) fcc and bcc metals [1-5]. The occurrence of yield point phenomenon has two important consequences to the yield stress and tensile ductility. The yield stress shows a sharp increase as compared with samples showing continuous flow (smooth stress-strain curve), which is, in general, attributed to a strengthening mechanism by dislocation source hardening [3]. The tensile ductility, in particular, the uniform elongation after the Lüders banding, shows a rapid decrease, which is considered as a result of reduced strain hardening capability of the fine-grained and UFG materials.

Very recently, we found a similar yield point phenomenon in a fine-grained Mg-3Gd alloy [6]. A consequent significant increase in yield stress was observed, as seen in the fine-grained fcc and bcc metals [1-5]. However, an increase, instead of decrease, in uniform elongation was also observed, which is in contrast with the finding in the fcc and bcc metals. This observation of a simultaneous increase in both yield stress and uniform elongation is of significance as it breaks the strength-ductility trade-off. Preliminary observations [6] have shown that new type of slip systems were activated in the tensile deformed fine-grained sample that enhanced the work hardening during tensile deformation. This study aims to further understand the underlying mechanisms for the increase in tensile ductility based on detailed transmission electron microscopy (TEM) observations of the dislocation structures at different tensile strains of a selected fine-grained sample.

2. Experimental

The material used in the present study was a Mg-3Gd (wt.%) alloy. The alloy preparation was described in detail in [6]. Accumulative roll bonding (ARB) and annealing were applied to prepare samples of different grain sizes that were tensile tested to evaluate the flow behavior [6]. In this study, the tensile behavior of samples with grain size in the range of 3.3 to 45 μm was selected to illustrate the transition from continuous to discontinuous flow and the occurrence of a yield point phenomenon in the fine-grained samples.

Microstructural characterization was carried out with a JEM-2100 transmission electron microscope operated at 200 kV. TEM samples were prepared from the uniformly deformed gauge section of the tested tensile samples, and the observation plane was the longitudinal section containing the rolling direction and the normal direction (ND). Thin foils for TEM observations were prepared by ion milling using Gatan PIPS 691. TEM images for Burgers analysis of dislocations observed in the deformed samples were taken under two-beam diffraction conditions using different diffraction vectors g, see [6].

3. Results and discussion

3.1 Transition from continuous to discontinuous flow and yield point phenomenon

Fig. 1a shows the tensile stress-strain curves of Mg-3Gd samples with different grain sizes. The coarse-grained samples (grain sizes: 12.0 – 45.1 μm) show smooth stress-strain curves, namely continuous flow, but low yield stresses with a weak grain size dependence (relatively low Hall-Petch slope [6]). The fine-grained samples (grain sizes: 3.3 – 6.3 μm) exhibit a yield drop in the stress-strain curves that is referred to as discontinuous flow. A significant increase in the yield stress is seen in the fine-grained samples, raising the yield stress to above 150 MPa (3.3 and 5.0 μm) that is helpful to activate the slip systems that are of higher critical resolved shear stress. This transition from continuous to discontinuous flow by reducing the grain size has also been observed in fcc and bcc metals, and as an example, a similar observation [2] in an interstitial free (IF) steel is shown in fig. 1b for comparison. In the case of IF steel [2], the transition from continuous to discontinuous flow and the associated yield point phenomenon occurred when the grain size is reduced to be smaller than 2 μm. However, a remarkable difference is evident in the grain size dependence of the tensile elongation. In the present Mg-3Gd alloy, a continuous increase with decreasing grain size (or increasing yield strength) is seen within the grain size range studied. In contrast, the tensile elongation decreases monotonously with decreasing grain size for the IF steel, i.e., showing the normal strength-ductility trade-off behavior.

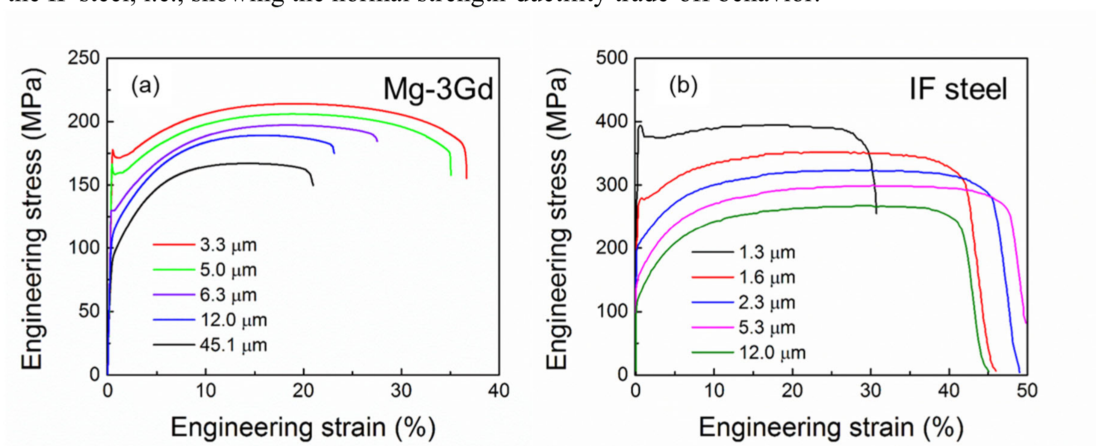

Fig. 1 Tensile stress-strain curves of samples with different grain sizes for (a) Mg-3Gd alloy and (b) an IF steel (reproduced from [2]).

3.2 Uniform elongation versus yield stress

To further illustrate the unique relationships between strength and ductility, the relationship between the yield stress and uniform elongation for the Mg-3Gd alloy was determined and shown in fig. 3a, which is compared with the literature results for an IF steel (fig. 3b) [2], 99.99% pure Al (4N-Al) (fig. 3c) [3] and AA1050 (fig. 3d) [4]. In these figures, the samples associated with a yield drop in their tensile stress-strain curves are indicated by solid arrows for the four materials. It is seen that there are large drops in the uniform elongation when the yield point phenomenon occurred in the latter three materials (fig. b-d) and that the Mg-3Gd alloy (fig. 2a) is the only material that overcomes the strength-ductility trade-off.

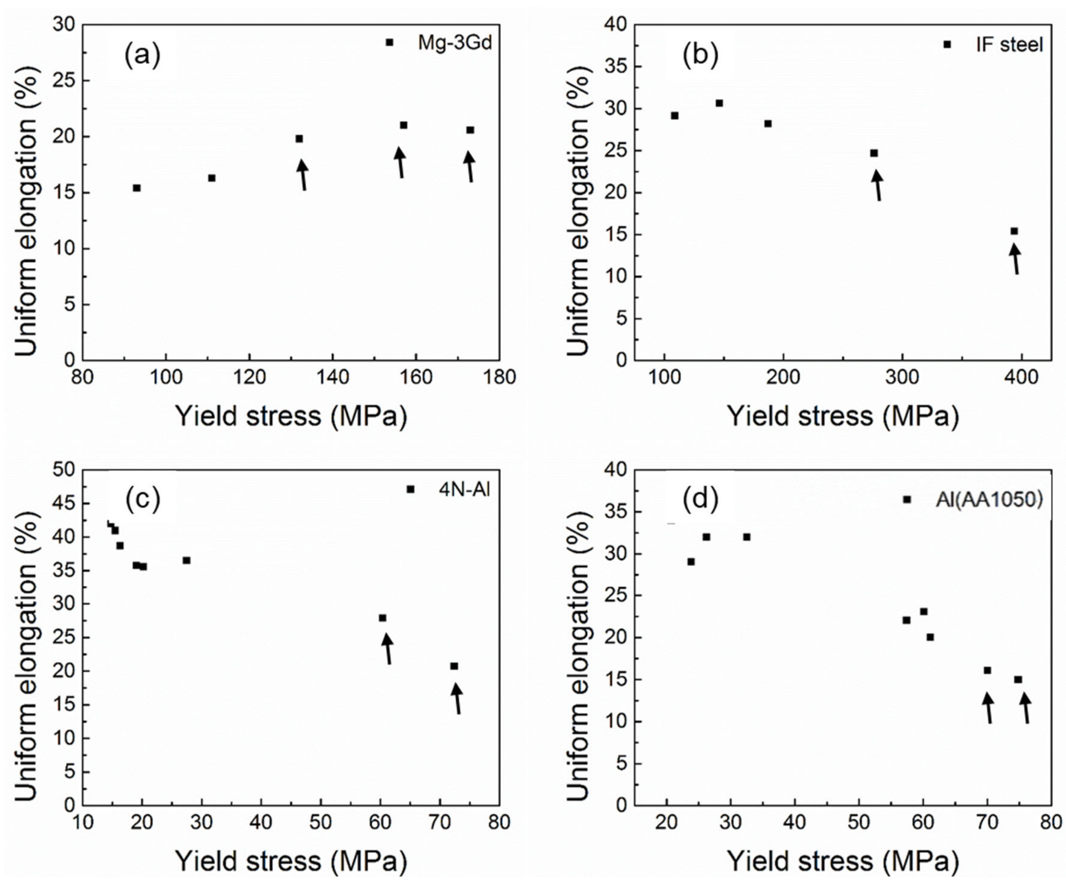

Fig. 2 Yield stress versus uniform elongation for (a) Mg-3Gd, (b) IF steel [2], (c) 4N-Al [3] and (d) AA1050 [4].

3.3 Active slip systems in fine-grained Mg-3Gd sample

To understand why the fine-grained Mg-3Gd samples break the strength-ductility trade-off, TEM studies were carried out to identify the dislocation Burgers vectors in the 3.3 μm grain-sized sample tensile deformed to 2%, 5% and 20%. Fig. 3 shows the results at strains of 2% and 5%. After 2% deformation (near the end of Lüders elongation) that only dislocations of <a> type Burgers vector are observed (marked by white dotted arrows). However, after 5% deformation dislocations of <c+a> type of Burgers vector (marked by red dotted arrows) are also observed in addition to but separate from the <a> type dislocations. The dislocations of different Burgers vectors cannot annihilate through cross slip, and their accumulation will enhance the storage of dislocations. Fig. 4 shows a cell-like dislocations structure associated with a high density of interacting dislocations in a 20% deformed sample.

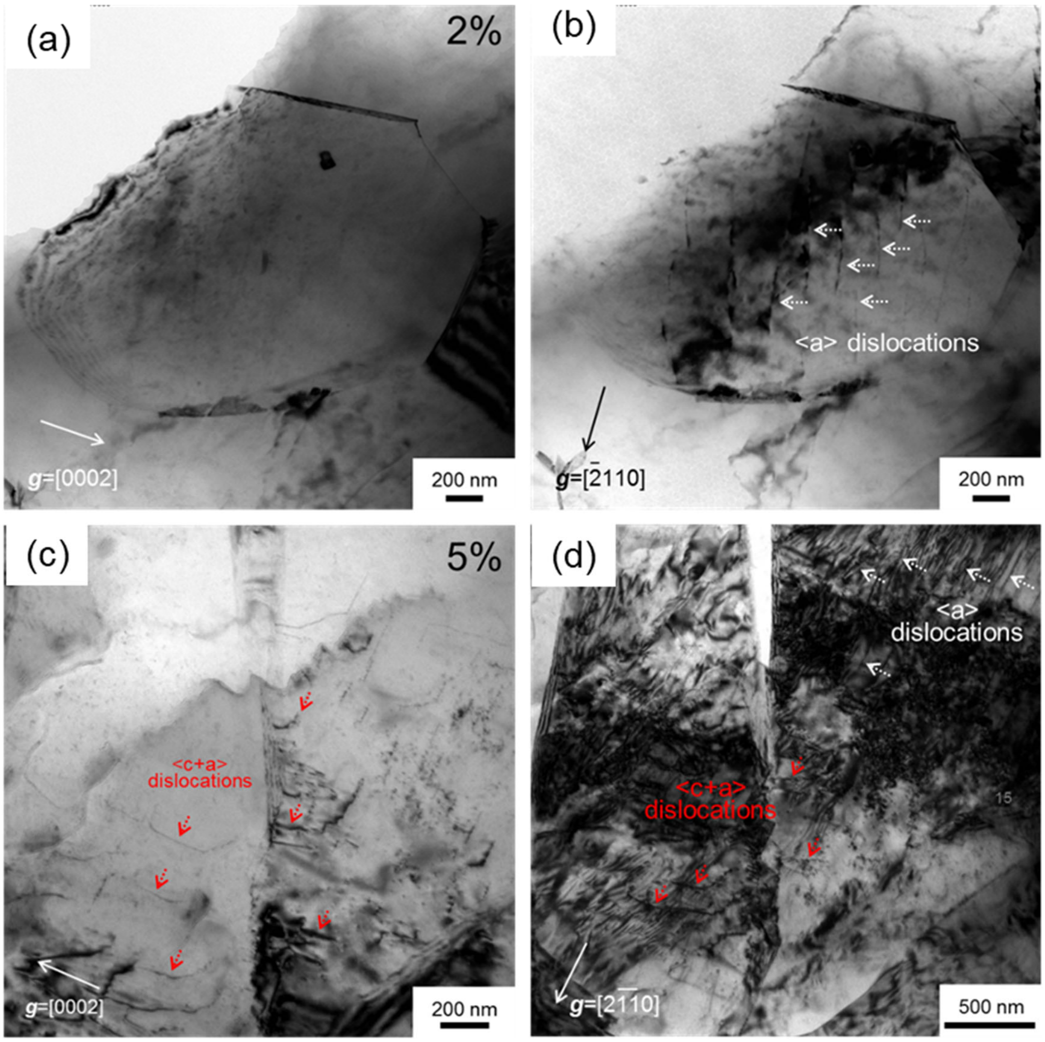

Fig. 3 Identification of dislocation Burgers vectors for the 3.3 μm grain-sized sample tensile deformed to 2% (a, b) and 5% (c, d).

The activation of <c+a> type dislocations may have its cause in an increased yield stress following a decrease in grain size. In the present system such a reduction may have a two-fold effect on the yield stress due to (i) a reduction in pile up length and (ii) the introduction of a contribution from source strengthening. The observed yield stress-ductility relationship in Fig. 2a reverses the well-known relationship dubbed the banana curve. This reversal was unexpected and it has significant scientific and technological importance, as it points to the characteristics of the individual glide dislocations， <a> and <c+a> dislocations. These dislocations may not as in fcc and bcc metals accumulate in low energy dislocation structure (LEDS) minimizing the energy per unit length of dislocation line. However interaction may gain in importance with increasing strain and dislocation density, see Fig. 4. Tentatively it is suggested that increased interaction may reduce the line energy of dislocations bringing hcp structure more in line with fcc and bcc structures.

It is suggested that the introduction of dislocations with a new type of Burgers vector <c+a> plays a crucial role in enhancing the work hardening rate and the tensile ductility in the fine-grained Mg-3Gd alloy. This understanding points to a new microstructural design strategy to enhance work hardening by operating dislocations of different types of Burgers vector.

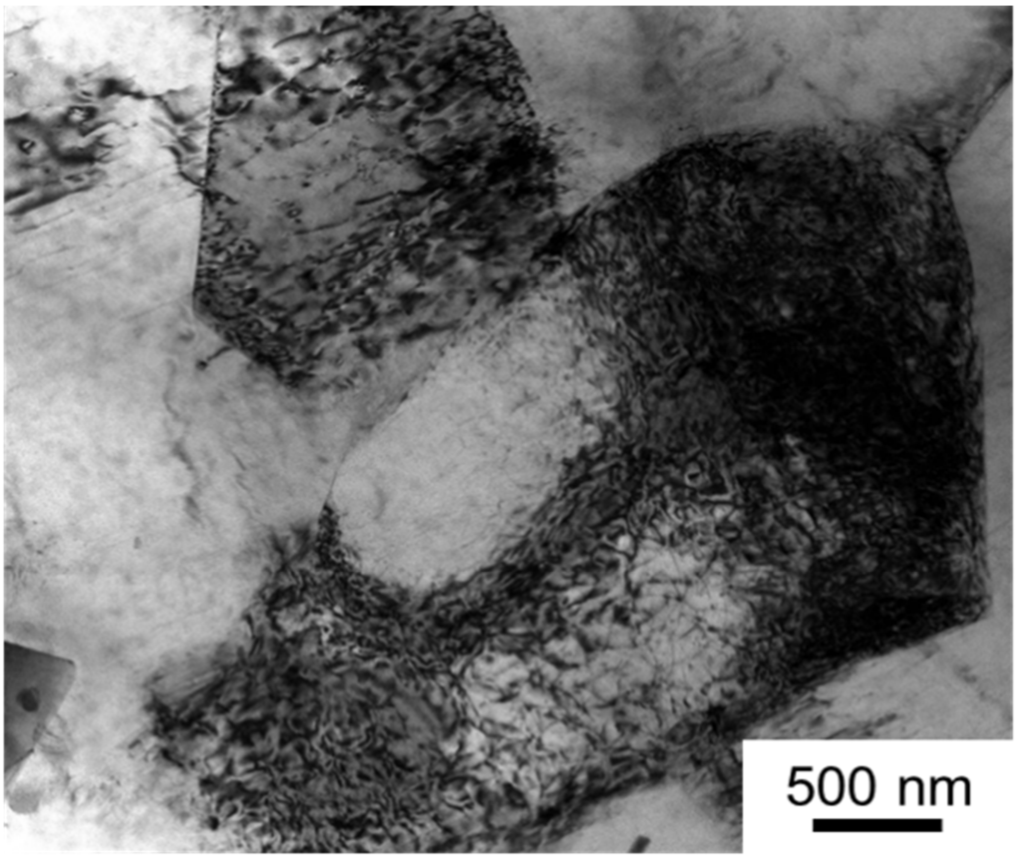

Fig. 4 Dislocation structure observed in the 3.3 μm grain-sized sample tensile deformed to 20%.

4. **Conclusions**

In a fine-grained hcp Mg-3Gd alloy, yield point phenomenon has been observed that is associated with large increases in both yield stress and tensile ductility, in contrast to the conventional strength-ductility trade-off in fine-grained fcc and bcc metals. Transmission electron microscopy has been carried out to follow the evolution of the dislocation structure during tensile deformation of a 3.3 μm grain-sized sample. It has been identified that besides the <a> dislocations, <c+a> type dislocations are also activated soon after Lüders elongation. It is suggested that the interactions between dislocations of different types of Burgers vector will enhance the storage of dislocations in the deformed sample and thus the work hardening, which explains the simultaneous improvement in yield stress and ductility.

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References

[1] Tsuji N, Ito Y, Saito Y and Minamino Y 2002 *Scripta Materialia* **47** 893–899
[2] Gao S, Chen M C, Chen S, Kamikawa N, Shibata A and Tsuji N 2014 *Materials Transactions* **55** 73–77
[3] Kamikawa N, Huang X, Tsuji N and Hansen N 2009 *Acta Materialia* **57** 4198–4208
[4] Yu C Y, Kao P W and Chang C P 2005 *Acta Materialia* **53** 4019–4028
[5] Le G M, Godfrey A and Hansen N 2013 *Materials and Design* **49** 360–367
[6] Luo X, Feng Z Q, Yu T, Luo J Q, Huang T L, Wu G L, Hansen N and Huang X 2019 submitted for publication.