Compressive behaviour of nanocrystalline Mg–5Al alloys

H. Diao[1], C. Yan*[1], J. M. Bell[1], L. Lu[2], G. P. Zhang[3], S. Kabra[4], K.-D. Liss[4] and M. W. Chen[5]

Magnesium alloys are attracting increasing research interests due to their low density, high specific strength, good machinability and availability as compared to other structural materials. However, the deformation and failure mechanisms of nanocrystalline (nc) Mg alloys have not been well understood. In this work, the deformation behaviour of nc Mg–5Al alloys was investigated using compression test, with focus on the effects of grain size. The average grain size of the Mg–Al alloy was changed from 13 to 50 nm via mechanical milling. The results showed that grain size had a significant influence on the yield stress and ductility of the Mg alloys, and the materials exhibited increased strain rate sensitivity with a decrease in grain size. The deformation mechanisms were also strongly dependent on the grain sizes.

Keywords: Nanocrystalline Mg alloy, Strain rate sensitivity, Texture, Strain hardening, Deformation mechanism

Introduction

Magnesium alloys have been a growing interest as lightweight structural materials due to their low density and high specific strength. However, most Mg alloys suffer from poor ductility due to their hexagonal close packed (hcp) structure. A recent study showed that grain refinement would help to improve the ductility of Mg alloys.[1] Several methods such as mechanical alloying and severe plastic deformation have been used to refine the grain size down to the nanometre level.[2] Most previous investigations on the deformation behaviour of nanocrystalline (nc) metals and alloys were focused on those with face centred cubic and body centred cubic crystal structures. Relatively, less attention has been directed to alloys with hcp structure, such as nc Mg alloys,[3] although the deformation behaviour of conventional coarse grained Mg alloys has been widely investigated. The systematic investigation of the deformation behaviours of Mg alloys with grain size ranging from micrometre down to nanometre is still lacking. In this study, bulk microcrystalline and nc Mg–5Al alloys with grain size varying from micrometres down to nanometres were prepared. The deformation behaviour of these Mg alloys was investigated using uniaxial compression tests. The effects of grain size and strain rate on the deformation mechanisms were examined.

[1]School of Chemistry, Physics and Mechanical Engineering Queensland University of Technology, Brisbane, Qld 4001, Australia
[2]Department of Mechanical Engineering, National University of Singapore 117576, Singapore
[3]Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, 72 Wenhua Road, Shenyang 110016, China
[4]Australian Nuclear Science and Technology Organization, Lucas Heights, NSW 2234, Australia
[5]WPI-Advanced Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan

*Corresponding author, email c2.yan@qut.edu.au

Experimental

Bulk Mg–5Al alloys were fabricated using mechanical milling, sintering and then extrusion, with different milling durations of 0 (as blended), 10, 20, 30 and 40 h. For convenience, we refer to these samples as MA0, MA10, MA20, MA30 and MA40 respectively. Round specimens with 5 mm diameter and 10 mm length were machined from the extruded bar for compression tests. The compression test was conducted using an Instron universal testing machine at ambient temperature. The strain rate was changed from 0·01 to 0·0001 s^{-1}. To check the repeatability of the results, between three and five tests were conducted under each condition. Variations in stress and elongation were within 5% in most cases. Textures were measured using the WOMBAT neutron diffractometer at the Bragg Institute at ANSTO, Australia.

Results and discussion

Figure 1 shows that the Mg alloys developed a strong texture with the basal plane parallel to the extrusion direction, which was due to the limited number of active deformation systems in hcp metals. The strong basal texture may lead to the activation of $\{10\bar{1}2\}$ twinning under compression load as the critical resolved shear stress required is only slightly higher than the smallest one for basal dislocation slip.

The average grain size of the Mg alloys decreased from 13 μm (MA0) to 50 nm after 40 h milling. As shown in Fig. 2, the yield strength initially increases with reduction in grain sizes, e.g. from ~137 MPa

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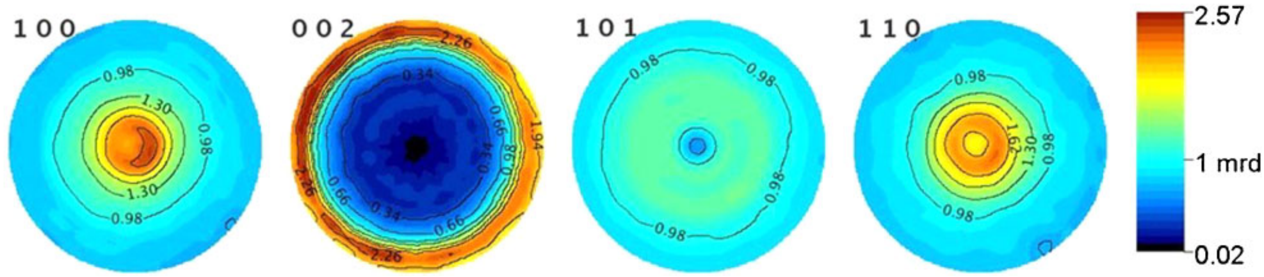


1 Pole figures of MA0 measured by X-ray diffraction showing basal fibre structure

(MA0, 13 μm) to 395 MPa (MA20, 78 nm), but starts to decrease with further reduction in grain size to 50 nm (290 MPa, MA40). Obviously, the increase in yield strength can be attributed to the grain refinement. On the other hand, large ductility has been observed in these nc Mg alloys, in particular in MA30 and MA40. Compression tests under various strain rates showed that the strain rate sensitivity (SRS) of the materials increased from 0·006 (MA0) to 0·107 (MA40).

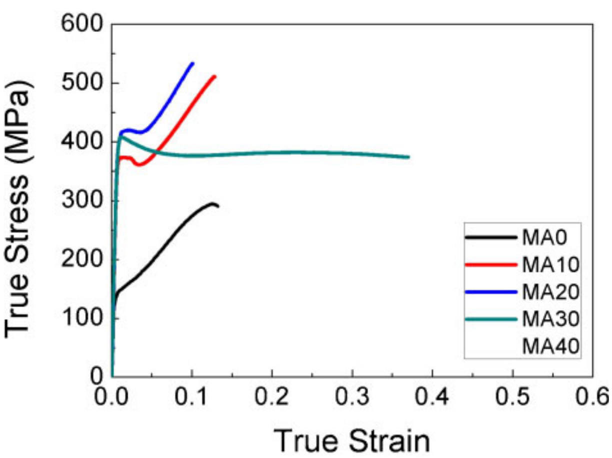
In Fig. 2, the true stress–strain curve for MA0 was characterised by continuous strain hardening until fracture. At the initial stage of deformation, tensile $\{10\bar{1}2\}$ twinning is considered to be activated due to the favourable orientation of the grains with respect to the strain direction. The pronounced workhardening behaviour was caused by both forest dislocations and twinning. The stress–strain curves for MA10 and MA20 showed strain softening in the initial stage of deformation after yielding, followed by strain hardening. The softening effect was largely due to the activation of $\{10\bar{1}2\}$ twinning. Since the $\{10\bar{1}2\}$ systems could produce compressive strain up to 3–4%,[4] strain hardening started to take effect after 4% strain when the slip systems were activated to accommodate further plastic deformation. In general, the plastic deformation in coarse grained Mg alloys is largely dominated by the activation of twinning in compression but non-basal slip in tension. The present work further confirmed the effect of twin on plastic deformation in even ultrafine grained Mg alloys, i.e. MA10 and MA20.

Figure 3 shows the Hall–Petch (H–P) relationship of extruded Mg alloys from the present study under compression and tensile tests.[5,6] The H–P relationship is no longer upheld when the grain size is reduced to 50 nm. In addition, MA30 and MA40 exhibited constant strain softening, as shown in Fig. 2, indicating localised plastic deformation.

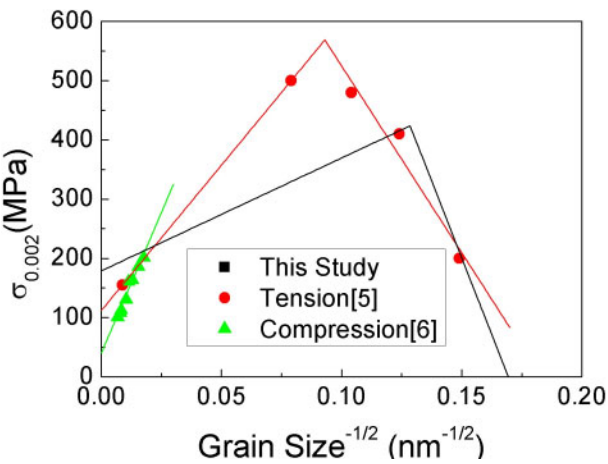
The inverse H–P relationship suggested that the conventional grain boundary strengthening effect via pile-up of dislocations was not upheld in the nc Mg alloy (MA40). In fact, when the grain size decreases down to the nc regime, the Frank–Reed source ceases to operate, and the relatively high fraction of grain boundaries is believed to be the sources and sinks of dislocations.[7] In addition, recent studies revealed that grain boundary sliding and diffusion creep may play a critical role in accommodating plastic deformation.[8] In this work, SRS of the MA40 (m=0·107) was still smaller than that expected for significant grain boundary sliding (m=0·5) or coble creep (m=1·0).[9] Therefore, the plastic deformation in MA40 is considered to be dominated by combined dislocation and grain boundary activities. Further investigation on the strain softening mechanism is required.

Conclusions

In the present study, microcrystalline and nc Mg–5Al alloys were fabricated by mechanical milling, with the grain size ranging from 13 to 50 nm. The deformation behaviour of these alloys was evaluated using compression tests under different strain rates. The SRS increased from 0·006 to 0·107 when the average grain size was reduced from 13 mm to 50 nm. The H–P relationship was no longer upheld when the grain size was reduced down to 50 nm. Strain softening followed by strain



2 True stress–true strain curves of Mg alloys at strain rate of 0·0001 s^{-1}



3 Hall–Petch relationship for extruded Mg alloys

hardening was observed in samples with relatively greater grains (78 nm–13 μm). The reason was attributed to the initial activation of twinning in compression and then slip dominated flow. With the decrease in grain size to 50–58 nm, only strain softening can be observed in the compression stress–strain curves. Large ductility (35–55%) was retained in these nc Mg alloys subjected to quasi-static loading. The deformation mechanism was proposed as combined dislocation and grain boundary activities.

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