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Influence of rare earth addition on texture development during static recrystallization and mechanical behaviour of magnesium alloy sheets

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Abstract. The role of rare earth addition on the microstructure and texture during recrystallization of cold rolled sheets is investigated by a comparative study of pure Mg, Mg-3Y and Mg1.5Nd sheets. In pure Mg, nucleation occurs mainly at shear bands which results in a texture weakening. The basal-type texture re-strengthens rapidly during grain growth of the pure Mg sheet. In contrast, in the Mg-RE alloys the weaker texture formed during early recrystallization strage is retained during further annealing due to retarded grain growth. Uni-axial tensile and Erichsen tests show that ductility and sheet formability are significantly improved by addition of rare earth elements.

Introduction

Poor formability and strong mechanical anisotropy of conventional Mg alloys, especially at room temperature, are decisive drawbacks which hinder industrial application of this lightest structural metal. It is understood today that the ductility and formability of Mg alloys can be significantly improved by the addition of rare-earth elements (RE) [1, 2]. Moreover, RE addition is known to be an effective way of weakening the strong basal-type crystallographic texture, which is typically observed in conventional Mg alloys such as Mg-3Al-1Zn. The mentioned effects could be related to the increased activity of <c+a> slip and contraction twinning [3]. Furthermore, the weaker texture characterized by a broader distribution of the basal poles around the sheet normal direction (ND), makes the activation of basal <a> slip easier under loading in directions either parallel or perpendicular to the sheet plane such that sheet formability can be considerably improved [1, 3]. An understanding of the mechanisms responsible for the increased ductility and texture modification through such a RE addition will guide the development of a new class of Mg alloys with improved room temperature formability.

The present study examines the microstructure and texture developments during static recrystallization of cold rolled Mg alloy sheets. The role of RE addition on the microstructural evolution has been investigated by comparative studies of pure Mg, Mg-1.5Nd and Mg-3Y (in wt.-%) alloy sheets. By employing cold rolling as deformation process, the influence of dynamic recrystallization (DRX) on the final microstructure could be minimized. Moreover, uni-axial tensile tests and Erichsen tests were performed using fully recrystallized sheets, by which the influence of texture and, further, RE addition on the mechanical behaviour of Mg sheets was examined.

Experimental procedures

Mg-1.5Nd and Mg-3Y alloys were cast into steel moulds using an electrical furnace under Ar + SF_6 atmosphere, while a commercially available cast block served as initial material for pure Mg. Slabs were machined from the cast blocks with a thickness of 25 mm and a width of 50 mm. After hot rolling at 450 °C to a thickness of 2 mm, a part of the plates were further cold rolled at room temperature to 1 mm which corresponds to 50 % of thickness reduction. To minimize cracking during cold rolling, the thickness reduction per pass was controlled not to exceed 4 %, as suggested in the literature [4]. Only a small amount of edge cracks with lengths of 2 ~ 3 mm appeared after cold rolling to 50 % thickness reduction even in pure Mg, so that microstructural studies at the mid part of the sheets were not influenced by cracking. However, some surface cracks occured at the rolling plane after 30 % thickness reduction during cold rolling of the pure Mg sheet. Therefore, the samples for the mechanical tests were prepared from 30 % cold rolled sheets, while the microstructural evolution during static recrystallization was examined by annealing of the 50 % cold rolled sheets at 350 °C for different times, from 5 to 3600 s.

Microstructures and textures of the rolled and annealed sheets were investigated using electron backscatter diffraction (EBSD) and X-ray diffraction. For X-ray diffraction, 6 incomplete pole figures of {10-10}, (0002), {10-11}, {10-12}, {11-20} and {10-13} planes were collected, and the complete pole figures were calculated using MTEX software. EBSD measurements were conducted on the longitudinal sections parallel to the RD. Samples were prepared by mechanical polishing using alumina powder followed by electrolytic polishing using a Struers AC2 solution (for 90 s at 33 V and -25 °C).

To avoid the influence of grain size on the mechanical properties, the samples for tensile and Erichsen tests cut from 30 % cold rolled sheets annealed at different conditions to achieve comparable grain sizes for pure Mg and Mg-RE alloys. Fully recrystallized grain structures with an average grain size of ~ 30μm were achieved in pure Mg by annealing at 400 °C for 600 s and in Mg-RE alloy sheets at 450 °C for 900 s. The tensile specimens were machined from the sheet transverse direction (TD) with a gage length of 13 mm, and tensile tests were performed at room temperature with an initial strain rate of 5×10^{-4} /s. Round blanks with a diameter of 100 mm were used for Erichsen tests (Φ 20 mm punch) at room temperature with punch speed of 5 mm/min.

Results and discussion

Fig. 1 shows the optical micrographs and recalculated (0002) pole figures of 50 % cold rolled sheets. Although a large amount of shear bands are observed in the cold rolled sheets, there is an important difference in their evolutions between pure Mg and Mg-RE. As reported in [3], each shear band in Mg-RE alloys covers only few grains, whereas in pure Mg macroscopic shear bands develop throughout the whole sheet thickness. The homogeneously distributed band structures initiated from twins in the Mg-RE alloy sheets serve to retard fracture at macroscopic shear bands [3]. The pure Mg sheet shows a strong basal-type texture after cold rolling with a maximum (0002) pole density, P_{max_0002}, of 11 and a slight broadening of the basal poles into the sheet rolling direction (RD). The texture sharpness of the cold rolled Mg-RE sheets is lower compared to that of pure Mg, i.e. P_{max_0002} = 7.8 and 7.7 for Mg-3Y and Mg-1.5Nd sheets, respectively. Moreover, the Mg-RE sheets show a clear splitting of the basal poles into the RD. The texture evolution with a basal pole split, attributed to high activity of <c+a> slip, was also shown by Agnew et al [5] in Mg alloys containing Li and Y.

The EBSD kernel average misorientation (KAM) maps of pure Mg and Mg-RE sheets annealed to partially recystallized microstructures are presented in Fig. 2. By selecting the respective grain fractions based on the grain interior misorientation, the textures of the recrystallized (average grain-

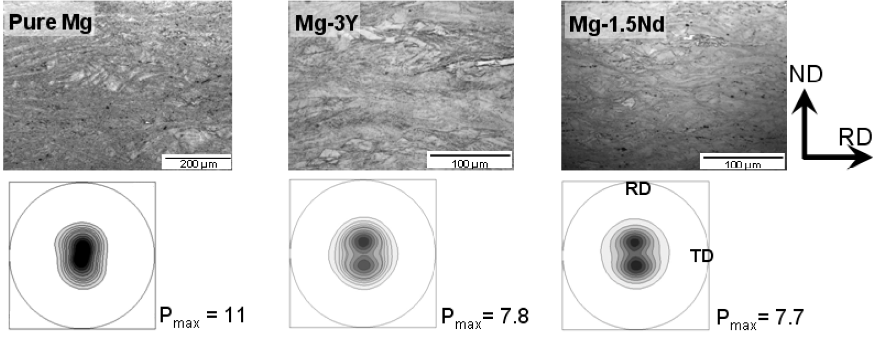

Fig. 1 Optical micrographs and recalculated (0002) pole figures of 50 % cold rolled sheets.

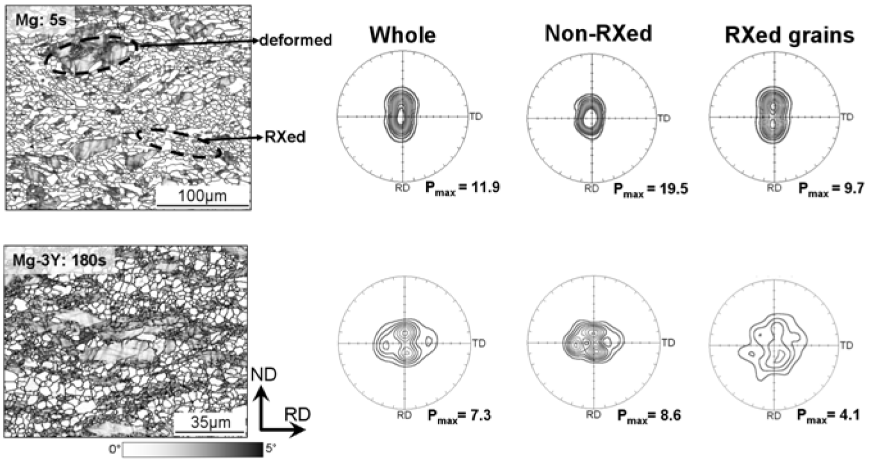

Fig. 2 EBSD kernel average misorientation maps and recalculated (0002) pole figures, separately evaluated from the whole area, deformed grains and recrystallized grains, of partially recrystallized pure Mg and Mg-3Y sheets.

interior misorientation < 0.5°) and deformed grains (average grain-interior misorientation > 1.0°) were evaluated separately, Fig. 2. The deformed grains remaining after 5 s annealing of pure Mg have a strong basal type texture with P_{max_0002} = 19.5, whereas the recrystallized grains clearly have their basal poles rotated about 15° from the ND towards the RD and a relatively weak texture with P_{max_0002} = 9.7. The recrystallized grains in the Mg-3Y and Mg-1.5Nd alloys have a weak texture with a basal pole split, which is similar to the pure Mg sheet. However, the remaining deformed matrix grains in the Mg-RE alloys show a clear basal pole split, which indicate again that more deformation mechanisms, i.e. <c+a> slip, {10-11} contraction and {10-11}-{10-12} secondary twinning, than in pure Mg were activated in these alloys [3]. The development of the weak texture with the basal pole broadening towards the RD is understood as a result from the beginning of the recrystallization at the shear bands. Based on a high strain energy and large lattice distortion induced at the shear bands, the recrystallized grains are triggered at the shear bands and they have rather diffuse orientations at early recrystallzation stage [6].

Fig. 3 illustrates the variation of the average grain sizes and texture intensities, P_{max_0002}, as a function of the annealing time at 350 °C. It is clearly seen that the grain growth of the Mg-RE alloys is remarkably retarded, Fig. 3 (a). It is also to note that the recrystallization process of the pure Mg sheet is surprisingly fast so that full recrystallization is reached after annealing for 60 s, whereas in the 50% cold rolled Mg-RE sheets fully recrystallized microstructures were observed after 1800 s annealing at 350 °C. In viewpoint of the texture evolution, the retarded recrystallization and grain growth caused by the RE addition, in form of the solute and/or particle drag, has an important meaning. Since a relatively equal growth potential for grains having diverse orientations is provided by the retarded grain growth, the weak texture induced mainly from the shear band nucleation can be retained to the fully recystallized stage. Therefore, the Mg-RE alloy sheets show a decrease in the texture sharpness as recrystallization and grain growth occur, while the rapid growth of the grains having the basal orientations leads to a significant strengthening of basal-type texture.

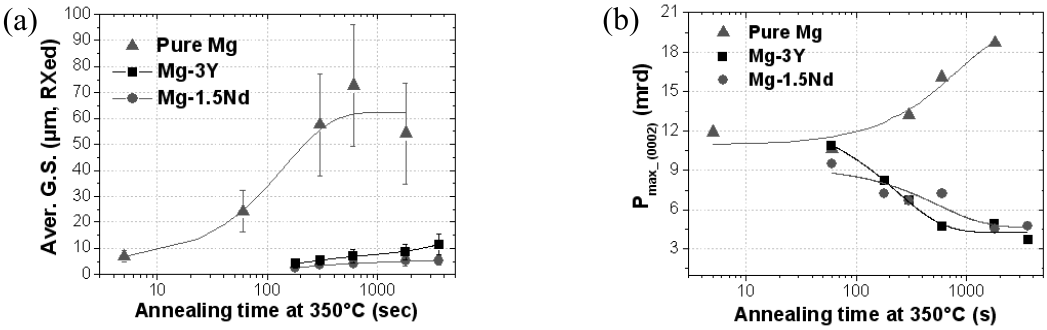

Fig. 3 Variation of (a) average size of recrystallized grains and (b) P_{max_0002} as a function of the annealing time at 350°C.

The stress-strain curves measured by uni-axial tensile loading and the blanks after Erichsen tests of the fully recrystallized sheets after 30 % cold rolling are presented in Fig. 4 and Fig. 5, respectively. The pure Mg shows a fracture strain (ε_f) of ~3%, whereas the Mg-RE alloys have a remarkably high ductility with ε_f = ~15%. Moreover, the Erichsen values of the Mg-RE sheets are almost 2 times higher than that of the pure Mg sheet. The high ductility and improved sheet formability with well-balanced work hardening in the Mg-RE sheets can be understood as a result of the weak texture, which is favourable for deformation in the sheet planar and thickness directions, and higher activities of non-basal dislocation slip as well as more twinning systems [3, 7].

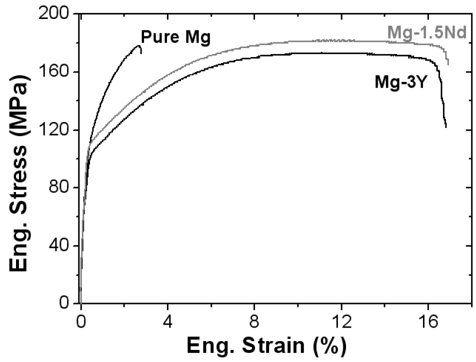

Fig. 4 Stress-strain curves of the RXed sheets after 30 % cold rolling.

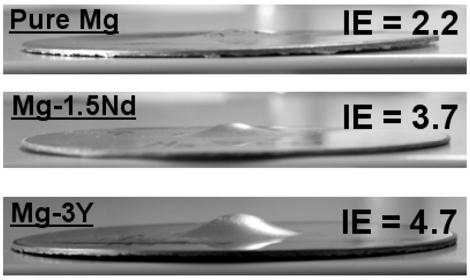

Fig. 5 Round blanks after Erichsen tests at room temperature (IE = Erichsen value).

Summary

Microstructural evolution during annealing of cold rolled pure Mg, Mg-1.5Nd and Mg-3Y sheets were examined. Rapid recrystallization and grain growth results in rapid strengthening of the basal-type texture in pure Mg sheet, whereas the RE elements addition leads to a significant retardation of recrystallization and a considerable texture weakening. High ductility and improved sheet formability are achieved in the Mg-RE sheets resulting from weaker textures and enhanced activity of non-basal slip modes.

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