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Sediako, D. G.; Gharghouri, M. A.

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Study of Texture Evolution during Channel-Die Compression of Mg-Al Alloys by In-Situ Neutron Diffraction

D.G. Sediako, M.A. Gharghouri [1]

[1] Canadian Neutron Beam Centre, National Research Council, Chalk River Laboratories, Chalk River, ON, Canada K0J 1J0

Introduction

The chemistry of alloys and the casting-rolling production routes determine the cost and properties of magnesium sheets [1]. For example, the coarse-grained structure usually associated with DC casting requires complex rolling schedules to refine the grain size. Added complexity comes from micro- and macro-segregation of the alloying elements, as well as from localized, such as radial or edge, stress accumulation. These affect rolling productivity, and can also result in product defects, such as cracking, and inferior mechanical properties.

Rolling can result in a strong crystallographic texture, which is responsible for the tension-compression strength asymmetry exhibited by rolled magnesium alloys. The strength asymmetry is due mainly to the common {1012} twinning mechanism, which can accommodate tensile strain, but not compressive strain, parallel to the HCP c-axis. Thus, the stronger the basal texture, the stronger is the tension-compression asymmetry.

Alloy composition influences deformation behavior. The behavior of pure magnesium and of two binary Mg-Al alloys was investigated by neutron diffraction, as aluminum is one of the most common alloying elements in Mg alloys. The simple Mg-Al system was used in order to isolate the influence of aluminum on deformation behavior, which can be strongly influenced by other alloying additions.

Experiment

A channel-die insert compatible with the CNBC high-temperature vacuum furnace was designed and fabricated to simulate industrial rolling operation. Two binary Mg-Al alloys (3 wt.% and 9 wt.% Al) were subjected to plane strain compression with continuous monitoring of texture and lattice strain. For each experiment, the specimen was mounted in the furnace and load frame, heated to the target temperature, and the temperature was allowed to stabilize for at least 30 minutes. A sequence of loading steps was then applied, with data collected at the end of each step, with the material in the unloaded condition. The pure Mg was deformed at 250°C, while the Mg-3%Al and Mg-9%Al alloys were deformed at 350°C.

Metallography

As shown in Figure 1(a)-(d), the Mg-3%Al alloy has a grain size of 40-75 μm, while the Mg-9%Al alloy has finer grains in the 20-40 μm range. Another clear difference between the starting structures of the alloys is the presence of twinning in the Mg-3%Al alloy; the Mg-9%Al metal is free of twinning.

The Mg-3%Al alloy underwent a slightly higher degree of deformation (1.75:1 reduction ratio) than the Mg-9%Al alloy (reduction ratio 1.5:1). This deformation resulted in grain refinement of 65% for the Mg-3%Al alloy (from an average size of 57 μm down to 20 μm), Figure 1(b). In the case of the Mg-9%Al alloy, the grain refinement was just ~ 20%, from an average of ~ 30 μm to 25 μm, Figure 1(d).

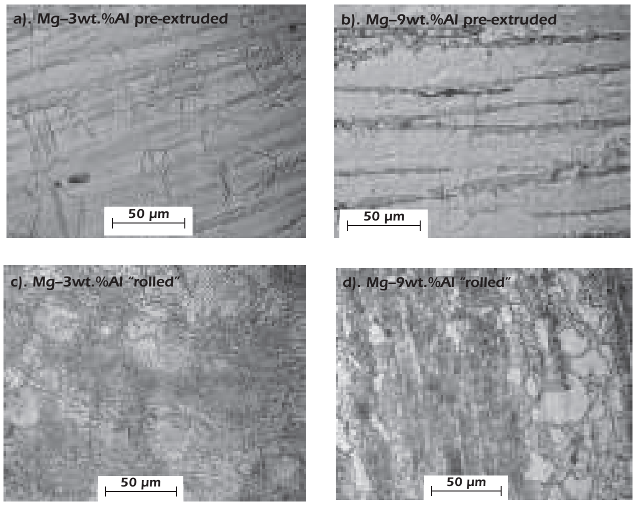

Fig. 1 Microstructural evolution of Mg-Al binary alloys:(a, c) starting (pre-extruded) structure, and (b, d) resulting "rolled" structure.

The Mg-3%Al alloy twinned extensively during deformation, which should have an effect on the crystallographic texture of the material. The 9%Al alloy does not exhibit any twinning, which can be attributed to greater mechanical strength of this material.

Little or no $Mg_{17}Al_{12}$ precipitates were present prior to testing for both alloys. The resulting structures, however, show numerous β-phase precipitates, which can have an influence on texture development.

Results: Texture Evolution

In magnesium and its alloys, extrusion results in the basal poles aligning themselves normal to the extrusion axis, as shown in the (0002) pole figure for pure Mg before deformation (Figure 2a). Two different pure Mg specimens were compressed parallel and normal to the extrusion axis. The reduction ratio used was 4.8:1. The (0002) pole figure for the specimen compressed parallel to the extrusion axis is shown in Figure 2(b). The constraint from the channel die was parallel to Y, while free expansion was allowed parallel to X. The resulting (0002) pole figures for the specimens compressed normal and parallel to the extrusion axis were identical. Comparing the (0002) pole figures for the deformed and undeformed states, it is clear that the (0002) poles have rotated, such that they have become aligned with the compression/extrusion direction. The pole figure is symmetric with respect to the loading axis.

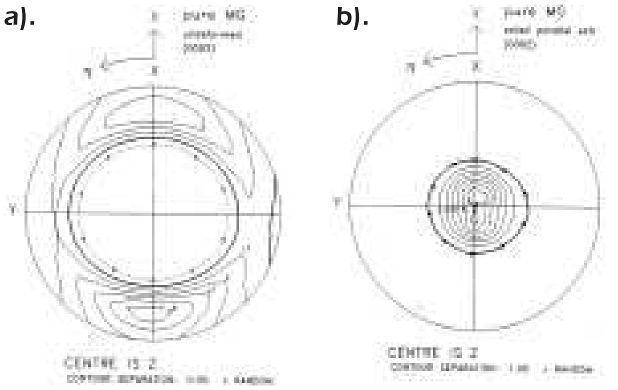

Fig. 2 *(0002) pole figures for Mg (a) before and (b) after deformation. The heavy solid line in the pole figure corresponds to 1xRandom; the solid lines are at the noted contour intervals up to the maximum contour marked with x's. The dashed lines are for contours below random and the minimum contour is marked with circles. The extrusion axis is parallel to the Z-axis in the pole figure.*

The (0002) pole figures for Mg-3%Al before and after deformation are shown in Figure 3. The specimen was compressed parallel to the extrusion axis (Z). The constraint from the channel die was parallel to Y, while free expansion was allowed parallel to X. As in the case of the pure Mg, the (0002) poles have aligned themselves with the direction of the compression and extrusion. However, unlike in the pure Mg, the texture has become asymmetric with respect to the compression axis.

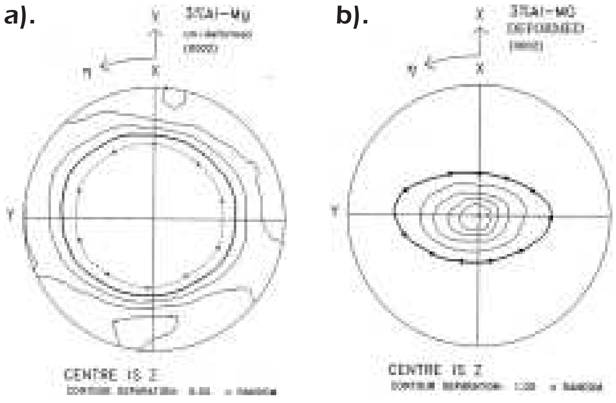

Fig. 3 *(0002) pole figure for binary Mg-3% alloy (a) before and (b) after deformation.*

The (0002) pole figures for Mg-9%Al before and after deformation are shown in Figure 4. The specimen was compressed normal to the extrusion axis (Z). The extrusion axis was parallel to X, and the material was allowed to expand freely in that direction. The channel-die walls constrained expansion parallel to Y. As shown in the figures, very little texture evolution has occurred.

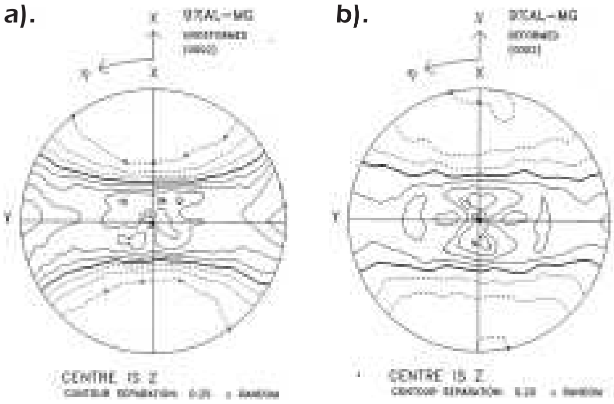

Fig. 4 *(0002) pole figure for Mg-9wt.% Al (a) before and (b) after deformation.*

Discussion: Deformation Mechanisms

The texture evolution exhibited by the three materials can be attributed to basal slip and {1012} twinning, both of which are consistent with the observed changes in texture. Basal slip results in the basal poles aligning themselves with the compression/extrusion direction. Reorientation due to slip occurs gradually over a large strain interval, and is generally favored at higher temperatures and low strain rates. {1012} twinning results in an 86.4° reorientation of the crystal lattice, which would result in grains having an orientation represented by points at the periphery of the pole figures moving to the centre of the pole figures. Lattice reorientation due to twinning occurs abruptly, at the speed of sound, and is favored at lower temperatures and higher strain rates.

The pole figures for the materials before deformation show a weak extrusion texture, with a maximum intensity of 2-3.5×random. The maximum intensity after deformation is about 8×random for the pure Mg, about 6×random for Mg-3%Al, and only about 1.6×random for Mg-9%Al. The differences in the deformation textures exhibited by the three materials are due to differences in the relative amounts of basal slip and {1012} twinning, which are influenced by strain, temperature and composition (as it pertains to solid solution and precipitation strengthening).

The pure magnesium was deformed at a lower temperature, and to a much higher strain, than the two binary alloys. It exhibits the strongest deformation texture, which is symmetric about the compression axis, despite the constraints imposed by the channel walls. Pure magnesium deforms easily by basal slip and {1012} twinning at elevated temperatures. [2] Typically, lenticular twins form within a grain, and grow until the original grain is entirely consumed. For the specimen compressed parallel to the extrusion axis, most of the grains are favourably oriented for {1012} twinning; the material can thus be expected to twin completely, resulting in the observed lattice reorientation. Once twinning has occurred, basal slip can take place on the reoriented basal planes. The specimen that was compressed normal to the extrusion axis (pole figure identical to Figure 4) presents an interesting case. The resulting deformation texture suggests that significant {1012} twinning has occurred likely due to the constraints imposed by the channel walls, which impose a compressive load normal to the c-axis in many grains.

The Mg-3%Al exhibits a similar deformation texture to the pure Mg, though it is weaker, due to the much lower strain imposed, and it is not symmetric about the compression axis. It is likely that {1012} twinning is the dominant mechanism contributing to texture evolution. However, it appears that the constraints imposed by the channel walls, perhaps combined with the precipitation that takes place, restrict twinning in some grain orientations, resulting in the asymmetric texture

The Mg-9%Al exhibits relatively little change in texture. This can only be explained by basal slip since no twinning was observed in the metallographic structure of the sample. The presence of copious precipitation appears to inhibit twinning.

References

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