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Modeling of the work hardening in magnesium alloy sheets

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ABSTRACT

The deformation behavior of rolled Mg–Al–Zn and Mg–Zn–RE (rare earth) sheets after annealing was investigated in tension. The tensile axis was oriented in either the rolling direction (RD) or the transverse direction (TD). The deformation tests of the sheets were accompanied by *in situ* measurements of the acoustic emission (AE); AE signal analysis correlates the microstructure and the stress-strain curves to possible deformation mechanisms. X-ray diffraction is applied to determine information about the deformation textures both prior to and after the tests. Both texture analysis and AE for different loading and texture conditions suggest that the prismatic slip is dominant in larger deformation stages.

A strain hardening model, based on the generalized Kocks-Mecking approach, is fitted to the observed deformation behavior, including the mechanical anisotropy of the Mg alloy sheets. The model enables the determination of the work hardening coefficient, considering the glide obstacles of both dislocation and non-dislocation origin; the distribution of grain orientations is also considered. The work hardening analysis is applied to the late stage of deformation, where twins are included only as non-dislocation barriers for mobile dislocations.

1. Introduction

Magnesium alloys, as the lightest construction metals, offer numerous interesting mechanical and physical properties and have, therefore, much potential for different advanced applications (Easton et al., 2008). The expansion of existing industrial applications of magnesium alloys are currently focused on the utilization of magnesium sheets. The mechanical properties (especially strength, ductility and formability) of magnesium alloys with their hexagonal close packed (hcp) lattice are strongly influenced by strong textures (Bettles and Gibson, 2005). Strong textures in magnesium alloys are observed when the samples are prepared by rolling or extrusion (Agnew et al., 2005; Bohlen et al., 2005, 2007; Kabirian et al., 2015). It is well known that magnesium alloys with strong textures may exhibit both tension-compression asymmetry and anisotropy of plastic properties with respect to the forming geometry. The texture development and deformation behavior of magnesium alloys depend on the activity of the slip and twinning systems. There are only two independent slip systems of the easiest

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basal mode, which is not sufficient for a hexagonal material to be able to undergo general continuous straining. Five independent deformation modes are required for the homogeneous deformation of polycrystalline materials (von Mises, 1928; Taylor, 1938).

In general, magnesium and its alloys can be deformed along the axis <a> = $\langle 11\overline{2}0\rangle$ by the activation of dislocation slip on the basal {0001}, prismatic $\{10\overline{1}0\}$ and 1st order pyramidal $\{10\overline{1}1\}$ planes. To accommodate the deformation along the <c>-axis, the first- and second-order pyramidal slips with a Burgers vector <c + a>, the latter of which, $\{\overline{11}22\}\frac{1}{3}\langle 11\overline{2}3\rangle$, occurs more easily, and/or tensile or compression twinning on the pyramidal planes $\{10\overline{1}2\}$ or $\{10\overline{1}1\}$, respectively, should be considered (Kocks and Westlake, 1967; Kelley and Hosford, 1968a, b). The simultaneous activity of five slip/twinning systems, which is a necessary condition for the general deformation of a polycrystalline material, appears somewhat difficult in a hexagonal material because of the extremely different resolved shear stresses of the available deformation systems. For magnesium monocrystals, the resolved strengths of the prismatic and 2nd order pyramidal slips are approximately 80 times greater than that of the basal one (Tonda and Ando, 2002) at room temperature; this ratio (relative resolved shear stress) decreases for higher temperatures. For the tensile twinning $\{10\overline{1}0\}\langle\overline{1}011\rangle$ frequently observed in magnesium, with a unipolar dilatation along the c-axis $\sqrt{3}a/c - 1 = 6.72\%$, the relative shear stress takes on the value 2–4 (Roberts, 1964 or Barnett, 2003).

Because the compatible deformation of hexagonal polycrystals requires the simultaneous activity of very distinct slip systems in nearby grains, some mechanisms that can bring the apparent resolved stresses of these systems closer together must be considered. For example, an accommodation stress proposed to enhance the basal slip resistance during the in-plane straining of a rolled AZ31 sheet may be cited (Balík et al., 2012). A similar trend for slip resistances is also confirmed by existing models of polycrystalline plasticity. For several rolled magnesium alloys, the visco-plastic and elasto-plastic self-consistent models yield relative slip resistances of 2–5.5 for prismatic slip, 3–7 for pyramidal slip and 0.5–1.6 for tensile twinning (Agnew et al., 2001, 2003; Agnew and Duygulu, 2005; Jain and Agnew, 2007; Bohlen et al., 2007). The consideration of twinning grains via a Voigt-type composite-like model (Barnett et al., 2006) leads to the relative resolved stresses of prismatic slip, pyramidal slip and twinning of 2, 15, and 0.7, respectively, for the AZ31 alloy. Somewhat larger strengths ranging from 8.5 to 15.6, 16–32 and 4.8–9.6, respectively, for glide mechanisms result from the crystal plasticity finite element method (Hama and Takuda, 2011). The wide ranges in the above ratios may be caused by, in addition to the approximate nature of such models, the considerable sensitivity of the deformation regime to the specific texture. It should be further noted that crystallographic reorientation due to twinning may facilitate the activity of previously unfavorable dislocation slip systems.

It is generally accepted that the dislocation glide in basal planes invariably occurs at the onset of tensile in-plane deformation in Mg alloys sheets and is followed by dislocation glide on non-basal planes and/or twinning. However, the operation and type of non-basal slip systems and twinning when plastic deformation increases is still being discussed in the literature. Prismatic slip has been considered several times and is reported to be of great relevance (Koike and Ohyama, 2005; Barnett et al., 2006; Balík et al., 2012; Hama and Takuda, 2011; Mayama et al., 2011; Boehlert et al., 2012). Hama and Takuda (2011), modeling the stress-strain curves for loading and unloading tests of the alloy AZ31B, have found that a considerable contribution from prismatic slip should appear after a short region of pure basal slip dominance. Mayama et al. (2011) performed a detailed study concerning the influence of different slip and twinning systems on texture development. They concluded that a non-basal slip system with a $\langle 11\overline{2}0\rangle$ slip direction is the dominant mechanism for the alignment of the $\{10\overline{1}0\}$ planes in the extrusion direction.

Using polycrystalline plasticity modeling, Agnew and Duygulu (2005) have shown that a decrease in the anisotropy of AZ31 at higher deformation temperatures may be explained by an increase in the activity of second-order pyramidal slip systems and primary (tensile) twinning modes (see also Brown et al., 2005; El Kadiri et al., 2013; Khosravani et al., 2013; Wang et al., 2013). Khan et al. (2011) investigated the mechanical properties and texture evolution of AZ31 magnesium alloy sheets both under tension and under compression as a function of temperature and strain rate. They observed no twinning at higher temperatures and concluded that the non-basal deformation was likely accommodated by the <c + a> slip.

Rolled sheets of the Mg-based alloys (e.g., AZ31 and ZE10) exhibit a typical basal texture with basal planes oriented nearly parallel to the plane of rolling (Wagoner et al., 2006; Hantzsche et al., 2010; Yi et al., 2010; Al-Samman and Li, 2011; Nürnberg et al., 2011). Such a texture favors deformation twinning if a compressive stress is applied along the rolling direction (Reed-Hill, 1973). In the case of tensile in-plane tests, deformation can be realized practically with near-zero tensile twinning (Agnew and Duygulu, 2005; Jain and Agnew, 2007). Bohlen et al. (2007) have recently reported the texture development in six Mg–Zn alloys with dilute additions of Y, Nd, Ce and Mn. In the case of the alloy ZE10, the angular basal pole distribution appears appreciably broader in the transverse direction (TD) than in the rolling direction (RD), whereas the prismatic poles are distributed almost isotropically in the rolling plane, with a slight preference for the RD. According to the strong basal texture, a marked in-plane tension, compression asymmetry and anisotropy in mechanical properties are displayed in magnesium rolled sheets.

Twinning is an important mode influencing the mechanical properties of AZ31, as shown in an analysis reported by Barnett (2007a, b). A model describing the influence of mechanical twinning and temperature on the compression deformation behavior of magnesium alloy sheets has been developed by Jain and Agnew (2007). Fernández et al. (2011) have recently published a model describing the slip and twin system activities during the compression of AZ31 rolled sheets. The model describes the texture development during deformation. The model's mechanisms of hardening by twinning in magnesium were recently presented by Oppedal et al. (2012). They reported that pure magnesium at large strains develops