Materials Science & Engineering A 659 (2016) 295–305

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Flow transitions and flow localization in large-strain deformation of magnesium alloy

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ARTICLE INFO

Article history:
Received 10 August 2015
Received in revised form
17 February 2016
Accepted 18 February 2016
Available online 2 March 2016

Keywords:
Magnesium alloys
Bulk deformation
Thermomechanical processing
Recrystallization
Shear bands
Twinning

ABSTRACT

Understanding transitions from homogeneous to localized flow, and mechanisms underlying flow localization, is of paramount importance for deformation processing of magnesium. In this study, a shear-based deformation method is utilized for imposing large strains (~1), under controllable strain rates (10–10^5/s) and temperatures (80–300 °C), in order to examine flow patterns in a magnesium alloy. Based on microstructure characterization, deformation twinning is suggested to contribute to the localized flow at temperatures below 200 °C and at low strain rates. The transition from the localized to homogeneous flow with increasing temperature is due to reduction in twinning activity, and enhanced strain-rate sensitivity. At constant temperature, an increase in the strain rate decreases the propensity for flow localization. A model is presented for characterizing the maximum uniform strain as a function of temperature and deformation state (simple shear, plane-strain compression). The model incorporates temperature-sensitive microstructural changes and flow properties of magnesium into a classical framework to capture the flow localization phenomena at low temperatures and strain rates.

1. Introduction

Deformation processing of magnesium (Mg) alloys has received much interest in recent years in view of exploiting their light-weight properties for automotive and other structural applications. Several thermo-mechanical forming routes, including traditional as well as emerging ones, have been applied for processing wrought forms having enhanced mechanical properties over cast counterparts [12345]. All of these processes necessarily involve large-strain deformation, with effective strains in the range of 0.5–1, for ingot breakdown and refining the microstructure. However, flow localization and cracking continue to pose challenges that limit deformation processing capacity of these alloys [6789]. In order to overcome these issues, wrought processing is commonly carried out under small incremental strains at elevated temperatures (above 200 °C) [1]. Additional annealing treatments are commonly required between the deformation steps for restoring ductility. This requirement for high-temperature processing and intermediate annealing not only contributes to high energy/economic costs, but also limits the scope for microstructure (grain size, texture) control and design.

The poor workability of Mg and its alloys, long known, is generally attributed to the lack of enough independent slip systems to accommodate the large deformation. More recently, severe flow localization has been identified as the most likely cause for premature failures in forming [7810]. In Mg, basal ⟨*a*⟩ slip has the lowest critical resolved shear stress (CRSS), and is therefore the dominant deformation mode. This is particularly true at ambient temperatures (<100 °C) where the CRSS for non-basal slip modes, such as prismatic ⟨*a*⟩ and pyramidal ⟨*c* + *a*⟩ modes, is ~100 times that of the basal slip [1112]. With increasing temperature, CRSS values for non-basal modes decrease significantly, becoming comparable to that of basal slip beyond 200 °C [111213]. The oft-quoted flow transition from brittle to ductile type in the 200–250 °C temperature range is attributed to the thermal activation of non-basal modes, which provide enough independent slip systems (total of 9, including basal slip) for homogeneous deformation. Under stress states wherein the basal slip is restricted due to geometric constraints, as in compression along the *c*-axis, twinning predominantly contributes to the flow. It has been suggested

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http://dx.doi.org/10.1016/j.msea.2016.02.054
0921-5093/

that the large crystal reorientations associated with twinning induce flow localization and cause overall flow softening [61014151617]. At the microstructure level, however, the way the localized flow inside the twins initiates macro-scale localization patterns (e.g., shear bands) is unclear. Dynamic recrystallization (DRX) is another important characteristic of large-strain deformation that contributes to flow softening and grain size refinement, especially at elevated temperatures. The DRX phenomena in wrought processing of Mg have been studied extensively in the context of elucidating microstructure/texture evolution [318192021]. The objective of the current study is to understand the possible effects of twinning and DRX on flow localization, and characterize the flow transitions occurring with changes in strain rate and temperature.

Flow localization in Mg–3Al–1Zn alloy (AZ31B) is studied using extrusion-machining (EM) [22]. In EM, a layer of workpiece surface material is removed in the form of a chip by simultaneous cutting and extrusion – in fact, quite analogous to the action of a kitchen peeler. Supplementary Video 1 shows a high-speed video of material flow in EM. The underlying deformation is simple shear. The effective strains (ε) imposed in the chip are quite large ($\varepsilon \sim 1$), and the strain rate ($\dot{\varepsilon}$) and temperature (T) in the deformation zone are controllable over a range by adjusting the process parameters. In the current study, $\dot{\varepsilon}$ is varied from ~10/s to 10^5/s, and T in the range of 80–300 °C. These conditions encompass those prevailing in conventional wrought processing of Mg alloys. Detailed microstructural observations of the flow, deformation analysis, and comparison with rolling provide the basis for a model, which qualitatively predicts the susceptibility to flow localization and its dependence on deformation parameters.

2. Background

The inhomogeneity of plastic flow in metals is ubiquitous across multiple length scales. Slip bands and Newmann bands (twins) are some manifestations of the micro-scale (grain level) inhomogeneity, while Lüders bands and shear bands are examples of macro-scale localization. This study is concerned with the flow localization in the form of shear bands. Shear bands have been observed in diverse metallic systems and are generally believed to arise from flow-stress softening, due to either adiabatic heating (under dynamic loading conditions) [23] or in-process texture reorientation [24]. An alternative theory suggests dynamic stored energy and DRX as playing a critical role in initiating shear bands [25].

A distinct feature of deformation of Mg, when compared with other metals, is the occurrence of inhomogeneous flow at the macro-scale even under relatively low strains [6726]. Furthermore, the initial texture and the imposed deformation (stress) state largely determine the deformation mechanisms and have a strong effect on the flow [1626]. The highly inhomogeneous flow in Mg is indeed expected, given the shortage of independent deformation modes. As noted, basal slip and twinning are the dominant deformation modes at low temperatures (<200 °C), which by themselves are not sufficient to homogeneously accommodate the large strains typical of forming. Localized flow inside twins has been attributed as the origin for this inhomogeneous flow [61415161726]. This phenomenon is best illustrated in rolling of a strongly basal-textured sheet. Since basal slip is geometrically restricted in the "hard" basal texture orientation, the resultant high stresses lead to "contraction" twinning modes (twinning on $\{10\bar{1}1\}$ or $\{10\bar{1}3\}$ planes) that accommodate compressive strain along the c-axis. The crystal reorientation associated with these modes places the twin in a "soft" orientation for favorable basal slip or secondary twinning. Consequently, the twin experience

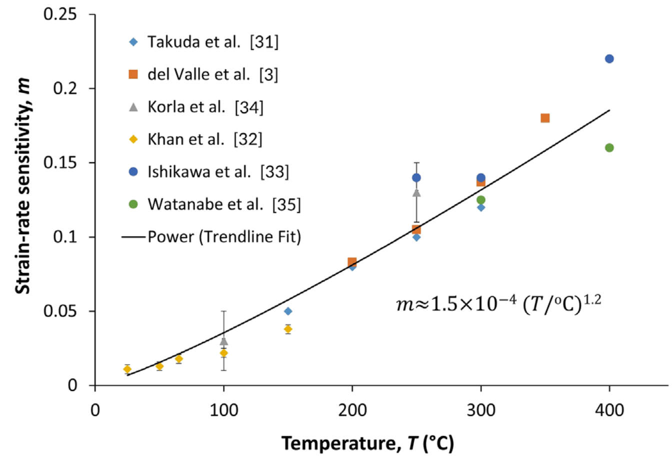

Fig. 1. Temperature effect on the strain-rate sensitivity (m) in Mg AZ31B alloy; 10^{-3}/s ≤ $\dot{\varepsilon}$ ≤ 1/s and 0.05 ≤ ε ≤ 0.7.

intense localized deformation. In fact, shear strains up to 7 were noted inside the twins [27]. Preferential recrystallization inside the twins, referred to as the twinning-induced dynamic recrystallization (TDRX) [151617], and the signature dark etching contrast [14] are some other indications of the localized flow inside the twins. The incompatibility stresses, which develop across the twin boundaries due to local deformation, also initiate voids and are a cause for premature failure under tension [14]. Under compressive stress states, typical of bulk forming, profuse twinning is believed to contribute to the global flow softening and attendant shear banding [26].

The onset of flow softening or shear banding is generally predicted using load instability [82829] and perturbation [930] analyses, assuming a power-law relation for the flow stress (σ), given by $\sigma \approx \varepsilon^n \dot{\varepsilon}^m T^{-\nu}$, where n is the strain-hardening exponent, m is the strain-rate sensitivity, and ν is a thermal-softening parameter. The material properties (n, m and ν) are typically treated as constants, independent of the deformation parameters (ε, $\dot{\varepsilon}$ and T). However, for Mg alloys, the effects of deformation parameters on material properties cannot be simply ignored. For example, Fig. 1 illustrates the effect of temperature on m [33132333435], wherein a 20-fold increase from ~0.01 to 0.20 occurs for an increase in T from 25 °C to 400 °C, this commonly attributed to the enhanced activity of non-basal slip modes. This study takes into account these dynamic material properties, together with the microstructural effects (twinning), for modeling flow localization.

3. Experimental

3.1. Extrusion-machining (EM)

Extrusion-machining (EM) is used to impose large-strain deformation in Mg alloy AZ31B over a range of $\dot{\varepsilon}$ and T in order to characterize flow localization and flow transitions. In EM, a sharp, wedge-shaped cutting tool removes a preset depth (undeformed chip thickness, t_0) of workpiece material in the form of a thin chip/ribbon (see Supplementary Video 1). The stress state is simple shear, as imposed by simultaneous cutting and extrusion. The deformation field in EM has been characterized by in situ high-speed imaging and image analysis using particle image velocimetry (PIV) [2236]. PIV has been traditionally used in fluid mechanics to map the velocity field of fluid flows by tracking motions of particle ensembles. When using PIV to study deformation, the role of the particles is played by "asperities" – roughness features, deliberately introduced by abrasion onto a side of the workpiece