Materials Science & Engineering A 712 (2018) 140–145

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Formability of a wrought Mg alloy evaluated by impression testing

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ARTICLE INFO

Keywords:
Mg alloy
Formability
Impression testing
Twinning

ABSTRACT

This study is focused on furthering our understanding of the different factors that influence the formability of Magnesium alloys. Towards this end, formability studies were undertaken on a wrought Mg-2Zn-1Mn (*ZM21*) alloy. In contrast to conventional formability studies, the impression testing method was adopted here to evaluate the formability parameter, *B*, at temperatures ranging from 298 to 473 K. The variation of *B* of *ZM21* with temperature and its rather limited values were discussed in the light of different deformation mechanisms such as activation of twinning, $<c+a>$ slip, grain boundary sliding (GBS) and dynamic recrystallization (DRX). It was found that the material characteristics such as grain size, texture and testing conditions such as temperature and strain rate, were key determinants of the mechanism of plastic deformation. A by-product of this analysis was the observation of an interesting correlation between the Zener-Hollomon parameter, *Z*, and the ability of Mg alloys to undergo DRX.

1. Introduction

Wrought Mg alloys possess an attractive combination of properties such as low density and good specific strength. However, they often have poor room temperature ductility which limits their formability. This is primarily due to the *hcp* crystal structure of Mg which provides only 3 independent slip systems, contributed by basal slip, rather than the minimum five required to satisfy the *von Mises* criterion. Although twinning is known to complement slip during plastic deformation, the plastic strain contribution from twinning is of the order of a few percent, and furthermore, extension twins based on $\{10\bar{1}2\}\langle 10\bar{1}1\rangle$ reorient the Mg alloy grains into rather hard modes that restrict further plastic deformation [1]. As a result, improvements in plastic deformation have been sought by increasing the number of slip systems either by activating slip on the prismatic and pyramidal slip systems through solute addition [2,3] or by introducing secondary phases based on *bcc* structure [4]. The prismatic and pyramidal slip systems are generally inactive at room temperature due to their relatively high critical resolved shear stress (*CRSS*) compared to basal slip and twinning. It has been observed that at higher temperatures ($T \sim 473\,K$), the CRSS of prismatic and pyramidal slip experiences a sharp drop [5] relative to *CRSS* of basal slip and twinning, and hence plasticity of Mg and its alloys is enhanced. Between prismatic and pyramidal slip, the latter is considered more beneficial for reducing the anisotropy of plastic deformation, which stems from the *hcp* structure of Mg. Unlike prismatic slip which occurs in $<a>$ direction only, the $<c+a>$ slip encouraged by pyramidal slip systems allows accommodation of strain in the *c* direction as well thereby leading to more homogeneous plastic deformation, a pre-requisite for higher formability. Systematic work by Agnew and Duygulu [6] has revealed that the Lankford coefficient, *r*, which is a measure of the anisotropy of plastic deformation, decreases with increasing temperature and this decrease was attributed to the contribution of $<c+a>$ slip to the overall plastic deformation. In contrast to the work by Agnew and Duygulu [6], Barnett et al. [7] attributed the reduction in, *r*, with increasing temperature to grain boundary sliding as a result of the strong dependence of anisotropy on grain size. The role of GBS as a chief controller of anisotropy in Mg alloys was however discounted by Stanford et al. [8] based on surface relief and grain boundary shear measurements and their contribution to the overall plastic strain. In addition to $<c+a>$ slip and GBS, dynamic recrystallization (DRX) processes [9–11] become important with increasing temperature and hence their role in the formability of Mg alloys must be evaluated. During thermomechanical processing, DRX leads to the formation of fine strain-free grains which serve the dual purpose of refining the structure and randomizing texture while providing opportunities for more homogeneous plastic deformation. Samman and Gottstein [12] investigated the role of DRX during hot working of AZ31 and found that the transition from a brittle to ductile

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https://doi.org/10.1016/j.msea.2017.11.088
Received 2 October 2017; Received in revised form 20 November 2017; Accepted 21 November 2017
Available online 22 November 2017
0921-5093/

behavior in this alloy is influenced by the ability of the material to undergo DRX. Indeed compression tests carried out at 473 K at a strain rate of $10^{-2}\,s^{-1}$ revealed cracking on the specimen surface while the core displayed a ductile behavior. The core was found to have undergone dynamic recrystallization, and based on this Samman and Gottstein [12] hinted at the role of DRX in controlling the formability of Mg alloys. Since the ability of the Mg alloy to undergo twinning, $< c + a >$ slip or GBS or DRX during plastic deformation is linked to the grain size, starting texture and the temperature and strain rate of deformation, the study focuses on evaluating the role of these mechanisms guided by the above mentioned parameters during plastic deformation of a thin sheet of ZM21, a Mg-2Zn-1Mn alloy. The mechanical behavior of this material was studied using the impression testing method. The formability of this alloy was evaluated using the impression testing method and instead of the Lankford coefficient, *r*, the formability parameter *B* was determined from the impression testing data to understand the formability of this alloy at various temperatures.

2. Experimental

A plate of ZM 21, with a thickness of 17 mm, was obtained in the wrought form. Optical metallography was carried out on the three surfaces to reveal the grain structure as well as to determine the grain size. The specimens were first polished with 1200 grit emery paper and later cloth polished to final surface roughness of 1 µm. Following mechanical polishing, the specimens were chemically etched using a picric acid based etchant which is basically a solution of 25 ml of saturated solution of picric acid in ethanol with 10 ml acetic acid, 5 ml deionized water and 5 ml methanol. The etched structure was then studied using an optical microscope. The material had an equiaxed grain structure along the three surfaces and average grain size determined using the mean linear intercept method was found to be 34 ± 3 µm for the RD, TD and ND surfaces. EBSD studies were undertaken to characterize the texture of these plates. EBSD studies were carried out on FEI Quanta SEM and TSL software was used to perform the analysis. Fig. 1 is the EBSD map of ZM21 as captured from the ND surface. The color map along with the inverse pole figure of ND surface reveals a predominantly basal texture, as is also validated by the pole figure. Due to the small thickness of plate an impression testing technique was adopted to determine the strength properties and formability parameters. In this test, a cylindrical indenter with a flat end is allowed under the action of a stress to make a shallow impression on the surface of the specimen. The depth of penetration of the indenter at a given stress is a measure of plastic strain and this is correlated with the applied stress to evaluate the stress-strain characteristics of the material. It has been observed that the impression mechanical data correlates well with conventional tensile testing, and hence it offers several advantages over the latter, viz., small quantity of testing material being sufficient.

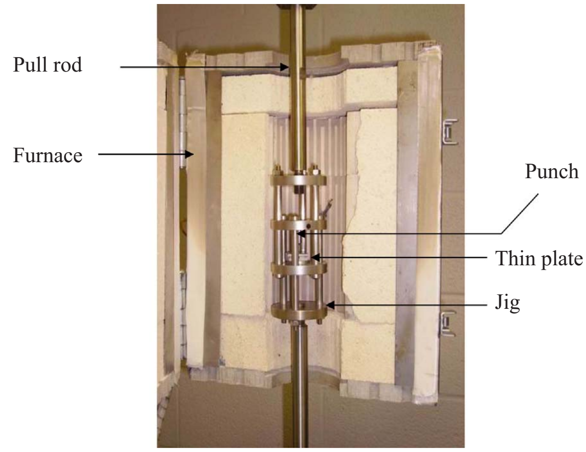

Fig. 2. Impression creep testing set-up used for evaluating the mechanical properties and formability of ZM21.

In the present case, the impression testing was carried out using an indenter with tip diameter of 1 mm. The experimental arrangement is as shown in Fig. 2 and the testing was carried out on an INSTRON machine at a constant strain rate of $8 \times 10^{-3}\,s^{-1}$. Tests were carried out at different temperatures from 298 K to 473 K on the RD, TD and ND surfaces.

3. Results and discussion

The impression stress, σ, was calculated from the following relation, $\sigma = 4P/\pi d^2$, where *P* is the applied load and d is the punch tip diameter. The impression strain, ε, was calculated using the relation, $\varepsilon = \delta/d$ where δ is the penetration depth and *d* the diameter of the impresser. Typical impression stress-strain curves obtained from the tests are shown in Fig. 3. Using the impression stress-strain curves from tests at different temperatures, the 0.2% impression strength was determined. The 0.2% impression strength for the three surfaces at different temperatures is listed in Table 1. With the impression strength data, the anisotropy parameters *R*, *P* and formability parameter *B* were evaluated. The anisotropy parameters *R* and *P* can be calculated by Hill's equation and are as follows,

$$R = \frac{(\sigma_{ND}\sigma_{RD})^2 + (\sigma_{ND}\sigma_{TD})^2 - (\sigma_{TD}\sigma_{RD})^2}{(\sigma_{TD}\sigma_{RD})^2 + (\sigma_{ND}\sigma_{TD})^2 - (\sigma_{ND}\sigma_{RD})^2} \quad (1)$$

$$P = \frac{(\sigma_{ND}\sigma_{RD})^2 + (\sigma_{ND}\sigma_{TD})^2 - (\sigma_{TD}\sigma_{RD})^2}{(\sigma_{TD}\sigma_{RD})^2 + (\sigma_{ND}\sigma_{RD})^2 - (\sigma_{TD}\sigma_{ND})^2} \quad (2)$$

where σ_{RD}, σ_{TD} and σ_{ND} are the yield stress values along RD, TD and ND directions, respectively. The formability parameter, *B,* was

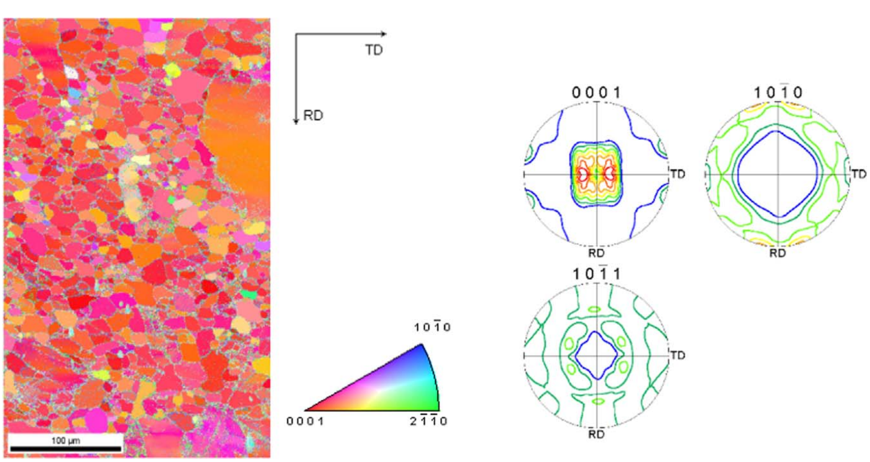

Fig. 1. EBSD map obtained from ND surface. The color coding suggests that most of the grains have their ND direction oriented parallel to the basal poles which is also validated by the inverse pole figure and pole figure data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)