Materials Science and Engineering A 527 (2010) 735–744

Contents lists available at ScienceDirect

Materials Science and Engineering A

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

Hot workability analysis of extruded AZ magnesium alloys with processing maps

F.A. Slooff*, J.S. Dzwonczyk, J. Zhou, J. Duszczyk, L. Katgerman

Department of Materials Science and Engineering, Delft University of Technology, Mekelweg 2, 2628 CD Delft, The Netherlands

ARTICLE INFO

Article history:
Received 18 January 2009
Received in revised form 21 August 2009
Accepted 26 August 2009

Keywords:
Hot working
Processing maps
Magnesium alloy
Hot deformation
Compression testing
Dynamic recrystallization

ABSTRACT

The processing conditions applied to deform wrought magnesium alloys greatly affect their final microstructure and mechanical properties. Defining an applicable processing window in terms of the ranges of temperatures and strain rates to achieve a homogeneous microstructure is a prerequisite for process optimization, since magnesium alloys show a peculiar deformation behaviour. By using trustworthy input data from uniaxial hot compression tests, processing maps were constructed for the alloys AZ41, AZ61 and AZ80. These maps clearly indicate the conditions leading to dynamically recrystallized homogeneous microstructures after hot deformation, as verified by analysing the microstructures after hot deformation under different conditions. It is found that a strain rate of 5 s^{-1} and a temperature of 375 °C for AZ41 and 325 °C for both AZ61 and AZ80 would result in dynamically recrystallized homogeneous microstructures.

1. Introduction

The combination of low density and moderate strength makes wrought magnesium alloys well suited for applications where weight is of critical importance. Several attempts have been made to search for optimum deformation conditions for wrought magnesium alloys [1–5], since the unfavourable deformation behaviour of magnesium at ambient temperature causes difficulties as a result of its hexagonal close packed crystal structure, leading to limited slip systems. Processing magnesium alloys at elevated temperatures enables the activation of non-basal slip systems. Coupling the processing conditions such as deformation rate and temperature to a desired microstructure is a valuable approach to deformation process optimization and this can be achieved by using processing maps.

Processing maps have been proven to be a useful tool for the optimization of hot working processes for a wide range of metals and their alloys [6–8], or for the design of process parameters for new materials. It is helpful in identifying different deformation mechanisms within different domains. As a product of the dynamic materials model [9], it combines the efficiency of power dissipation and the instability of deformation. The dissipated power is related to the rate of internal entropy production due to the metallurgical processes involved and the partitioning of the total power between that due to the temperature rise and that due to microstructural changes. Strain rate sensitivity is considered a power partitioning factor [10]. The efficiency of power dissipation η with respect to the linear dissipator is given by:

$$\eta = \frac{2m}{m+1} \quad (1)$$

in which m is the strain rate sensitivity. Plotting the efficiency (in %) against temperature and strain rate at different strains results in the power dissipation maps, which can be seen as 3D surfaces; an increase of efficiency will result in the development of a hill. Above a threshold of efficiency, the area can be denoted as “safe” and such mechanisms as dynamic recrystallization, dynamic recovery or super plastic deformation may operate. The verification of this area needs to be done using optical microscopy. On the other hand, the valleys represent “damaging” microstructural changes, such as void formation, wedge cracking, intercrystalline cracking and other types of cracking.

The instability map is developed on the basis of an instability criterion and given by a dimensionless parameter ξ:

$$\xi = \frac{\partial(\ln(m/m+1)}{\partial \ln \dot{\bar{\varepsilon}}} + m \leq 0. \quad (2)$$

When ξ turns negative under specific temperature and strain rate conditions, flow instabilities like adiabatic shear bands or flow localization can be observed in the microstructure. The physical meaning of Eq. (2) is that if the system is unable to generate entropy at a rate that at least matches with the imposed rate, it will localize the flow and cause flow instability.

Superimposing an instability map on a power dissipation efficiency map produces a processing map. The instability map shows

* Corresponding author. Tel.: +31 6 1805 0603; fax: +31 1 5278 6730.
E-mail address: slooff@gmail.com (F.A. Slooff).

0921-5093/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.msea.2009.08.070

the areas that will cause flow instability, whereas the power dissipation map shows the most efficient power dissipation areas. Therefore, the combined areas (or domains) represent various microstructural changes, which can be safe, damaging or transitory. In the case of a transitory area, the term bifurcation is generally used to describe it. It is not linked to any specific domain but represents a qualitative change in the system dynamics, which is associated with a change in the topology of a processing map.

The processing maps constructed for magnesium alloys in most of the current literature concern specific alloys and cover only a limited range of strains [11]. In the case of wrought magnesium alloys, strain is significant for reliable hot workability analysis due to the occurrence of dynamic recrystallization (DRX), which strongly influences the mechanical response to deformation [12]. The processing maps developed by Sivakesavam [3] and Srinivasan [7], for example, were based on the flow stress data of ZM21 and magnesium alloys containing 3 wt.% Al at a strain of 0.4 and 0.5, respectively. At these strains and strain rates beyond $10\,s^{-1}$, the flow stresses are not fully in the steady state. Furthermore, Srinivasan used isothermal compression tests without further specification. While others did specify their methods for (adiabatic) temperature correction, the methods are inferior to the point-to-point (PPI) temperature correction method described elsewhere [13]. This accuracy is of importance, because at moderately elevated temperatures the temperature rise during deformation at high strain rates can exceed 80 °C and this temperature increase will lower the measured flow stress and the conventional linear method for temperature correction will overestimate the corrected flow stress. Correcting the measured flow stress to obtain isothermal flow stress data according to the PPI method leads to more accurate constitutive constants and activation energy for deformation in constitutive equations.

The Mg–Al–Zn alloy system is the most widely investigated one, with emphasis on the alloy having 3 wt% Al and 1 wt% Zn. Expanding the research to alloys having higher alloying contents will contribute to the overall knowledge of the deformation behaviour of this promising alloy system. In previous investigations [11,14–15] on the workability of wrought magnesium alloys in this system, mainly alloys with relatively low alloying contents such as AZ31 were analysed. The preceding research on the processing map for AZ31 concerned the as-cast alloy hot-compressed at strain rates up to $100\,s^{-1}$ [11] and the extruded alloy hot-compressed at strain rates up to $10\,s^{-1}$ [15].

In the present research, three alloys with increasing amounts of Al up to 8 wt% Al were subjected to investigation in order to clarify the influence of the alloying content on the hot workability. The alloys were in the as-extruded condition and the strain rates applied were up to $100\,s^{-1}$ as may be locally encountered in extrusion. Comparisons with the processing maps of AZ31 were made. The objectives of the present research were to obtain the processing maps for selected wrought magnesium alloys in the AZ group (Al and Zn containing) at different strains, using reliable input data, and to determine optimum windows for the forming processing of these alloys.

2. Experimental details

Three wrought magnesium alloys subjected to hot compression tests were Mg–Al4–Zn1 (AZ41), Mg–Al6–Zn1 (AZ61) and Mg–Al8–Zn0.5 (AZ80). Their compositions were determined using X-ray fluorescence spectrometry and are given in Table 1. Although AZ80 has a reduced Zn content compared to the other two alloys, previous research [16] indicates that variation of the Zn content below 1 wt.% will not significantly influence the mechanical properties and the difference in the Zn content between the alloys can therefore be neglected. The alloys were supplied in the form of cylindrically shaped cast ingots by Dead Sea Magnesium, Israel. These ingots were machined from a diameter of 74 mm to a diameter of 48 mm and cut to a length of 200 mm for extrusion. Extrusion was carried out at a ram speed of 1.5 mm/s using a 2.5 MN extrusion press with the container and die both preheated to 350 °C. Prior to extrusion, billets were preheated to 400 °C for 1 h. The die having an orifice diameter of 15.8 mm led to a reduction of 10:1 and to the dimensions of an extruded bar suitable for making hot compression specimens. Moreover, the extrusion process brought the materials to the same as-extruded metallurgical state. The cylindrical specimens used for compression testing were machined from the extruded bar to a height of 12 mm and a diameter of 10 mm. The testing temperature for AZ41 was varied between 250 and 500 °C with an interval of 50 °C. For AZ61, the temperature range was from 250 to 450 °C with an interval of 50 °C, while for AZ80 the temperature range was between 300 and 375 °C with an interval of 25 °C. The reason for these differences will be clarified later. For all the alloys, the strain rate was varied over a range of 0.01–$100\,s^{-1}$, with increment by one order of magnitude. Compression tests were carried out up to a true strain of 1.0.

Table 1
Chemical compositions of the alloys (wt.%) investigated.

	Al	Zn	Mn	Si	Mg
Mg–Al4–Zn1 (AZ41)	4.76	0.85	0.32	0.01	Bal.
Mg–Al6–Zn1 (AZ61)	5.6	0.81	0.18	0.08	Bal.
Mg–Al8–Zn0.5 (AZ80)	7.81	0.44	0.23	0.03	Bal.

For hot uniaxial compression tests, a Gleeble 3800 thermomechanical simulator was used. The specimen chamber was twice evacuated to 1013 mbar below ambient pressure and flushed with nitrogen prior to heating and kept at a reduced pressure of 169 mbar below ambient pressure to limit the oxidation of the specimen during the test. A thermocouple was welded on the surface of the specimen at the mid height for temperature control. A graphite sheet and nickel-containing paste were applied between the specimen and the cylindrical tungsten carbide anvils to minimize friction during the test. The specimen was resistance-heated at a rate of 10 °C/s and soaked at a preset temperature for 75–90 s to allow temperature to equalize. Fig. 1 shows the test chamber of the thermomechanical simulator prior to testing.

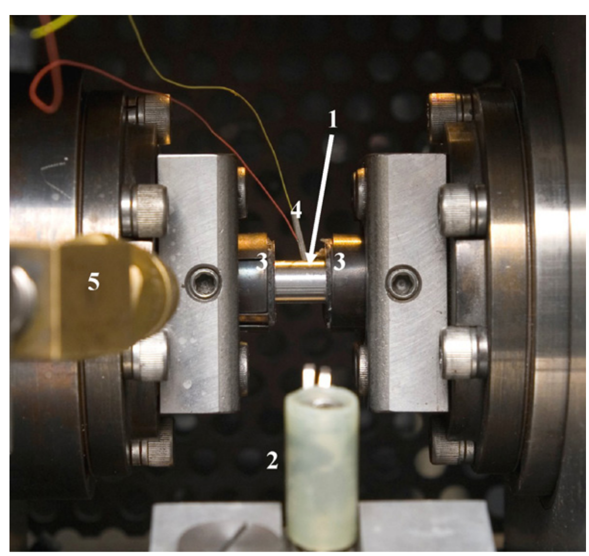

Fig. 1. Close-up view of the testing chamber with the specimen (1) put in place by the specimen holder (2), which retracts prior to testing. Before testing, the anvils (3) clamp the specimen and the thermocouples (4) are used for temperature control. After testing, the nozzles (5) located on both sides of the main axis allow quenching using forced air.