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Study on hot deformation behavior and microstructure evolution of cast-extruded AZ31B magnesium alloy and nanocomposite using processing map

M. Srinivasan [a,*], C. Loganathan [b], R. Narayanasamy [c,*], V. Senthilkumar [c], Q.B. Nguyen [d], M. Gupta [d]

[a] Department of Mechanical Engineering, Saranathan College of Engineering, Tiruchirappalli, Tamil Nadu 620 012, India
[b] A.V.C. College of Engineering, Mayiladuthurai, Tamil Nadu 609 305, India
[c] Department of Production Engineering, National Institute of Technology, Tiruchirappalli, Tamil Nadu 620 015, India
[d] Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117 576, Singapore

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ABSTRACT

The hot deformation behavior and microstructural evolution of cast-extruded AZ31B magnesium alloy and nanocomposite have been studied using processing-maps. Compression tests were conducted in the temperature range of 250–400 °C and strain rate range of 0.01–1.0 s^{-1}. The three-dimensional (3D) processing maps developed in this work, describe the variations of the efficiency of power dissipation and flow instability domains in the strain rate ($\dot{\varepsilon}$) and temperature (T) space. The deformation mechanisms namely dynamic recrystallization (DRX), dynamic recovery (DRY) and instability regions were identified using processing maps. The deformation mechanisms were also correlated with transmission electron microscopy (TEM) and optical microscopy (OM). The optimal region for hot working has been observed at a strain rate ($\dot{\varepsilon}$) of 0.01 s^{-1} and the temperature (T) of 400 °C for both magnesium alloy and nanocomposite. Few instability regimes have been identified in this study at higher strain rate ($\dot{\varepsilon}$) and temperature (T). The stability domains have been identified in the lower strain rate regimes.

1. Introduction

Magnesium based alloys are better alternate structural materials due to their light weight. They have high specific strength, good castability, good machinability and high damping capacity but poor workability due to their crystal structure (HCP) and limited number of slip planes [1,2]. The magnesium AZ31 (Al 3%, Zn 1%) alloys exhibit poor workability at room temperature which restrict their commercial applications. However, these alloys exhibit good workability at elevated temperatures than at room temperature. Hot deformation is concerned with the extent to which a material plastically deforms during forming at higher temperature without the occurrence of flow instability. Deformation is associated with the change in temperature, strain rate and strain. Workability of a material is dependent on externally controllable variables like strain (ε), strain rate ($\dot{\varepsilon}$), temperature of the work piece and on the inherent flow characteristics of the material [3]. In this work the hot deformation behavior has been obtained with the help of the standard kinetic approach as well as processing maps as demonstrated by Prasad and Seshacharyulu [4].

The hot workability of magnesium alloys plays a very important role in the study of hot deformation of AZ31B magnesium alloy [5,6]. Prasad et al. [2] have studied the hot deformation behavior of Mg/nano-Al_2O_3 using processing maps. They studied the increase in peak efficiency with the addition of nano-Al_2O_3 particles. Ganesan et al. [7] reported that a safe workable domain occur at higher temperature and lower strain in their study on the development of processing map for 6061 Al/15% SiC_p. Senthilkumar et al. [8] analyzed the hot deformation behavior of Al 5083–2% TiC nanocomposite. The deformation mechanisms such as DRX, DRY and flow localization were validated by the manifestation of many microstructural features after deformation. Adiabatic shear band formation was observed at higher strain rates. Though many studies have been carried out on the issues specific to the super plastic deformation in the commercial wrought Mg alloys, only a few have discussed the deformation behavior of as-cast Mg alloy AZ31B during hot deformation.

In the present study, a constitutive model based on Arrhenius equation was formulated relating the flow stress (σ), strain rate ($\dot{\varepsilon}$) and temperature (T) during the hot deformation of cast-extruded samples. Further, the hot deformation behavior has also been studied using processing maps. The manifestation of various hot deformation mechanism, namely, DRX, DRY instabilities were analyzed with TEM and OM images.

2. Hot workability analysis

During hot deformation, the relationship of flow stress with deformation temperature and strain rate can be described using

* Corresponding authors. Tel.: +91 0431 2503504; fax: +91 0431 2500133.
E-mail address: narayan@nitt.edu (R. Narayanasamy).

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standard kinetic rate equation relating the steady state flow stress (σ), strain rate ($\dot{\varepsilon}$) and temperature (T) which is given as follows as discussed elsewhere [9].

$$\dot{\varepsilon} = A\sigma^n \exp^{\left[-\frac{Q}{RT}\right]} \tag{1}$$

where A is a constant, n is a stress exponent ($n = 1/m$, m is the strain rate sensitivity), Q (kJ/mole) is the activation energy for hot working and R is the gas constant. In the earlier studies constitutive equations were formulated for conventionally hot worked magnesium alloys. To evaluate the validity of Eq. (1) the constitutive equation is correlated to the Zener–Hollomon parameter, which is defined as follows as discussed elsewhere [10].

$$Z = \dot{\varepsilon} \exp^{\left[\frac{Q}{RT}\right]} \tag{2}$$

The Zener–Hollomon parameter (Z) combines the control variables of $\dot{\varepsilon}$ and T through an Arrhenius function with activation energy (Q).

The flow stress, when the strain and deformation temperature are constants, is given below as discussed elsewhere [11]

$$\sigma = K\dot{\varepsilon}^m \tag{3}$$

The work-piece undergoing hot deformation is considered to be a dissipater of power and the strain rate sensitivity (m) of flow stress is the factor that partitions power between deformation heat and microstructural changes as given below as discussed elsewhere [12]

$$m = \left|\frac{\partial(\ln\sigma)}{\partial(\ln\dot{\varepsilon})}\right|_{\varepsilon,T} \tag{4}$$

J co-content represents the power dissipation due to metallurgical changes. J is controlled by the constitutive flow behavior of the material and is decided by the strain rate sensitivity (m). The non-dimensional efficiency index η occurring through microstructural changes during deformation is derived by comparing the non-linear power dissipation which is given below [12]:

$$\eta = \frac{J}{J\max} = \frac{2m}{m+1} \tag{5}$$

The variation of the efficiency with temperature and strain rate constitutes a dissipation efficiency map, which exhibits different domains that may be correlated with specific microstructure processes. The domain of dynamic recrytallisation is chosen for the hot working of material since this process yields good workability and microstructure free from defects and instabilities. The superimposition of power dissipation map and instability map provide processing maps. The extremum principle of irreversible thermodynamics is applied to continuum mechanics of large plastic flow as described by Ziegler [13] to define the stability criterion developed by Prasad and Seshacharyulu [4] .

Thus, a dimensionless parameter for microstructural instability is given as follows as discussed elsewhere [12]

$$\zeta(\dot{\varepsilon}) = \frac{\partial \ln\left(\frac{m}{m+1}\right)}{\partial \ln\dot{\varepsilon}} + m < 0 \tag{6}$$

The instability map can be obtained by plotting ξ at different temperatures and at different strain rates where ξ is negative. The flow instabilities are mainly in the form of adiabatic shear bands or flow localizations in the microstructure. A colored plot of power dissipation and a red line plot of flow instability are drawn.

3. Material and processing

The received AZ31B magnesium alloy (MGAL) and nanocomposite (MGNC) of magnesium used in the present investigation were synthesized by hybrid casting process (Disintegrated Melt Deposition) and hot extruded at 350 °C with an extrusion ratio of 20:1. The chemical composition of the alloys was as follows: for the AZ31B alloy (MGAL), 2.94% Al, 0.87% Zn, 0.57% Mn, 0.0027% Fe, 0.0112% Si, 0.0008% Cu, 0.0005% Ni, and balance Mg; for the AZ31B nanocomposite (MGNC) 1.5% (vol.%) Al_2O_3 (with average particle size of 50 nm), 1% Ca, 2.94% Al, 0.87% Zn, 0.57% Mn, .0027% Fe, 0.0112% Si, 0.0008% Cu, 0.0005% Ni, and balance Mg [14]. Nguyen and Gupta [14] reported that the nanocomposite (AZ31B – 1.5% (vol.%) Al_2O_3 – 1% Ca) was found to exhibit better tensile strength coupled with good ductility.

Isothermal hot compression tests were conducted using FIE servo-controlled universal testing machine with a maximum load capacity of 100 kN. The hot deformation of the material was investigated by hot compression tests at the temperature (T) range of 250–400 °C and in the strain rate ($\dot{\varepsilon}$) range of 0.01–1.0 s^{-1}. The size of the specimens used in the test was 15 mm in height and 15 mm in diameter as described elsewhere [3]. For inserting a thermocouple to measure the specimen temperature and the adiabatic temperature rise during deformation, the specimens were provided with 0.8 mm diameter hole machined at midheight to reach the center of the specimen. Dry graphite spray was used as the lubricant in all the experiments. The specimens were deformed up to a true strain of 0.5 and then quenched in water. The compression test samples used for hot deformation were well lubricated and uni-axial compression was conducted, and no barreling was experienced because there was no friction.

The deformed specimens were sectioned in the center parallel to the compression axis. The cut-surface was mounted and polished for metallographic examination using TEM. The cut disks were mechanically ground to less than 100 μm in thickness, followed by dimple grinding the disk center to less than 20 μm in thickness. Finally, the samples were ion-milled to perforation at an ion accelerating voltage of 3 kV.

The load–displacement data were converted into true stress–true strain curves using standard equations. The flow stress data as a function of temperature, strain rate and strain were obtained from the above curves and used for constructing the power dissipation maps. The log σ/log $\dot{\varepsilon}$ data were fitted using a polynomial and the strain rate sensitivity (m) was calculated as a function of strain rate. This was repeated at different temperatures. Processing maps were developed using the procedures described [4] earlier and with the flow stress data at different temperatures, strain rates and strains obtained from the above experiments as inputs. The 3D processing maps were constructed using MiniTAB Software taking temperature (T) in ordinate (x-axis), log strain rate (s^{-1}) in abscissa (y-axis) and strain on z-axis. The resultant contour plot from the 3D plot was used to interpret various domains of the processing maps. The values in the contour line indicate the efficiency (η). Hot workability (Section 2 of the manuscript) analysis provides a detailed procedure for the calculation of strain rate sensitivity parameter (m), dissipation efficiency η and instability parameter ξ ($\dot{\varepsilon}$) expressed in Eqs. (4)–(6).

4. Results and discussions

4.1. True stress–true strain curves

The typical true stress–true strain plots in the temperature range of 250–400 °C and strain rates of 0.01–1.0 s^{-1} for magnesium alloy and the nanocomposite, is shown in Fig. 1. The flow stress