

Full Length Article

Effect of temperature and strain rate on compressive response of extruded magnesium nano-composite

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Abstract

The hot deformation behaviour of extruded magnesium-zinc oxide nano composite has been studied using hot compression test. The test was conducted in the temperature range of 250–400 °C and in the strain rate range of 0.01 to 1.5 s⁻¹. The processing map was obtained using the power dissipation efficiency with the functions of temperature and strain rate. The workability and instability domains were observed in the processing map for a nano composite. The optical microscopy (OM), scanning electron microscopy (SEM) and transmission electron microscopy (TEM) images were used to confirm the formation of dynamic recrystallization (DRX), dynamic recovery (DRY) and instability regions. The workability region of the composite was identified at a working temperature of 400 °C and the strain rate of 0.01 s⁻¹ from the processing map. The instability regions were observed at higher strain rates (>0.1 s⁻¹) and temperatures (250–400 °C).

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1. Introduction

Magnesium and its alloys are used in aerospace, automobile and electronics applications due to their properties such as light weight and high damping capacity [1,2]. Magnesium-based composites are the most suitable for modern industrial applications in which weight is a critical problem due to its excellent specific strength and dimensional stability [3]. But magnesium and its alloys are having poor formability at room temperature because of its hexagonal close-packed crystal (HCP) structure. These types of materials are found most suitable for hot working to get the desired shape and size [4].

The mechanical properties of metals and alloys such as flow stress, workability etc. are reformed due to the changes in microstructure under the hot deformation [5]. The understanding of relationship between hardening and softening mechanism of metals and alloys under the hot deformation processes

is the prime requirement to establish the optimum working parameters [6]. Many researchers [7–10] have proved these mechanisms and their influences in the mechanical properties for several metals, alloys and composite materials. The manifestation of dynamic recrystallization (DRX) occurred during the hot working processes under the high temperature with low strain rate in several metals and alloys. In recent years, many researchers have worked and provided hot working data for magnesium composites using processing map through microstructural study [1,11,12].

The mechanical properties of pure magnesium/alloys are enhanced by the addition nano-particulates, such as aluminium oxide, zinc oxide etc., at low volume fractions as reinforcements [13–15]. An Mg composite reinforced with 0.5 vol.% of nano-ZnO has a higher compressive yield strength than an Mg composite reinforced with 1.0 and 1.5 vol.% of nano-ZnO [16]. Based on the yield strength, the Mg composite containing 0.5 vol.% of nano-zinc oxide was used to study the hot deformation behaviour.

Processing maps, which are developed based on dynamic materials modelling (DMM), are widely used to study the workability of different materials [17–19]. The microstructure

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changes of a composite during hot working has revealed the dissipation power, which is expressed with the efficiency of power dissipation term (η) [20], as shown in equation (1):

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

where m is the strain rate sensitivity, which can be calculated by plotting the double logarithmic flow stress and strain rates [21]:

$$m = \left. \frac{\partial \ln \sigma}{\partial \ln \dot{\epsilon}} \right|_{\epsilon, T} \quad (2)$$

The aim of the present study is to investigate the effect of temperature and strain rate (hot deformation behaviour) of an Mg-0.5% vol. ZnO nano-composite and analyse the deformation mechanism through processing maps. The developed processing map has been used to extract the data regarding workability and instability domains.

2. Hot workability

The power dissipation efficiency map was constructed using the temperature and strain rate which shows the domains that may be associated with a specific microstructure. The hot working suitability of metals was identified using the domain of dynamic recrystallization, which has a microstructure free from defects and instability with good workability. The processing map was prepared by superimposing the power dissipation and instability maps [14]. The continuum criterion for the evidence of flow instabilities is explained in terms of a dimensionless parameter by using the maximum irreversible thermodynamics extremum principle. The dimensionless parameter of microstructural instability is given below in equation (3) as discussed elsewhere [15]:

$$\xi(\dot{\epsilon}) = \partial \ln \left(\frac{m/(m+1)}{\partial \ln \dot{\epsilon}} \right) + m \leq 0 \quad (3)$$

The strain rate sensitivity (m) was calculated using the slope values derived from the $\log(\dot{\epsilon})$ and $\log(\sigma)$ curves. The power dissipation efficiency and instability parameter were obtained using equations (1) and (3) for a strain (ϵ) of 0.5 at different temperatures and strain rates. Processing map was developed by superimposing power dissipation efficiency map and instability map.

3. Experimental procedure

The zinc oxide particulate-reinforced magnesium nano-composite was fabricated via powder metallurgy. Magnesium powder having a purity of 98.5% and particle size of 60–300 μm (Merck, Germany) and zinc oxide powder with a particle size of 50–200 nm (Nanostructured and Amorphous Materials, Inc., USA) were blended in a high-energy ball mill at 200 revolutions per minute for a period of 1 hour. Composite green compacts of 35 mm in diameter and 40 mm in height were produced by applying 510 MPa pressure in a 1000 KN

press at atmospheric temperature. The hybrid microwave technique was used to sinter the green compacts at 640 °C for 14 minutes. The 10-mm diameter zinc oxide-reinforced rods were produced from the sintered compacts with an extrusion process at 350 °C and an extrusion ratio of 13:1. The mechanical properties of zinc oxide-reinforced magnesium composites are described elsewhere [16].

The hot deformation study was carried out on composite samples that were 8 mm in diameter and 12 mm in height. The surfaces of the sample specimens were smoothened and maintained flat to obtain a uniform load distribution. A 0.8 mm diameter hole was drilled at the mid-height of the composite samples to insert a thermocouple in order to measure the temperature of the inner portion; thus, the adiabatic principle can be applied to this study [22,23]. The hot deformation tests were carried out in a FIE servo-controlled Universal Testing Machine with the capacity of 100 KN. The study was performed over a temperature range of (T) 250–400 °C and strain rates ($\dot{\epsilon}$) of 0.01 s⁻¹, 0.1 s⁻¹, 1 s⁻¹ and 1.5 s⁻¹. The compression axis was used parallel to the extrusion direction during the hot deformation study. The composite samples were heated to the predetermined temperatures, i.e., 250 °C, 300 °C, 350 °C and 400 °C, for 20 minutes and then hot compressed to reduce the height by up to 50% for each strain rate. The hot compressed samples were quenched in water to retain the microstructure developed during the process. The compression tests of each condition were repeated twice to study the variation of the process. The average of two readings of each condition was used to construct flow curves. The engineering stress and engineering strain values were obtained from the experimental study. The true stress and true strain values were calculated from the experimental values using standard formulae [18]. Fig. 1(a)–(c) shows the microstructures of extruded Mg/ZnO nano composite before the hot deformation. The details of extrusion and compression directions are shown in the Fig. 1(a). The arrow mark indicates the direction of extrusion. The direction of compressive loading and extrusion is parallel to the axis of cylindrical surface as shown in Fig. 1(a). The microstructures were taken on the compressive surface which is perpendicular to the direction of extrusion. Fig. 1(b) shows composite microstructure with the energy dispersive spectrum (EDS) to provide evidence for the presence of Mg and ZnO.

4. Results and discussions

4.1. Processing map

Fig. 2 exhibits the relation between the $\log$ (flow stress) and $\log$ (strain rate). Fig. 2 proves that the flow stress is increased when the strain rate increases; however, the reverse effect occurs with respect to increase in temperatures. The flow stress is gradually decreased irrespective of strain rates when the deformation temperature increases.

The processing map was developed using dynamic materials model (DMM) [18], as developed by Prasad and Sheshacharulu [24]. The values were compared to the dissipation power efficiency, temperatures and $\log(\dot{\epsilon})$, and used to build a processing map. Fig. 3 shows the processing map for the Mg-0.5vol.%

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