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Dynamic tensile response of magnesium nanocomposites and the effect of nanoparticles

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ABSTRACT

AZ31 Mg alloy and its composites, reinforced by different volume fractions (1 vol%, 1.4 vol% and 3 vol%) of 50-nm Al_2O_3 nanoparticles, were fabricated by a disintegrated melt deposition technique. The tensile mechanical behavior of these materials at strain rates spanning 10^{-4}–10^{3} s^{-1} was investigated. Compared to their monolithic counterpart, significantly increased ductility and yield stress of the nanocomposites under both low and high rate loading were observed, and indicate the positive effect of the nanoparticles. The addition of nanoparticles was found to increase the material strength by a constant value for both low and high rate loading, and decrease the strain rate sensitivity of the composites, and does not change the strain hardening behavior of AZ31. X-ray diffraction (XRD) results for AZ31 and AZ31/Al_2O_3 nanocomposite samples before testing, as well as after quasi-static and dynamic tension tests, indicate that (1) the nanoparticles alter the initial texture configuration; (2) addition of nanoparticles maintains the texture configuration during tensile tests. These are interpreted as the fundamental reason for enhancement of dislocation movement and increased ductility of the nanocomposites.

1. Introduction

Magnesium is the lightest structural metal, with only two thirds the density of aluminum, and possesses a high specific strength. These characteristics endow Mg with great potential to reduce energy consumption if it can be extensively adopted in the automobile, aerospace, electronics and other industries. However, the ductility of Mg alloys is relatively poor because of the low symmetry hexagonal close-packed (HCP) internal lattice structure, which significantly hinders their usage.

Much research has been carried out to seek effective ways to improve both the strength and ductility of Mg and its alloys. Equal-channel-angular pressing (ECAP) techniques have been employed by some researchers to induce severe plastic deformation to Mg and its alloys [1–3]. Grain refinement is achieved and the resultant material shows some increase in strength and ductility. However, applying ECAP to induce significant plastic flow without premature fracture in HCP metals is not easy, because of the strong dependence of plastic flow on the initial texture of the material; moreover, the unsymmetrical HCP lattice structure gives rise to anisotropy, which decreases formability of the material [3,4]. Another way to improve the properties of Mg and its alloys is to add appropriate reinforcements into the material. Recent studies show that when nano-sized fillers – carbon nanotubes, ceramic particles (Al_2O_3, Y_2O_3 and ZrO_2) – are added to Mg or AZ31 Mg alloy, significant enhancement in both strength and ductility is achieved [5–8]. The disintegrated melt deposition (DMD) technique, a liquid phase processing technique, is an easy and practical means of fabrication to synthesize magnesium metal matrix composites, and potentially scalable for large-scale manufacturing [9–11].

For potential applications in vehicles, aircraft and armor, an understanding of the dynamic behavior of Mg alloy and its composites is necessary to evaluate their resistance to dynamic loads associated with accidental collisions or foreign-object impact [12]. There are several reports on the dynamic behavior of Mg alloys. Yokoyama [13] investigated the tensile impact properties of three different wrought Mg alloys. Ulacia et al. [14,15], Khan et al. [16], Watanabe et al. [17] and Tan et al. [18] discussed the mechanical behavior and microstructure evolution of AZ31 for a wide range of strain rates and temperatures. Li et al. [3,19] studied the dynamic compressive response of ultrafine-grained ZK60 magnesium alloy, which is obtained by ECAP, and examined its deformation mechanisms. However, information on the dynamic properties of magnesium nanocomposites is very limited. Recently, Guo et al. [12,20] reported the dynamic tensile and compressive response of Mg–6 wt%Al alloy-based composites containing 0.22 vol% alumina nanoparticles. Habibi et al. [21] studied the properties of pure Mg-based composites reinforced by sub-micron Al particles and carbon nano-tubes (CNTs) under low and high rate loading.

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In this study, AZ31-based nanocomposites reinforced by 50-nm Al_2O_3 nanoparticles are synthesized using the DMD technique. This is possibly the first report on characterizing the dynamic tensile behavior of AZ31/Al_2O_3 nanocomposites. The effect of nanoparticles on strength and ductility is studied for both low and high rate loading.

2. Experiments

2.1. Material preparation

AZ31 Mg alloy (60-mm diameter round bar, Tokyo Magnesium, Japan) was used as the matrix material. Its composition is given in Table 1. 50-nm alumina particulates (Baikowski, Japan) were used as the reinforcement. The particulates were placed into holes drilled into AZ31 disks (Fig. 1) to help generate a more uniform distribution within the matrix material.

A disintegrated melt deposition (DMD) technique was employed to fabricate the monolithic and nanocomposite materials. The resulting materials, with three different volume percentages of nanoparticles (1 vol%, 1.4 vol% and 3 vol%), were placed in a graphite crucible and heated to a temperature of 750 °C in an inert argon gas atmosphere using an electric resistance furnace. When the super-heated temperature was attained, the melt was stirred for 5 mins at a speed of 450 rev/min by a twin blade (45° pitch) mild steel impeller. The impeller was coated with Zirtex 25 (86% ZrO_2, 8.8% Y_2O_3, 3.6% SiO_2, 1.2% K_2O and Na_2O, and 0.3% trace inorganics) to prevent contamination by iron from the stirrer into the molten metal. The melt was then discharged through a 10 mm diameter orifice at the bottom of the crucible, and disintegrated by two argon gas jets blowing at ~25 L/min, oriented normal to the melt stream, and deposited onto a steel mold; a 40 mm diameter preform was obtained. The preforms were machined into 36 mm diameter cylinders and subjected to a temperature of 400 °C for 60 min in a furnace, then hot extruded using a 150 t hydraulic press at 350 °C, with an extrusion ratio of 20.25:1. Colloidal graphite was used as lubricant, and rods of 8 mm diameter were obtained from the extrusion.

Table 1
Chemical composition of AZ31 magnesium alloy (wt%).

Al	Zn	Mn	Fe	Ni	Cu	Si	Mg
2.8	0.83	0.59	0.0023	0.0009	0.001	0.01	Balance

Fig. 1. Array of blind holes in AZ31 disk to be filled by nanoparticles.

2.2. Materials characterization

An electronic balance (Mettler Toledo AB304-S analytical balance scale) with a resolution of 0.1 mg was used to measure the mass. The densities of the extruded rods were measured using a Mettler Toledo density kit, which operates on Archimedes' principle. Microstructural characterization was conducted by means of an optical microscope (Olympus) and a field emission scanning electron microscope (Hitachi FESEM-S4300) to observe specimen surfaces after preparation by fine grinding, polishing and etching, as well as fracture surfaces. The morphology of the nanoparticle distribution and second phase was studied using a JEOL JSM-5800 LV Scanning Electron Microscope (SEM). The etchant was composed of 10 ml acetic acid, 5 g picric acid and 95 ml ethyl alcohol [8]. The grain size of the materials produced was determined using the image analysis software, ImageJ. X-ray diffraction (XRD) analysis was carried out on polished specimens using an automated Shimadzu LAB-X XRD-6000 diffractometer (Cu Kα, $\lambda = 1.54056$ Å) operating at a scanning speed of 2°/min.

2.3. Tensile tests

Quasi-static tension tests on the materials at a strain rate of 10^{-4} s^{-1} were carried out using an Instron 8874 universal testing machine. The gauge length of the dog-bone specimens was 25 mm and the diameter was 5 mm. The loading axis for both low and high strain rate tests was parallel to the extrusion direction.

Dynamic tension tests were conducted using a Split Hopkinson Tensile Bar (SHTB), as shown in Fig. 3. The gauge length of the dog-bone specimen for dynamic tests was 7.5 mm and the diameter was 3 mm (Fig. 2). Specimens were mounted between the input and output bars using a screw thread connection, and a 0.5 m long tubular striker, made of the same material, was propelled by compressed gas to strike an anvil attached to the end of the input bar, thereby generating a tensile loading pulse (incident stress pulse). Aluminum rings were employed as pulse shapers and attached to the anvil to improve the profile of the incident pulse by reducing spurious oscillations. The strain waves in these two bars were measured by pairs of strain gauges mounted diametrically-opposite to each other, and an oscilloscope was used to record the strain signals.

Based on the one-dimensional stress wave theory, the strain rate $\dot{\varepsilon}(t)$, engineering strain $\varepsilon(t)$ and engineering stress $\sigma(t)$ histories of the sample can be calculated from [22]:

$$\dot{\varepsilon}(t) = \frac{2C_B}{L_0}(\varepsilon_I(t) - \varepsilon_T(t)); \quad \varepsilon(t) = \int_0^t \dot{\varepsilon}(t)dt; \quad \sigma(t) = \frac{E_B A_B \varepsilon_T(t)}{A_0} \tag{1}$$

where $\varepsilon_I(t)$ is the incident strain pulse and $\varepsilon_T(t)$ the transmitted strain pulse; L_0 and A_0 are the length and cross-sectional area of the specimen, and A_B and E_B the cross-sectional area and Young's modulus of the bars, respectively. C_B is the longitudinal elastic wave speed of the bar material, which is obtained from:

$$C_B = \sqrt{E_B/\rho} \tag{2}$$

where ρ is the density of the bar material.

3. Results and discussion

3.1. Microstructure

Results on the density and grain size of the material are presented in Table 2. The reference density is calculated theoretically using the rule-of-mixtures. The small difference between the reference and experimentally-measured densities indicates that the porosity of these materials is negligible. A significant reduction in grain size associated with the presence of nanoparticles can be