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Effects of soft phase on the mechanical behaviors of hierarchical Mg nanocomposites

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ABSTRACT

The magnesium matrix nanocomposites (10 vol% and 15 vol% of SiC particles) with a hierarchical structure, which contained flake-like soft phases, were investigated by compression and modeling. Fortunately, the unique malleability of hierarchical Mg nanocomposites was observed. The fracture surfaces indicated that the hierarchical Mg nanocomposites demonstrated ductile rupture. The “pull-out” phenomenon on the fracture surfaces suggested that the flake-like soft phase could sustain the additional deformation, consequently improving the malleability of Mg nanocomposites. Additionally, the modeling demonstrated that the effects from soft phase were not negligible, where the modified model exhibited a better agreement on the yield strength of the hierarchical Mg nanocomposites.

1. Introduction

The low density and high specific mechanical properties of the magnesium (Mg) and Mg alloys stimulate the corresponding applications in the automotive, aerospace and other industries [1,2]. In addition, the Mg based materials also display good machinability, thermal stability and damping characteristics. However, the hexagonal close packing (hcp) structure strongly affects the plastic deformation of Mg and Mg alloys, which encounter the challenge from their relatively low strength and poor room temperature ductility, limiting their uses in many applications [3–6]. To introduce the hard ceramic particles into the matrix is an effective method to further improve the mechanical properties of Mg and corresponding alloys, such as high elastic modulus, high strength, superior creep and wear resistance at elevated temperature [7–10]. Therefore, more and more attention has been paid on the lightweight metal matrix composites, especially on the Mg based nanocomposites in recent years [11–13].

The strength-ductility trade-off has been a long standing dilemma in materials science [14]. Generally, the Mg matrix composites were reinforced with micrometer-sized or submicron-sized ceramic particles, whereas the obtained composites exhibited high strength and low ductility [15–17]. Subsequently, the nanometer-sized ceramic particles with low volume fraction (usually less than 5 vol% due to the limitation of processing) were applied to fabricate Mg matrix nanocomposites (MMNCs). Unfortunately, the strength of nanocomposites with low volume fraction particles is poor [18,19]. Then, Shen et al. [20] investigated the quasi-static mechanical properties of Mg-based nanocomposites with uniform distribution of SiC nanoparticles. The 10 vol% SiC reinforcements produced a significant growth in the yield strength (539 MPa) and ultimate strength (600 MPa). In addition, a reverse volume fraction effect takes place in homogeneous Mg nanocomposites with 15 vol % SiC, whereas special attention should be paid on the poor ductility (less than 4%) of the homogeneous nanocomposites [21]. Inspired by biological materials which displayed lightweight and unique combination of high strength and high toughness, simultaneously [22]. Liu et al. [23] synthetized a Mg-based nanocomposite with a hierarchical structure to overcome the terrible ductility. The resultant nanocomposite consisted of a continuous “hard phase” and an isolated “soft phase”. It was displayed that the flake-like soft phases were embedded into the “hard phase”. The hierarchical Mg nanocomposite with 10 vol% SiC exhibited significantly increased

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yield strength (320 MPa) and retained the corresponding malleability (~20%) in comparison with the pure Mg (50 MPa and ~20%), offering an effective strategy to design the Mg-based nanocomposite with high strength and acceptable ductility.

It demonstrated that the hierarchical Mg nanocomposite overcame the reversed volume fraction effect in the homogeneous nanocomposites, and exhibited excellent malleability [24]. However, the toughening and strengthening mechanism of hierarchical Mg nanocomposite is still covered. In this paper, the contribution of the soft phase in the overall malleability of the hierarchical Mg nanocomposites was investigated. A modified model was also developed to predict the yield strength of the hierarchical Mg-based nanocomposites, and verified using the experimental data.

2. Experimental procedure

2.1. Material and specimen preparation

The commercially available magnesium powder of analytical reagent grade phase-purity and a mesh size of − 100 (Tianjin Kermel Chemical Reagent Co., Ltd., Tianjin, China), along with the 50 nm β-SiC powder (Hefei Kaier Nanometer Energy & Technology Co., Ltd., Hefei, China) were utilized to fabricate a series of Mg-based nanocomposites samples. A significantly detailed procedure for the preparation of the Mg-based nanocomposites was given in previous papers [23,24]. Mg-based composites powders with volume fractions 10% and 15% SiC particles were synthesized by the ball milling process. The milled powder mixture was consolidated with the sintering system of DR. SINTER (Model SPS-1030, Sumitomo Coal Mining Co., Ltd., Japan) at 575 °C for 5 min under vacuum (10 Pa or lower) and at a uniaxial pressure of 50 MPa. The heating and cooling rates were 100 and 60 K/min, respectively. Subsequently to consolidation, bulk samples were annealed at 673 K under a vacuum atmosphere for 1 h, respectively. A pure Mg specimen was also fabricated following the same procedure to compare with the Mg-base nanocomposites.

2.2. Characterization

The specimens were severed from the disk-like samples and polished to a 1-μm finish through a metallographic routine (AutoMet 250, Buehler, USA). The polished surfaces of the specimens were observed by a scanning electron microscope (SEM) (Quanta FEG 250, FEI, USA) equipped with a backscatter detector. The size of flake-like soft phase was measured by the ImageJ software, based on the SEM images.

Cylinder specimens for compressive tests were prepared by an electrical discharge machine. The obtained specimens had dimensions of 2.5 mm in diameter and 5 mm in length. The quasi-static compression tests on the samples were conducted at a strain rate of 1×10^{-3}/s, through a universal testing system (Instron 2367, Illinois Tool Works Inc., USA) with maximum load of 30 kN at room temperature. To provide an insight into the possible fracture mechanism, the fracture morphology of the broken samples was characterized by SEM successfully.

3. Results and discussion

3.1. Microstructure

The representative SEM images of the Mg-based nanocomposites were presented in Fig. 1. It was apparent that both nanocomposites had a hierarchical microstructure (Fig. 1a and b), whereas this unique structure comprised of two phases (it has been reported in our previous publications [23,24]): one phase was the Mg with high volume fraction of SiC particles, which was called the "hard phase"; the other phase was called the "soft phase", only consisting of pure Mg, and almost no SiC nanoparticles were observed inside. Besides, "soft phases" were randomly and uniformly distributed in the "hard phase". It should be mentioned that the SiC nanoparticles were dispersed within the hard phase uniformly. Simultaneously, certain aggregates could be discriminated in Fig. 1, where the SiC particles aggregates (white dots) exceeded 100 nm, which was pointed out by the arrows. Fig. 1a presents that most of the soft phases exhibited slender features in the Mg-10 vol% SiC nanocomposite, just like the short fibers. As presented in Fig. 1b, the similar flake-like soft phase could also be observed in the Mg-15 vol% SiC composite, whereas the flake-like soft phases had smaller size and less amount compared to the Mg-10 vol% SiC composite. This phenomenon was attributed to a higher volume fraction of SiC nanoparticles, which resulted in the higher proportion of the hard phase. In addition, the average length (measured as the distance between the farthest two points of a soft phase) of the flake-like soft phases in the nanocomposites are presented in Fig. 1c and d, whereas the average length of the flake-like soft phase in the Mg-10 vol% SiC composite was approximately 6.29 μm and the corresponding value of the Mg-15 vol% SiC was approximately 2.49 μm. Apparently, it was approximately 150% longer in the Mg-10 vol% SiC composite compared to the average length of flake-like soft phase in the Mg-15 vol% SiC composite. Finally, the flake-like soft phases were randomly distributed in the hierarchical Mg nanocomposites.

3.2. Quasi-static compressive mechanical properties

Fig. 2a presented the typical true stress-true strain curves of the Mg-based nanocomposites under compression, along with the curve of milled pure Mg (marked as Mg- 0 vol% SiC). It was noted that all samples were tested in the same conditions until break. The hierarchical Mg nanocomposite with 15 vol% SiC obtained the highest strength (535 ± 10 MPa), as 21% and 138% higher than the Mg-10 vol% SiC (442 ± 12 MPa) and the Mg-0 vol% SiC (224 ± 12 MPa). The aforementioned enhancement might derived mainly from the outstanding mismatch of the thermal expansion coefficient between the SiC nanoparticles and the Mg matrix, which increased the density of geometrically necessary dislocations (see Refs. [25,26]; the existence of geometrically necessary dislocation (GND) was also discussed in Section 3.4). It should be mentioned that the yield strength of the Mg-0 vol% SiC exceeded 200 MPa in this work, which was significantly higher than pure Mg (60 MPa) in Ref. [27]. It was attributed to the ball milling process, accompanying grain refining and resulting in Hall-Petch effect [28–30]. The ductility was reduced when the volume fraction of SiC in the hierarchical Mg nanocomposites increased. Moreover, the ductility of the hierarchical Mg nanocomposites with flake-like soft phases was still significantly improved comparing with the homogeneous nanocomposites [20]. Although the particle size in Ref. [20] was a litter smaller than that in this work, it was not the major factor leading to the poor ductility. Actually, a lot of papers reported that homogeneous nanocomposites with varied particle sizes showed poor ductility [18,31–34], even though the volume fraction of reinforcement reported in those papers was far less than that in this work.

Moreover, a high specific toughness constitutes one of the most attractive properties of the hierarchical Mg-based nanocomposites, which could be calculated through the numerical integration of the area under the stress-strain curve [22,35]. The results were presented in Fig. 2b. The calculated toughness of the pure Mg in this work was 57.55 J m^{-3}, as slightly lower than the hierarchical Mg nanocomposite with 10 vol% in SiC (62.93 J m^{-3}) and slightly higher