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Effects of carbon nanotubes on twin and texture evolution of magnesium matrix composite during compression process

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ABSTRACT

A compression test is performed to investigate the effects of carbon nanotubes (CNTs) on twin and texture evolution of the 1.0 wt.% CNTs reinforced magnesium matrix (CNTs/Mg) composite. The compression process consists of elastic, yield and hardening stages, and the number of twin significantly increases at the yield stage. During the compression process, the crystal rotation and non-basal slip caused by twin shear alternately dominate the deformation of the 1.0 wt.% CNTs/Mg composite. The CNTs existing at grain boundaries lead to stress concentration, and the stress concentration stimulates the formation of twins at the yield stage. The formed twins interact with dislocations, result in crystal rotation and promotion of the non-basal slip system at the hardening stage under the effect of twin shear, thus, improve the toughness of the CNTs/Mg composite.

1. Introduction

Because of low density (1.738 g/cm^3), high stiffness and excellent machinability, magnesium (Mg) and its alloys have been widely used as lightweight structural components [1,2]. They are also the most promising materials in aerospace, automobiles industries and daily life in the past several decades [3–5]. However, Mg alloys often show poor formability at room temperature due to their hexagonal close packed (HCP) type crystal structure, which has less independent slip systems and restricts their application in various fields [6,7].

Many researchers have paid their attention on improving the performance of Mg alloys through alloying [8], heat treatment [9] and plastic deformation techniques [10] in recent years. Kim et al. [11] used an artificial cooling method to improve the yield strength and elongation of Mg alloys. Lu et al. [12] reported that the increase in density of twin boundaries (TBs) could effectively enhance the strength and toughness of materials. CNTs have been selected as an ideal reinforcement to fabricate high-performance metal matrix composites [13,14], ascribing to their ultra-high strengths (up to ~100 GPa), Young's modulus (~1 TPa) and large aspect ratios (50~500) [15]. In our previous papers [16,17], we reported that adding CNTs could enhance the elongation and tensile strength of Mg matrix composites. Goh et al. [18] studied the ductility improvement and fatigue behaviour of 1.3 wt. % CNTs/Mg composite using the disintegrated melt deposition technique. Fukuda et al. [19] reported that CNTs/Mg or CNTs/AZ61 composites having superior mechanical properties were produced via powder metallurgy route.

Although the statistical analysis of experimental results and atomistic simulation can present the mechanisms responsible for strengthening and toughening of Mg alloys at different deformation stages [20–23], these mechanisms may not be simply suitable for Mg matrix composites. In addition, there is fewer report and detailed analysis on the toughening mechanisms for the CNTs/Mg composite so far. In the present study, the microstructural evolution based on the characterization of twins and texture of the CNTs/Mg composite is investigated by using a compression test combining with EBSD observation, so that the toughening mechanisms responsible for the CNTs/Mg composite are discussed.

2. Experimental

2.1. CNTs/Mg Composite

Pure Mg powders (99.9% in purity, ~50 μm in diameter, Beijing Xing Rong Yuan Technology Co. Ltd., China) were coated by pre-dispersed multi-walled CNTs (MWCNTs, supplied by Chengdu Organic Chemicals Co. Ltd., Chinese Academy of Sciences) via the wet-coating process [16]. The as-received composite powders were compacted into a cylindrical block with 38 mm in diameter, under a pressure of 500 MPa and a dwell time of 60 s. The cylindrical block was heated to 573 K in a resistance furnace, then immediately hot extruded (extrusion ratio of 16) at a speed of 2.0 mm/s by a 1000 kN four columns hydraulic

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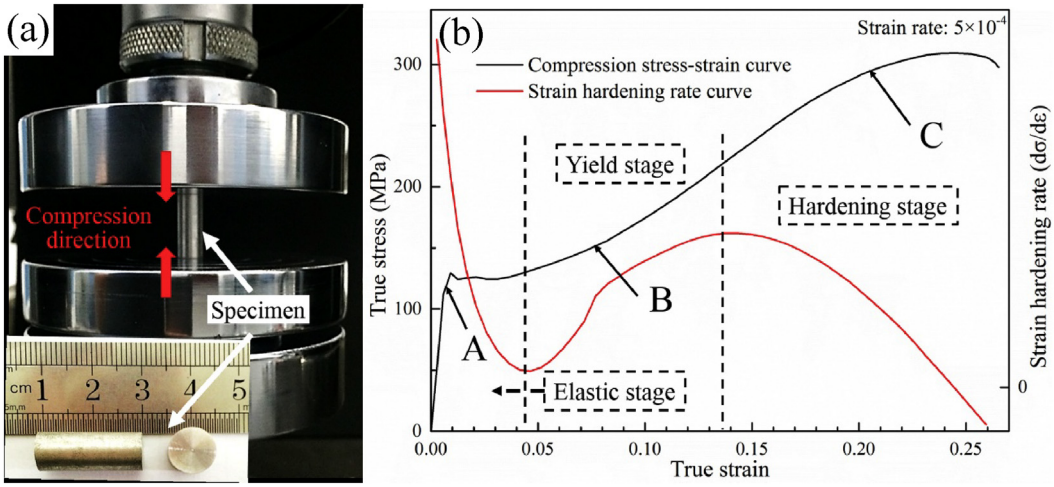

Fig. 1. (a) Compression process with the specimen, (b) three different stages in the compression stress-strain curve.

press machine (YTW32E-100). For comparison, pure Mg was also prepared via the same route.

2.2. Compression Test

A compression test was performed at a strain rate of $5 \times 10^{-4}\,s^{-1}$ by the electro mechanical universal testing machine (UTM4304) equipped with an axial extensometer at room temperature, as shown in Fig. 1. The specimen with 8 mm in diameter and 20 mm in height was placed into the indenter and pressed at a compression speed of 10 μm/s with the compression axis parallel to the extrusion direction (see Fig. 1a). The compression process was divided three stages: elastic, yield and hardening stage according to the strain-hardening rate curve. The microstructures corresponding to the positions of A, B, C (as indicated in Fig. 1b, represented for the elastic, yield and hardening stage, respectively) were observed.

2.3. Microstructure Characterization

The accurate element analysis was completed with the help of EPMA, which was used to characterize the dispersion of CNTs. The crystal orientation was analysed via FEI QUANTA FEG 650 equipped with electron backscatter diffraction (EBSD) detector. For the EBSD observation, the sample was mechanically polished with the sandpapers up to 5000 and the 0.5 mm diamond paste, then finished with the electro-chemical polishing at 8 V and 40 s using an acid solution with volume ratio of H_3PO_4: C_2H_6O = 3: 5. The grain boundaries were characterized by transmission electron microscopy (TEM, JEM-2100) with an accelerating voltage of 200 keV.

3. Results and Discussion

3.1. Microstructures and Compression Properties of CNTs/Mg Composite

Fig. 2 is the EPMA of 1.0 CNTs/Mg composite, which shows the element distribution in CNTs/Mg composite. It indicates that there is no existence of impurity defect caused by CNTs agglomeration. As shown in Fig. 2c, the homogeneous distribution of carbon element supports that the CNTs are uniformly dispersed in the CNTs/Mg composite. Also, it can be found that the content of oxygen element is very low from Fig. 2d, which implies that the magnesium matrix has not been oxidized by the preparation process. Fig. 3a and b presents the image quality (IQ) maps for pure Mg and the 1.0 wt.% CNTs/Mg composite, respectively. The yellow lines represent the grain boundaries with misorientation angles of 84°–88° and axis of ⟨11-20⟩. According to the previous report [24], these yellow lines were considered as tensile twin boundaries. The area proportion of the tensile twin boundaries increased from 2.97% in pure Mg to 8.12% in the 1.0 wt.% CNTs/Mg composite. We have found that the tensile twin boundaries increased as a function of the CNTs content, as listed in Table 1. Fig. 3c and d displays the pole figure (PF) of pure Mg and the 1.0 wt.% CNTs/Mg composite, respectively. It can be found that both of them exhibited (0001) basal texture, but the texture intensity of the 1.0 wt.% CNTs/Mg composite was weaker than that of pure Mg and the (0001) basal texture presented a slight deviation. It implies that the formation of a large number of twins in the 1.0 wt.% CNTs/Mg composite might lead to crystal rotation, which resulted in the weakening and deviation of the (0001) basal texture.

Table 2 lists the number of twins and texture intensity of pure Mg and the 1.0 wt.% CNTs/Mg composite before compression as well as at different stages of compression process. It shows that the number of twins in the 1.0 wt.% CNTs/Mg composite is more than that of pure Mg at the three stages. This means that the addition of CNTs promoted the twin formation in the process of compression. Moreover, the intensity of texture in the 1.0 wt.% CNTs/Mg composite is larger at the elastic and yield stages, but smaller at the hardening stage compared with those of pure Mg. This supports that the crystal orientation of the 1.0 wt.% CNTs/Mg composite tended to be more consistent than that of pure Mg at elastic and yield stages. In other words, due to the existence of CNTs, the crystal rotated toward the orientation of plastic deformation in the 1.0 wt.% CNTs/Mg composite. The weakened texture at the hardening stage demonstrates that the change of twins might influence the crystal orientation, which will be discussed in the following section.

Fig. 4a displays the compression stress-strain curves of pure Mg and the 1.0 wt.% CNTs/Mg composite examined at ambient temperature. It shows that the compression rate increased 29 % (from 17.9% to 23.1%) due to the addition of CNTs, whereas the compression strength shows no decrease. Fig. 3b shows the specimen appearance at the three compression stages. The longitudinal section of each specimen was taken to observe microstructure evolution.

3.2. Microstructure Evolution of CNTs/Mg Composite During Compression Process

Fig. 5 displays the IQ mapping and misorientation angle distribution of the 1.0 wt.% CNTs/Mg composite at different stages of compression process. It indicates that the amount of tensile twin boundaries decreased at the elastic stage, but increased at the yield stage, and finally reduced to the minimum at the hardening stage (Fig. 5a–c) with the