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Enhanced electromagnetic interference shielding in ZK60 magnesium alloy by aging precipitation

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ABSTRACT

Electromagnetic interference shielding, hardness, and electrical conductivity measurements were employed to evaluate the effect of aging precipitation on shielding characteristics of ZK60 magnesium alloy. During artificial aging $MgZn_2$ phase precipitates occurred and the age hardening peak happened at 150 °C for 15 h. Aging precipitation induced enhanced shielding effectiveness as well as tensile strength in the alloy. It is interesting to note that the shielding effectiveness exhibited a rapid increase with increase in aging time until 15 h, but for longer aging time it tended to remain largely unchanged. Artificial aging at 150 °C for 15 h can thus be considered as the optimum heat treatment condition. In this condition, the good combination of superior shielding effectiveness greater than 70 dB and high mechanical properties was achieved. The origin of the attractive electromagnetic interference shielding properties is discussed based on second phase precipitation in the alloy.

1. Introduction

Electromagnetic interference (EMI) is the electromagnetic (EM) radiation emitted by electrical and electronic equipments. EMI among electronic devices such as computers, cell phones, radios, and airplane navigators can degrade device performance [1]. It also induces potential health problems such as nervousness, insomnia, languidness, and headaches [2,3]. EM radiation has been becoming a new form of pollution in the environment discovered in recent years [4]. EMI shielding refers to the reflection and/or absorption of electromagnetic radiations by a material. With the rapid proliferation of electronic and telecommunication devices, the development of new materials with high shielding capacity at wide frequency range is increasingly required to meet the high demand of today's society all over the world [5,6].

Metallic materials and polymer composites are by far the most common candidates for EMI shielding materials [7–10]. Copper, steel, nickel and permalloy having excellent electrical conductivity or high magnetic permeability exhibit great EMI shielding capacity. Nevertheless, these metallic materials suffer from their heavy weight, which restricts some of their applications [10,11]. Polymer composites containing conductive fillers are attractive for radiation shielding due to their processability and low density. But most of the polymer composites are not strong enough for most of the structural applications [12]. It is still a challenge to develop a material combining low density, enough mechanical strength, and excellent shielding effectiveness (SE) to prevent EM radiation.

Magnesium not only possesses low density, high specific stiffness, high specific strength, excellent damping capacity and recyclability, but also has relatively good conductivity and shielding capacity [13]. In this sense, magnesium alloys may be considered as a potential candidate for EMI shielding materials [14]. However, some previous investigations revealed that a tradeoff was made between shielding capacity and mechanical strength in magnesium alloys [15]. This could be attributed to that high strength is usually achieved by the addition of some alloying elements in magnesium alloys, which is commonly detrimental to EMI shielding because the alloying is able to increase the electron scattering and thus reduce electrical conductivity. It is vital to find effective methods to enhance shielding capacity without deteriorating mechanical strength in magnesium alloys.

In this work, we report a study on the EMI shielding properties of ZK60 magnesium alloy in different aging conditions, which demonstrates that controlled precipitation process led to a significant increase in shielding properties as well as a favorable enhancement in mechanical strength. Such an investigation will provide important basis for developing high-performance metallic materials for shielding applications.

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2. Materials and methods

A ZK60 alloy ingot was melted in an electric resistance furnace and cast into bars with a diameter of 90 mm. Chemical composition of the alloy is as follows: 6.37 wt% Zn and 0.53 wt% Zr. The casting ingots were homogenized at 420 °C for 18 h and then hot extruded into plates with cross-section of $13 \times 125\ mm^2$ at 390 °C. Extrusion ratio was calculated to be about 3.3:1. One type of heat treatment was performed on the extruded plates, namely direct artificial aging at 150 °C for 4–50 h and cooling in air (T5).

Specimens for microstructure observations were prepared by mechanical grinding, polishing, and subsequent etching. Extruded and heat-treated specimens were etched with a mixture of 1.5 g picric acid, 25 ml ethanol, 5 ml acetic acid and 10 ml water. Microstructures of the alloys were investigated with scanning electron microscope (SEM, TESCAN VEGA II LMU), and electron backscatter diffraction (EBSD) analysis using an HKL Chanel 5 System (Oxford system equipped in FEI Nova 400 FEG-SEM). Phase analysis was carried out with a Rigaku D/MAX-2500PC X-ray diffractometer (XRD). The volume fraction of precipitates was counted by an Image-proplus software.

EMI SE (attenuation upon transmission) was measured using the standard coaxial cable method in accordance with ASTM D4935-2010. The setup consisted of a DN 1015A shielding effectiveness tester with its input and output connected to an Agilent 8753ES network analyzer. Full 2-port calibration was used to remove all the systematic errors for the related test ports to obtain the accurate measurements. The range of scan frequency was within the range from 30 MHz to 1.5 GHz. The samples were in a disc form with 115 mm in diameter and 2 mm in thickness. A plane wave electromagnetic field was used for vertical firing. The energy of plane wave before and after the sample shielding could be measured. Calculated expression of SE is as follows [10,16]:

$$SE\ (dB) = 10 \log \frac{P_0}{P_S} \quad (1)$$

where P_0 and P_S are the incident energy before shielding and the transmitted energy after shielding, respectively. SE was tested in decibels, and each datum was the average of at least two testing results.

Electrical conductivity of ZK60 alloy specimens in different conditions was measured with a conductivity meter (Sigmascope SMP10) at 20 °C. The as-extruded and aged ZK60 plates were machined into cylindrical conductivity testing specimens of 10 mm height and 12 mm diameter. Each datum was the average of at least five testing results.

Hardness measurements were conducted on a Vickers hardness testing machine with a load of 50 g and a loading duration of 10 s. For each specimen, at least 10 indents were performed. Tensile testing was carried out on a CMT5105 material testing machine with a strain rate of $10^{-3}\ s^{-1}$ at room temperature. Alloy plates were machined into tensile specimens of 5 mm gauge diameter and 50 mm gauge length.

3. Results

Fig. 1 shows the age-hardening curve for the extruded ZK60 alloy after direct artificial aging treatment at 150 °C for 4–90 h. The hardness increased first and then decreased after reaching a peak value at 15 h. The peak value was measured to be around 84 Hv, which was considerably higher than that of the extruded specimen prior to artificial aging. This can be attributed to the precipitation of numerous second phases in the α-Mg matrix during aging. Based on above-mentioned observations, four specimens in various conditions (extruded as well as aged at 150 °C for 4 h, 15 h (peak-aged), and 50 h (over-aged)) were chosen to explore the effect of aging precipitation on EMI shielding characteristics, as indicated in Fig. 1.

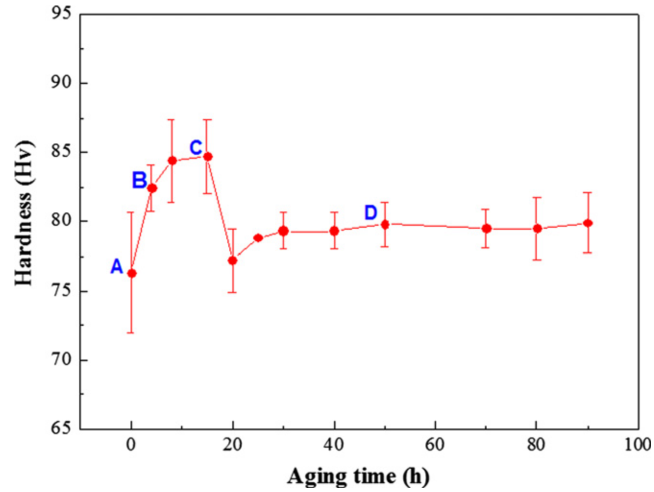

Fig. 1. Age hardening curves for the ZK60 alloy in different aging conditions.

Typical SEM micrographs of the alloy in various states are showed in Fig. 2. In the extruded state, a small quantity of second phase particles was distributed in α-Mg matrix, and the volume fraction of second phase was measured to be 0.64%. It was observed that plenty of precipitates formed in the matrix during aging treatment. The volume fractions of second phase precipitates were enhanced to be 1.13%, 1.68%, and 3.81% for the samples aged for 4 h, 15 h and 50 h, respectively. In addition, an obvious growth of the precipitates was detected in the sample aged for 50 h. The diameter of the precipitates in the sample aged for 50 h was about 1.3 times higher than that in the sample aged for 4 h. Statistical measurements of grain size, presented in Fig. 3, shows that all the samples contained equiaxed grains smaller than 50 μm and the average grain sizes were 4.9 μm, 5.4 μm, 6.0 μm, and 6.1 μm for the extruded sample and the samples aged for 4 h, 15 h and 50 h, respectively. This indicates that the artificial aging induced only a quite limited grain growth in the as-extruded alloy.

Fig. 4 displays typical XRD traces for the samples aged for 15 h and 50 h. XRD results indicate that the aged samples mainly consisted of α-Mg and $MgZn_2$ phases. It is thus certain that the precipitates observed in the aged samples in Fig. 2 were dominantly $MgZn_2$ intermetallic compounds, which possessed the coherence with the matrix [17,18]. In addition, the peak-aged and over-aged samples exhibited the nearly same diffraction peaks, which likely means that they had similar texture characteristics. The highest (0002) peaks demonstrate that similar {0001} basal plane preferred orientation was present in two samples.

Fig. 5 presents EBSD orientation maps (a,b) and misorientation angle distributions (c,d) of the extruded and peak-aged samples. It is seen that both samples contained equiaxed grains formed due to dynamic recrystallization. Some grains were elongated due to extrusion deformation and quite few twin boundaries were detected in the extruded and peak-aged samples. The misorientation angle distributions calculated based on the orientation maps show that the frequency of high angle grain boundaries was higher for the extruded sample, as compared to the sample peak-aged at 150 °C for 15 h. Such a fact indicates that artificial aging decreased the boundary energy of the extruded alloy.

The frequency dependence of EMI shielding characteristics of the alloy in different conditions is illustrated in Fig. 6. In the