Effect of Alloying Element on Electromagnetic Interference Shielding Effectiveness of Binary Magnesium Alloys

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Received: 24 November 2018 / Revised: 18 January 2019 / Published online: 18 March 2019
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Abstract

The microstructure, electrical conductivity and electromagnetic interference shielding effectiveness of Mg–X (X = Al, Sn, Y and Gd) alloys in as-cast and solution states were systematically investigated in this study. The electrical conductivity and electromagnetic shielding capacity of binary magnesium alloys decrease linearly with alloying element content. The electromagnetic shielding effectiveness of the binary magnesium alloys with the same alloying element content is as follows: Mg–Gd < Mg–Sn < Mg–Y < Mg–Al. The main reason for the differences in electromagnetic interference shielding of the binary magnesium alloys is the change in conductivity, which is mainly affected by volumetric difference of solute atoms and magnesium atoms, solute atomic valence and configuration of extranuclear electron.

Keywords Binary magnesium alloys · Electrical conductivity · Electromagnetic shielding effectiveness · Alloying element

1 Introduction

With the rapid development of electronic and communication industry, electromagnetic radiation (EMR) has become the serious source of public pollution, and then, electromagnetic interference (EMI) shielding has attracted great attention in aerospace, medical and other areas quite relevant to the livelihood of mankind [1, 2]. Shielding effectiveness (SE) is a common parameter for characterizing shielding performance and measurement in decibels (dB). Electric equipment can be protected from interference of electromagnetic radiation by shields and covers [3]. EMI shielding is a complex and tough task because it greatly depends upon the shield topology, the source (s) characteristics and materials. Furthermore, the materials usually play a key role [4] and usually require lighter weight in the electromagnetic protection field, so the density of the selected material should be as low as possible in practical engineering applications [5, 6].

Compared to the commonly used metal shielding materials [7–11], such as copper and aluminum with high conductivity and iron and nickel with high magnetic permeability, the magnesium alloy not only possesses low density, high specific stiffness and excellent damping capacity, but also has relatively good conductivity and shielding capacity [12, 13].

Recently, some researches have been carried out on the shielding properties of magnesium alloys. Liu et al. [4, 12] executed a study on the effect of heat treatment on electromagnetic shielding of ZK60 alloy and found that aging treatment could result in the precipitation of the second phase and significantly improve the shielding effectiveness of magnesium alloys. Song et al. [13] observed that the electromagnetic shielding of magnesium alloys gradually increased with the basal texture intensity [13]. It is reported that the increasing amount of the secondary phases with a specific orientation resulted in enhancement of EMI shielding capacity, which was mainly attributed to the improvement in reflection and multiple reflection losses [14]. Additionally, the results reported by Zhao et al. [15] show that the extrusion deformation could change EMI shielding effectiveness of Mg–Gd–Y–Zn–Zr alloys.

Alloying is widely used to improve the strength of metal materials. It has been reported that adding some elements, such as Al, Sn, Y and Gd, can further improve strength [16, 17]. Al element is the main additive element of magnesium

Available online at <http://link.springer.com/journal/40195>

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alloys [18, 19], which can improve the casting properties and mechanical properties. The addition of Sn can improve the heat resistance and the plasticity of magnesium alloys [20, 21]. The addition of rare-earth Y element can form LPSO phase in magnesium alloys and significantly improve the strength and plasticity of magnesium alloys [22–24]. The addition of rare-earth Gd element can act as a solid solution strengthening and improve the plasticity of magnesium alloys [25–29]. In a word, effects of different elements on mechanical properties have been studied extensively. However, the research on electrical conductivity and electromagnetic shielding property is still relatively rare. In this research, the Mg–X (X = Al, Sn, Y and Gd) binary alloys are selected to primarily investigate the effects of different alloying elements on EMI SE in various states. The SE value was measured in the frequency range of 30–1500 MHz by the coaxial cable method at ambient temperature and investigated through experimental observations made by a conductivity meter and an X-ray diffractometer (XRD) and analyzed using electromagnetic shielding theory. This work will provide an important basis for developing high-performance magnesium alloys for shielding application and broaden the practical application of magnesium alloys.

2 Experimental

The cast alloys were prepared by melting the raw materials in an electrical resistance furnace protected by a mixed gas of CO₂ and SF₆ with a ratio of 100:1. The molten alloys (740 °C) were poured from the melting crucible into a pre-heated die (300 °C) and air-cooled. A heat treatment schedule was performed on the as-cast specimens, including solid solution at 400 °C for 24 h and subsequently water quenched (T4). The chemical compositions of the samples were analyzed using the X-ray fluorescence (XRF), and the analyzed results are listed in Table 1.

Microstructures of the alloys were examined by Neophot 30 metalloscope (OM). The electrical conductivity of the alloys was measured with a conductivity meter (Sigmascope SMP 10) at ambient temperature. Each datum was the average of at least eight testing results. EMI SE was measured using the standard coaxial cable method in accordance with ASTM D4935-2010. The setup consists of a DN 1015A SE tester with its input and output connected to an Agilent

8753ES network analyzer [30]. Specimens in the form of disks, 115 mm in diameter and 2 mm in thickness, were prepared for EMI SE measurement and measured at the frequency range from 30 MHz to 1.5 GHz. A plane-wave electromagnetic field was used for vertically firing.

3 Results and Discussion

Figure 1 shows the dispersed second phases in the alloys studied. It can be seen that the as-cast Mg–X (X = Al, Sn, Y and Gd) binary magnesium alloys typically consist of the primary α -Mg matrix and second phase. After T4 treatment, all the second phases dissolved into matrix and the alloys transformed as the supersaturated solid solution (Fig. 2). In order to identify the types of the second phases clearly, the XRD patterns of binary magnesium alloys in various states are shown in Fig. 3. It can be seen that only peaks corresponding to the α -Mg matrix phase are found in the XRD patterns of the samples in the T4 state, while peaks corresponding to the second phase can be clearly identified for the as-cast state samples. Therefore, combining the OM and the XRD results, it is concluded that the Mg–X (X = Al, Sn, Y and Gd) binary magnesium alloys typically consist of the primary α -Mg matrix and second phase in the as-cast state. In the T4 state, all the second phases dissolved into the matrix and the alloys transform to the solid solution.

Variations of the electrical conductivity and SE values for Mg–X (X = Al, Sn, Y and Gd) binary magnesium alloys as a function of alloying element content are displayed in Figs. 4, 5, 6 and 7. The electrical conductivity of Mg–X (X = Al, Sn, Y and Gd) binary magnesium alloys is shown in Figs. 4, 5, 6 and 7a. The electrical conductivity for binary magnesium alloys decreases linearly with alloying element content. For Mg–Al alloys, the electrical conductivity of the as-cast samples decreases from 28.32% IACS for Mg–1Al to 16.21% IACS for Mg–5Al. For Mg–Sn alloys, the electrical conductivity of the as-cast samples decreases from 32.35% IACS for Mg–1Sn to 19.55% IACS for Mg–5Sn. For Mg–Y alloys, the electrical conductivity of the as-cast samples decreases from 30.91% IACS for Mg–1Y to 13.44% IACS for Mg–5Y. The case is the same for Mg–Gd alloys; the electrical conductivity of the as-cast samples decreases from 30.8% IACS for Mg–1Gd to 16.34% IACS for Mg–5Gd. After T4 treatment, the solution of alloying element content increases and electrical conductivity of all binary magnesium alloys reduces.

The electromagnetic shielding performance curves of various as-cast samples are presented in Figs. 4, 5, 6 and 7b. It can be observed that with increasing frequency, the value of SE demonstrates a monotonically decreasing trend and tends to be gradually stabilized at high frequencies, where Mg–5X (X = Al, Sn, Y and Gd) shows the lowest SE value.

Table 1 Chemical compositions of the four binary Mg alloys

Mg–X (wt%)	Al	Sn	Y	Gd
1	1.22	1.11	0.98	1.03
3	3.02	3.00	3.02	3.03
5	4.79	5.02	4.93	5.02

Fig. 1 OM images of as-cast Mg alloys: **a** Mg-5Al alloy, **b** Mg-5Sn alloy, **c** Mg-5Y alloy, **d** Mg-5Gd alloy

It can be seen from Figs. 4, 5, 6 and 7c that the electromagnetic shielding effectiveness of all binary magnesium alloys decreases significantly after T4 treatment.

Shielding effectiveness (SE) parameter is often used to quantify the shielding properties of the material when studying electromagnetism. The SE unit is the decibel (dB). When electromagnetic wave transmits through a single-layered metallic shield, there are three mechanisms to attenuate the electromagnetic wave: (1) reflection loss (SE_R), (2) absorption loss (SE_A) and (3) multiple reflection losses (SE_B) [31]. The shielding effectiveness (SE) parameter of a shielding material can be expressed as follows :

$$SE(\text{dB}) = SE_R + SE_A + SE_B, \quad (1)$$

$$SE_R = 168 - 10 \lg(f \mu_r / \sigma_r), \quad (2)$$

$$SE_A = 1.314 t (f \mu_r \sigma_r)^{1/2}, \quad (3)$$

$$SE_B = 20 \lg(1 - e^{2t/\delta}), \quad (4)$$

$$\delta = (\pi \mu \sigma f)^{-1/2}, \quad (5)$$

where μ_r , f , t , σ_r , μ and σ are the relative magnetic permeability, electromagnetic radiation frequency, the shield thickness, the relative electrical conductivity, the magnetic permeability and the electrical conductivity, respectively. As can be observed from Fig. 8, with increasing frequency, the absorption attenuation (SE_A) increases, whereas the reflection attenuation (SE_R) decreases. It could be neglected that the multi-reflection effect (SE_B) is equal to zero at high frequency. The reflection attenuation (SE_R) contributes significantly to the electromagnetic shielding effectiveness (SE) than the absorption loss (SE_A). The comprehensive results display that the SE value of Mg-5Al alloy decreases monotonously with increasing frequency, which is consistent with the experimental results in Fig. 4. On the basis of Eqs. 2–5, SE of a material depends on its electrical conductivity, magnetic permeability and thickness when the frequency of electromagnetic waves is constant. In this paper, the magnetic permeability and thickness of the alloy are constant, so the

Fig. 2 OM images of T4 Mg alloys: **a** Mg–5Al alloy, **b** Mg–5Sn alloy, **c** Mg–5Y alloy, **d** Mg–5Gd alloy

change trend of SE values is consistent with the conductivity. This indicates that the main reason for the differences in electromagnetic interference shielding of the binary magnesium alloys is the change in conductivity.

The SE values of binary Mg alloys in as-cast state decrease linearly with alloying element content, so it can be further surmised that the secondary phase will also have a certain effect on the electromagnetic shielding properties. For four kinds of binary magnesium alloys in as-cast state, there are inconspicuous changes in morphology and distribution of the secondary phase, but there are evident changes in the quantity of the second phases. More secondary phase can split α -Mg matrix and strengthen the discontinuity inside α -Mg matrix. The secondary phase can be regarded as an insulator owing to the electrical conductivity of the secondary phase that is two orders of magnitude lower than that of pure magnesium [14]. Severe impedance mismatch occurs because of the large difference between the impedance of the secondary phase and α -Mg matrix. The electromagnetic wave is more easily to be reflected when transmitting

through the interface between magnesium matrix and the secondary phase, accordingly improving the SE_B and SE_A . Because the wavelength of the electromagnetic wave is far greater than the size of a single second phase, the change of internal structure of the second phases that caused by the type of the secondary phase has negligible effect on the electromagnetic shielding properties of the binary magnesium alloys. For four kinds of as-cast binary magnesium alloys, the second phase dissolves into the matrix during T4 treatment, resulting in a decrease in electrical conductivity. This is mainly due to the fact that atoms dissolved in the matrix cause severe scattering of electrons during the transfer process, accordingly improving the SE_B and SE_A .

The electrical properties of four kinds of binary magnesium alloys with alloying element content of approximately 1 at.% in T4 conditions are summarized in Fig. 9. It can be seen from Fig. 9b that the electromagnetic shielding effectiveness of the binary magnesium alloys with the same alloying element content is as follows:

Fig. 3 XRD patterns of as-cast and T4 Mg alloy: **a** Mg–5Al alloy, **b** Mg–5Sn alloy, **c** Mg–5Y alloy, **d** Mg–5Gd alloy

Fig. 4 **a** Conductivity of as-cast and T4 Mg–Al alloys; **b, c** shielding effectiveness of as-cast and T4 Mg–Al alloys, respectively

Mg–Gd < Mg–Sn < Mg–Y < Mg–Al. This is consistent with the trend of conductivity, and similar rules are met for other high-alloy content samples. The electromagnetic shielding effectiveness values of magnesium alloys and other materials are listed in Table 2 [4, 9]. It can be seen that the shielding effectiveness of magnesium alloys is significantly higher than that of aluminum alloys. Compared to general commercial ZK60 magnesium alloys, four kinds of binary magnesium alloys have better electromagnetic shielding properties.

For different binary magnesium alloys, the electrical conductivity is different due to the influence of the different alloying elements on electrical conductivity. The effect of solute atoms on the resistivity of the alloy is affected by various factors, including the volumetric difference of solute atoms and magnesium atoms $\Delta V/V_{\text{Mg}}$, the valence of the solute atoms, the configuration of extranuclear electron, etc [31]. The above properties of Al, Sn,

Fig. 5 **a** Conductivity of as-cast and T4 Mg–Sn alloys; **b, c** shielding effectiveness of as-cast and T4 Mg–Sn alloys, respectively

Fig. 6 **a** Conductivity of as-cast and T4 Mg–Y alloys; **b, c** shielding effectiveness of as-cast and T4 Mg–Y alloys, respectively

Fig. 7 **a** Conductivity of as-cast and T4 Mg–Gd alloys; **b, c** shielding effectiveness of as-cast and T4 Mg–Gd alloys, respectively

Y and Gd are listed in Table 3 [32]. Large $\Delta V/V_{\text{Mg}}$ would cause serious lattice distortion of magnesium, resulting that the electron transmission and lattice vibration wave scattering are intenser which decrease the alloy resistivity. The influence of solute atomic valence on the magnesium

alloy resistivity is mainly based on Linde's rule [33]: The increment in resistivity caused by each addition of 1 at.% solid solution element is proportional to the square of the difference value of valence between solvent element and solute element. The difference value of valence between

Fig. 8 EMI shielding properties of T4 Mg-5Al alloy from theoretical calculations

Sn^{4+} and Mg^{2+} is higher compared with Gd^{3+} and Mg^{2+} , so it is more likely for Sn element to cause increment in alloy resistivity. The influence of the configuration of extranuclear electron on resistivity is mainly affected by the number of extranuclear electron vacancies. According to Hund's rule, the less electrons are filled in each sub-layer, the more vacancies in the sublayer, and it is more likely to absorb conduction electrons [34]. The number of vacancies in outer orbit of Sn ($4d^{10}5s^25p^2$) is less than Y ($4d^15s^2$), and the number of vacancies in outer orbit of Y ($4d^15s^2$) is less than Gd ($4f^75d^16s^2$). Given all that the resistivity increases more obviously when the same content of the Gd element is contained as compared with the other three elements.

Fig. 9 **a** Electrical conductivities, **b** electromagnetic shielding properties of four solid solution Mg-1 at.% X alloys

Table 2 Electromagnetic shielding effectiveness of magnesium alloys and aluminum alloy reported in the literature and this work

Alloys	Shielding effectiveness (dB)			References
	900 MHz	1200 MHz	1500 MHz	
ZK60	55	52	50	[4]
2024 Al alloy	35	35	35	[9]
Mg-1Al	80	80	80	This work
Mg-1Sn	74	70	63	This work
Mg-1Y	74	71	66	This work
Mg-1Gd	70	60	59	This work

Table 3 $\Delta V/V_{\text{Mg}}$, valence and configuration of extranuclear electron of the four alloying elements [34]

The four alloying elements	Al	Sn	Y	Gd
$\Delta V/V_{\text{Mg}}$ (%)	-28.420	+16.678	+41.732	+42.448
Chemical valence	+3	+4	+3	+2, +3
Configuration of extranuclear electron	$3s^23p^1$	$4d^{10}5s^25p^2$	$4d^15s^2$	$4f^75d^16s^2$

4 Conclusions

The electrical conductivity and electromagnetic shielding effectiveness of binary magnesium alloys are systematically investigated in the present work, and the following conclusions are drawn.

- (1) The electrical conductivity and electromagnetic shielding capacity of binary magnesium alloys decrease linearly with alloying element content. After T4 treatment, the electrical conductivity and electromagnetic shielding capacity of the binary magnesium alloys are reduced.
- (2) The conductivities of the binary magnesium alloy with the same alloying element content are as follows: Mg–Gd < Mg–Sn < Mg–Y < Mg–Al, and the electromagnetic shielding effectiveness shows the same change trend as the conductivity.
- (3) Volumetric difference of solute atoms and magnesium atoms, the valence of the solute atoms and the configuration of extranuclear electron may be the main reasons for the difference in electrical conductivity, and the electrical conductivity is a major factor affecting electromagnetic shielding performance in the binary magnesium alloys.

Acknowledgements The authors would like to thank the financial supports from the National Key R&D Program of China (No. 2016YFB0301100), the National Natural Science Foundation of China (No. 51571043) and Fundamental Research Funds for the Central Universities (Nos. 2018CDJDCL0019, cqu2018CDHB1A08 and 2018CDGFCL0005).

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