Electromagnetic shielding capability of magnesium based materials: A review

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Abstract

The rapid progress in the expanse of electromagnetic devices among the broad scale of industrial, military, commercial and consumer sector has led to a surge in electromagnetic interference which has now become the fourth most prevalent category of pollution. Thus, there is a dire need of developing materials which can shield the devices of its adverse effects. This review sets foot into what so far has been done in order to develop such shielding materials by targeting Mg. The dependence in shielding effectiveness on variation in heat treatment, concentrations of the alloying elements, forming processes and its combinations have been addressed in this review. Copyright © 2018 VBRI Press.

Keywords: Electromagnetic interference, Mg, shielding effectiveness**.**

Introduction

Electromagnetic interference (EMI), is a disturbance generated by the electromagnetic waves that affects the electrical circuit of the electronic devices by electromagnetic induction, electrostatic coupling or conduction. It has become a serious problem in scientific, defense and commercial sectors [**1-4**]. The disturbance adversely affects the performance of the devices [**5**] and sometimes even impedes their working. It affects the quality of the communication and sensitivity of the digital devices [**6**]. It leads to an increase in error rate or even loss of data in some cases [**7**]. EMI is also responsible for some of the very serious health problems such as headache, nervousness, insomnia, languidness and can damage human body's DNA structure [**2, 8**]. With rapid development of electrical and communication industries, the electromagnetic radiation has become one of the major sources of pollution. Thus, with ever increasing use of electronic devices and its rapid growth it becomes extremely critical to develop means to block these damaging radiations.

Electromagnetic shielding is a practice which reduces the effects of electromagnetic waves in a space by blocking the field with impediments made out of conductive or magnetic materials [**9**]. Shielding Effectiveness (SE) is the most common used parameter in order to define the capability of the material to protect the device from ele ctromagnetic radiations and it is measured in decibels (dB). Mechanisms which decide EMI shielding capacity are: i) reflection, ii) absorption and iii) multiple reflections [**9-11**]. For the reflection of the radiation, the shield must have mobile charge carriers, which interact with the electromagnetic field in the radiation. For absorption mechanism to take effect, the material should have electric/magnetic dipoles which in turn interact with the radiation. For this, the material should have a dielectric constant or magnetic permeability. Multiple reflection mechanism requires various phases and surfaces in the shielding material. The SE is calculated based on the following expression [4]:

$$SE(dB) = 10\log (P_0/P_S) \quad (1)$$

where, P_0 and Ps are the incident energy before shielding and the transmitted energy after shielding, respectively. Some of the most common materials implied for the electromagnetic shielding are metallic materials and polymer composites for e.g. copper, nickel, steel and permalloy. These materials exhibit high electrical conductivity and magnetic permeability which makes them ideal candidates to be used as a shield [**4, 11-13**]. Permalloy and mumetal are excellent for magnetic radiation absorption **[4**]. Nevertheless, due to the heavy weight of these metals, they are restricted in their use [**4**]. Polymer Composites with conductive fillers as well as metal foams have also been developed which are in line with the technique of enhancing the multiple reflection loss and also appear to be attractive choice to be used as a shielding material. However, due to their low strength and less shielding capabilities they do not fit properly for most of the structural applications. Conductive paints/coatings are also one of the prevalent technologies for EMI shielding applications. But again, the same problems persist with these coatings in reference to their shielding effectiveness and structural integration when compared to the metals and various alloys [**4**]. Thus, various sectors are in a dire need to develop materials that exhibit a combination of low density, acceptable mechanical strength and excellent shielding effectiveness to prevent leakage of EM radiation [**14**]. Magnesium is the lightest metallic element capable of serving in structural applications. Its alloys are known not only for low density (1.73g/cm^3), high specific stiffness, high specific strength, excellent damping capacity and recyclability, but also for relatively good conductivity and high shielding capacity [**15, 16**]. Thus, this leads us to the expectations that high strength magnesium alloys have the potential to be developed as EMI shielding materials. A variety of the researches have been carried out on the Mg alloys (Mg-Zn-Zr, ZK60, Mg-Zn-Cu-Zr) and their modified versions created by addition of various elements such as Ce, Zn, Sm etc.

Studies conducted so far on magnesium based systems

Limited research efforts have been made to study the electromagnetic shielding of magnesium based materials. Different variables that were investigated are described below:

Effect of Compositional Variance

Zinc is one of the most commonly used alloying element to augment the strength and corrosion resistance of the magnesium. Pan et al. investigated the effects of adding Zn from 0-5 wt% as an alloying element to Mg on the SE of the material [**17**]. In addition, two heat treatment processes were also performed: (a) solid solution treatment at 400^{0}C for 24h followed by water quenching and (b) solid solution treatment at 400^{0}C for 24h + water quenched + artificial aging at 170^{0}C for 48h (T6). The EMI SE was expressed as [6]:

$$EMI\ SE = -10\log (P_t/P_i) = SE_R + SE_A + SE_M \qquad (2)$$

where P_i and P_t are the magnitudes of the incident and transmitted power densities, respectively. SE_A is the absorption shielding effectiveness, SE_R is the reflection shielding effectiveness and SE_M is when the amount of Zn was increased and multiple reflection effectiveness inside the shield was witnessed. It was observed that the extent of precipitation increased with Zn addition and the Mg–5Zn alloy exhibited the maximum amount of secondary phases in the T6 condition. In the T4 state, all the secondary phases got dissolved into the α-Mg matrix and formed the super saturated solid solution. While in T6 state, the alloys with relatively low Zn (2 wt-%) and high Zn (3–5 wt-%) content consisted of α-Mg and α-Mg + $MgZn_2$ phases, respectively. The contribution of the alloying elements in the solid solution towards resistivity is greater than that of the alloying elements in the second phases, which is a known fact. Overall, Mg–4Zn in T6 state showed the best performance of EMI SE i.e. 94–114 dB in the whole test frequency range **[Fig 1].**

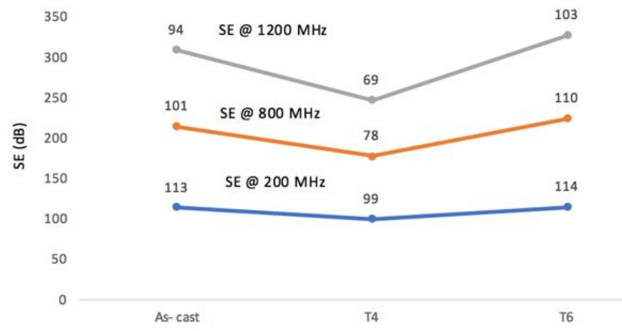

Fig. 1. EMI SE of Mg–4Zn alloy at varying testing frequencies for different heat treatment conditions.

Effect of thermal treatment

Chen et al., carried out a research to study the effects of aging treatment on electromagnetic SE in ZK60 Mg Alloy [**18**]. This work corroborated that in different aging conditions, the precipitation process can lead to significant increase in the shielding as well as the mechanical properties. Four aging variations for ZK60 alloy were attempted: (a) as extruded, and extruded and direct artificial aging at 150^0 C for (b) 4hrs, (c) 15hrs and (d) 50hrs. Hardness, tensile strength, composition, and electrical conductivity of the samples were determined. The EMI SE was calculated using the standard coaxial cable method in accordance with the ASTM D4935-2010. The range of scan frequency was set in the range of 30MHz to 1.5Ghz. The study revealed that, as the duration of the aging precipitation was increased, the volume fraction of the secondary phase particles ($MgZn_2$) increased in the α-Mg matrix. It varied from 0.64% to 3.81% for as extruded to aging precipitation for 50hrs at 150 ^{0}C, respectively. It was observed that the diameter of the precipitates in the sample aged for 50hrs was 1.3 times that of the precipitates in samples aged for 4 hrs. The study also provided an insight into the effects on the grain size. It appeared that the artificial aging had a very limited effect on the grain size of the as extruded alloy. Aging treatment for 4h, 15h and 50h showed an impressive increment of 10 dB, 16dB and 13 dB in the SE in the testing frequency of 1200 MHz, respectively **[Fig 2].**

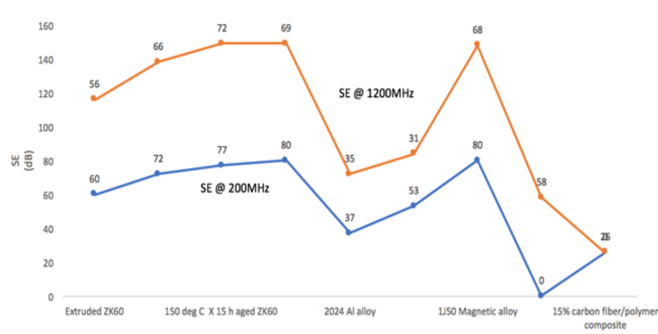

Fig. 2. Comparison of SE results among the ZK60 alloy and other shielding candidate materials.

In general, the SE value below 30dB is considered to be poor. The industrial requirement is 30-60dB and the military requirement is 60-120dB [**19**]. Thus, aging at 150^0 C for 4-50h showed an exemplary improvement in the shielding capacity over the entire frequency range of 30MHz to 1.5Ghz but there was no linear relationship with the aging duration. It was attributed that there was precipitation of brittle $MgZn_2$ intermetallic compounds due to the aging process which had detrimental effect on the elongation meanwhile, Tensile tests results revealed that the aging process contributed to the enhanced tensile strength. The overall SE can be calculated by the following equation:

$$SE(db) = R + A + B \qquad (3)$$

$$R(db) = 168 - 10\log(f\mu_r/\sigma_r) \qquad (4)$$

$$A(db) = 1.314t(f\mu_r\sigma_r)1/2 \qquad (5)$$

$$B(db) = 20 \log (1 - e^{-2t}/\delta) \qquad (6)$$

$$\delta = (\Pi\mu\sigma f)^{-1/2} \qquad (7)$$

where R, A, B, t, μ_r, σ_r, f, μ,σ are SE by reflection, absorption and multiple reflection, shield thickness, relative magnetic permeability, electrical conductivity relative to copper, frequency of electromagnetic radiation, magnetic permeability and electrical conductivity, respectively. The study also implied that aging process led to an increase in the electrical conductivity of the alloys. It was evident, that the relative electrical conductivity values increased from 29.93% to 32.67% when aged at 150^0 C for 50h due to the precipitation of the secondary phases **[Table 1]**. It was thus validated that, more the precipitation in the alloying super-saturated mixture, more is the electrical conductivity of the alloy. Thus, the artificial aging at the 150 ^{0}C for 15h was proposed as the optimum heat treatment condition as it led the SE to be higher than 70dB and a favorable tensile strength of 316 MPa was realized.

Table 1. Variation of relative conductivity with aging time for the ZK60 alloy.

Aging Time (h)	Relative Conductivity (%)
0	30
4	31
15	32
50	33

Another research carried out by Chen et al. studied the effects of heat treatment on ZK60 alloy in the testing frequency range of 30MHz to 1500MHz [20]. Two types of heat treatments were carried out: (a) the alloy was subjected to solid solution heat treatment at 400 ^{0}C for 5h and subsequently water quenched (T4) (b) solid solution at 400 ^{0}C for 5h and water quenched plus artificial aging at 130 ^{0}C and 170 ^{0}C for 4h and 40h respectively. The samples were also tested for hardness and tensile strength. The results revealed that the precipitation affects the conductivity of the material. The experiment also revealed that due to the formation of finer precipitates, the artificial aging at 130 ^{0}C induced higher peak hardness values as compared to aging at 170 ^{0}C. Also, it was observed that the subsequent artificial aging did not contribute to the grain growth in the ZK60 alloy. When subjected to SEM it was observed that the precipitation of the secondary phases in the α-Mg matrix increased with the duration of artificial aging at 130^0 C. The results also revealed that after solid solution treatment, the alloy exhibited a little higher EMI shielding properties when compared to samples in as-extruded condition. Artificial aging, following a solid solution treatment, remarkably improved the shielding effectiveness. The shielding effectiveness increased with increasing amount of precipitates. Thus, the study concluded that heat treatment had a clear influence on the EM shielding properties. The primary shielding mechanism of ZK60 magnesium alloy is reflection loss. The precipitation of numerous secondary phases from the supersturated mixture during the solid solution plus artificial aging, lead to the enhancement of the EMI shielding capacity of the ZK60 alloy. It was due to the increase in electrical conductivity that this augmentation was attributed. **(Fig. 3).**

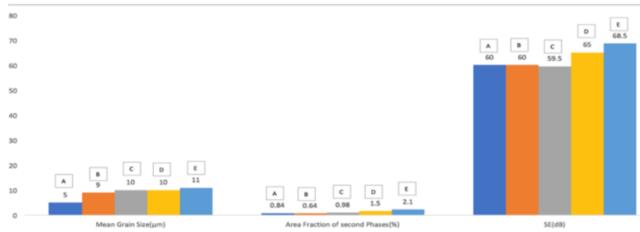

Fig. 3. Mean Grain Size, Area Fraction of Secondary Phases, SE comparison of ZK60 in various conditions (A= As Extruded, B = Solutionized, C = Solutionized and aged at 130deg C for 4h, D = Solutionized and aged at 130deg C for 20h, E = Solutionized and aged at 170deg C for 25h).

Effect of forming operations and microstructural variations

Chen et al. investigated the effects of forming operations in combination with the heat treatment on the shielding effectiveness of ZK 60 alloy [21]. The cold rolling technique was used because of its obvious advantages of saving energy and simplifying operational steps as compared to hot deformation.Cold rolling also leads to defects and high density of dislocations in the microstructure of the alloy which in turn enhances the strength [22-24]. The alloy was cold rolled and aged at 150^0 C for 15h and 50h. In the extruded state, a small quantity of secondary phases were distributed in the α-Mg matrix. For cold rolling followed by aging for 15h, there was some dispersal of ultrafine precipitates, distributed homogeneously in the matrix. When the aging time was increased to 50h, the secondary phases grew slightly, with a higher density of small phases. Based on EDS analysis, the type of the secondary phases was determined as $MgZn_2$ precipitates. Cold rolling and aging led to the precipitation of more secondary phases as compared with the extruded condition. This was partially due to the cold worked and aged samples having a greater amount of dislocation and twins, which resulted in a high strain concentration around their intersections and twin boundaries that was used as potential nucleation sites [25, 26]. The study concluded that pre-cold rolling and aging treatment resulted in a considerable improvement in the mechanical strength and EMI SE compared with the extruded state for ZK60 alloys **[Fig 4, 5].**

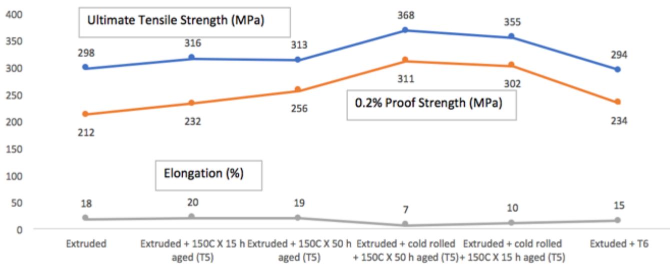

Fig. 4. Comparison of tensile properties of ZK60 alloys in different heat treatment states.

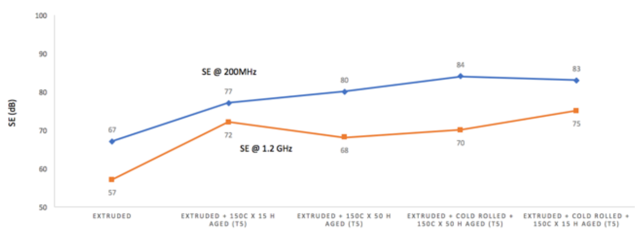

Fig. 5. EMI SE of ZK60 alloy at various testing frequency.

Another study investigated the electromagnetic shielding capabilities of the AZ31 magnesium alloy with different textures within the testing frequency range of 30MHz to 1.5GHz [27]. For this, the AZ31samples were preheated in the furnace at 350^0 C for 1h and then rolled to reduce the thickness of the samples in order to create variations. The samples tested were un-rolled, 20% rolled, 35% rolled and 60% rolled. The microstructure observation of the sample revealed that 20% and 35% rolled samples showed partial recrystallization whereas 60% rolled samples exhibited a completely recrystallized structure. This in turn showed a grain refinement. The study also concluded that the 60% rolled sample showed a greater EM shielding capacity as compared to the other samples. This was attributed to the refined grain size and strengthened basal texture. Zhang et al. also reported that there is no significant effect on the conductivity of the material with increasing or decreasing grain size.

Concluding Remarks

Magnesium based materials are emerging as potential materials for EM shielding. Fundamental studies have been conducted in recent years to identify factors that influence its EM shielding. Insights have been provided by researchers to delineate the effects of composition, thermal treatment, and microstructural aspects such as grain size, presence of secondary phases and texture. It is hoped that design and processing of the material will be optimized in near future using these findings for realizing high shielding effectiveness from lightweight magnesium based materials.

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