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A novel structure of Ferro-Aluminum based sandwich composite for magnetic and electromagnetic interference shielding

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ABSTRACT

A novel Ferro-Aluminum based sandwich composite for magnetic and electromagnetic interference shielding was designed and fabricated by hot pressing and subsequent diffusion treatment. The microstructure evolution of sandwich composite was characterized. Magnetic and electromagnetic interference shielding properties and mechanisms of the composites were also investigated. Sandwich composite is obtained with pure iron/Fe–Al alloy layer/pure iron structure and the Fe–Al/Fe interface shows good bonding. Al elemental content in reaction layer presents gradient distribution and the Al-riched brittle phase turns into ductile phase with diffusion time increasing. The electromagnetic shielding effectiveness of sandwich composite is higher than that of pure iron plate and increases with diffusion time extension, reaching 70 – 80 dB at the frequency of 30 KHz – 1.5 GHz. The multiple reflection loss in Fe–Al gradient layer is the primary contribution to the shielding effectiveness improvement of sandwich composite. The magnetic shielding effectiveness of sandwich composite can amount to 10 dB, about 2.5 times of that of pure iron plate. Fe–Al intermetallic layer, as non-magnetic spacer, is added between two iron plates and the permeable layer in sandwich composite can shunt magnetic field twice to improve shielding effectiveness.

1. Introduction

With the rapid development of electrical and electronic industry, electromagnetic radiation (including low frequency magnetic field) has become another serious source of public pollution [1–3]. Magnetic and electromagnetic field are usually generated by power cable and various of industrial devices, which can cause considerable disturbance to the operation and accuracy of sensitive electrical and electronic equipment, electromagnetic information divulge and even harmful to health of human beings. Thus, the magnetic and electromagnetic interference shielding materials are required not only in the sensitive devices to prevent the disturbance of external electromagnetic field, but also in the high power equipment to prevent electromagnetic pollution.

Electromagnetic interference (EMI) shielding often refers to the attenuation of electromagnetic radiation by a material, which thereby acts as a shield against the radiation [4]. There are three shielding mechanisms that could result in attenuation of EMI *viz.* reflection (R), absorption (A) and multiple reflections (B) [5]. The primary mechanism for shielding in highly electrically conductive structures is reflection. Metals [6,7] and carbon materials (*e.g.* carbon fibers, flexible graphite, carbon nanotube) [4,8,9] are by far the most common materials for EMI shielding. The secondary mechanism for shielding is absorption, which requires electic and magnetic dipoles interacting with the electromagnetic fields in the radiation. Absorption loss is proportional to the shield thickness and is a function of relative conductivity and permeability. Soft magnetic alloy powder and fiber are joined in polymer matrix with good shielding effectiveness, showing an absorption dominant mechanism [10,11]. The third mechanism for shielding is multiple reflections, taking place at surfaces or interfaces within the shield. The presence of large surface areas or interface within the shield are required and the multiple reflections depend on the part geometry rather than the material [12–14].

Magnetic field shielding, especially for low frequency and static magnetic field, is very different from EMI shielding with high frequency. The magnetic field shielding can only be achieved through shunting, not reflection or absorption as magnetic lines of force are continuous and cannot be cut off. Most of magnetic shielding materials are soft magnetic alloy, including pure iron, silicon steel [15], Fe–Al alloy and permalloy. New type of magnetic shieldig materials are also reported in succession, such as amorphous and nanocrystalline alloys [16]. They all have high magnetic permeability and the soft magnetic shield has low magnetic reluctance in magnetic field, compared to that of shielding area. Most magnetic lines of force will pass through the shield to avoid magnetic field disturbance and achieve shielding effect.

The most significant research trends of EMI shielding materials are the combination of multifuntional materials and reasonable shielding

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structure design. Polymer-matrix composite containing carbon materials [4], metal particles [17–19], fibres [20] and conducting coating [21] are all attractive for EMI shielding. Nanocomposites with different structure are also designed and prepared to apply for EMI shielding [22–25]. Multilayer composite is also an effective approach for improving shielding effectiveness and meeting broadband shielding application due to the more absorption and multiple reflections at the interfaces [26–29]. The shielding effectiveness of Ferrite plate/BPSCCO plate/Ferrite plate structure (FBF) is obviously higher than that of three-layer structure(FFB or BFF) with the same structural parameter [30]. Moreover, low conducting layer added between two high conducting layers contributes to an increase of shielding effectiveness due to the coherent multiple reflections at the internal interfaces [28]. Multilayer structrure is also widely adopted for magnetic shielding, optimized through numerical analysis [31] and different models of magnetic and conductive layers [32]. Various configurations of three-layer cylindrical magnetic shield sets are presented from modeling axial shielding effectiveness and the effect on shielding of spacer between layers, end gap geometry and end cap holes are also investigated in the literature [33]. The spacer (air or non-ferromagnetic materials) added between ferromagnetic shield layers is beneficial to improve magnetic shielding effectiveness.

In practical working environment, magnetic field and high frequency electromagnetic radiation may exist in the same time, disturbing sensitive devices. For the purpose of broadband shielding application, a novel structure of Ferro-Aluminum based sandwich composite are designed and fabricated based on Fe/Al/Fe diffusion couple in this paper. Inspired by the metal-intermetallic laminate composites, such as Ti–Al_3Ti and Ni–Al_3Ni [34,35], a very large number of interfaces and gradient distribution are prepared during the process of diffusion. The electromagnetic shielding property will be enhanced due to the multiple reflections effect of these diffusion induced interfaces. Fe–Al intermetallic layer with high Al content in the center has weak magnetism and high electrical resistivity, which is seen as dielectric and non-ferromagnetic spacer between the ferromagnetic shield layers. Thus, this sandwich structure design is reasonable and effective for improving both magnetic and electromagnetic shielding effectiveness. In addition, Fe–Al soft magnetic alloy with low Al content next to the iron substrate is also beneficial to magnetic shielding and can improve absorption loss for electromagnetic shielding due to their high magnetic permeability.

The novel Ferro-Aluminum based sandwich composite for magnetic and electromagnetic interference shielding was fabricated by hot pressing and subsequent diffusion treatment. The microstructure evolution of Fe–Al sandwich composite was characterized and the magnetic and electromagnetic shielding properties of sandwich composites with different diffusion time were investigated. Meanwhile, the magnetic and electromagnetic shielding mechanisms of Fe–Al based sandwich composite were also revealed.

2. Materials and methods

Commercial pure iron (DT4E) in the form of cold rolled plate with a thickness of 0.5 mm and commercially available 0.1 mm pure aluminum foil (with Al wt.% ≥ 99.99%) were chosen as the raw materials. The Al foils were chemically polished by Nital. Iron plates were mechanically polished and then cleaned with acetone in ultrasonic environment for 15 min. Fig. 1 shows the schematic diagram of fabrication process. The prepared plates were stacked alternatively together (Fe/Al/Fe) and kept at 700 °C for 30 min, and then were heated up to 900 °C for different diffusion time (1 h, 3 h and 10 h), in a vacuum furnace (10^{-3} Pa) and under the pressure of 10 MPa. The heating rate was 10 °C/min and the samples were taken out under 650 °C with air cooling. The pure iron plate with a thickness of 1 mm (two-layered substrates) was also studied as reference specimens. The iron was annealed at 900 °C for 4 h with heating/cooling rates of 40 °C/h.

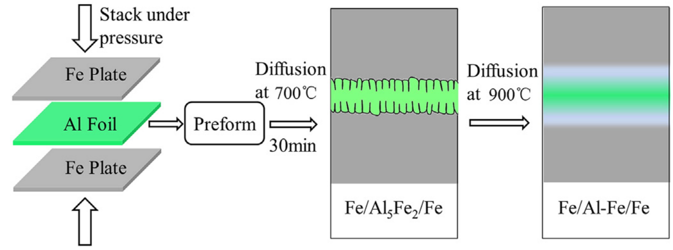

Fig. 1. Schematic diagram of fabrication process of the sandwich composite.

The microstructure of sandwich composite in cross-section were investigated with optical microscopy (OM, ZEISS-40MAT) and scanning electron microscopy (SEM, FEI Quanta 200F), operating at 20 kV. Energy dispersive spectroscopy (EDS) and electron backscatter diffraction (EBSD) were also performed to analysis elemental distribution and phases determined. X-ray diffraction (XRD), using monochromatic Cu-Kα radiation, operating at 40 kV and 100 mA, was conducted on D/MAX2200 X-ray diffractometer.

The direct current (DC) volume electrical resistivity was measured using the Kerthley 2400 multimeter and four-probe method. The specimens were rectangular, with a length of 10 mm, width of 2 mm and thickness of 1 mm. Each specimen was tested for five times in order to get the results. Maximum permeability was tested by DC magnetic measurement system of soft magnetic material (NIM-2000S, National Institute of Metrology, China). The test specimens present annular with inner diameter of 32 mm and outer diameter of 40 mm. Demagnetization was conducted before testing and every sample has been tested for three times.

Standard coaxial test method of planar materials specified in ASTMD 4935-2010 was used to measure EMI shielding effectiveness of sandwich composite. The electromagnetic shielding setup consisted of a shielding effectiveness tester with its input and output connected to a network analyzer, model HP8753D [36], as shown in Fig. 2a. The sample, with 115 mm in diameter, was placed in the center plane of the tester. A plane wave electromagnetic field was used for testing, and the range of scan frequency was within the range of 30 KHz–1.5 GHz. The energy of the plane wave before and after the shielding could be measured. The calculation expression of shielding effectiveness (SE) is as following: $SE = 10\lg(P_0/P_1)$, where P_0 and P_1 are the energy of the plane wave before and after shielding, respectively.

The magnetic field intensity at one point was measured by using the probe of vector magnetometer (MEDA FVM-400), as shown in Fig. 2b. Magnetic field source was generated by the copper coil with direct current and the magnetic shielding effectiveness was expressed as: $SE = 20\lg(H_0/H_S)$, where H_S was the magnetic field intensity with shield and H_0 was the magnetic field intensity at the same point without shield.

3. Results

3.1. Microstructure of sandwich composite

Fig. 3 shows the optical micrograph of sandwich composite with diffusion treatment for 1 h, 3 h and 10 h. At the temperature of 700 °C, Al foil has been molten and Fe–Al intermetallic compounds are formed due to the reactive diffusion. The microstructure evolution process of Fe–Al intermetallic compounds at 900 °C have been discussed in detail in our previous work [37]. As shown in Fig. 3, the thickness of Fe–Al reaction layer increases with diffusion time extension. Fe–Al sandwich composite is obtained with pure iron/Fe–Al reaction layer/pure iron structure and good bonding exists between the iron substrate and Fe–Al reaction layer with a clean and flat interface.

Fig. 4 reveals the X-ray diffraction patterns of cross section of sandwich composites with different diffusion time. Several intermetallic