Geomagnetic Shielding Property and Mechanism of Fe–Ni Laminated Composite

Xiangyu Ma · Qiang Zhang · Xiang Chen · Gaohui Wu

Received: 30 May 2014/Revised: 31 August 2014/Published online: 30 September 2014
© The Chinese Society for Metals and Springer-Verlag Berlin Heidelberg 2014

Abstract Ni layers were deposited on the two sides of pure Fe substrate by using electroplating to form Ni/Fe/Ni diffusion couple. After diffusion heat treatment, Fe–Ni laminated composite was obtained with Fe–Ni alloy/Fe/Fe–Ni alloy structure. The results indicate that the Fe–Ni layers combine well with the substrate and the Fe–Ni/Fe interface presents an interlocking microstructure with small-size grains. The concentration of element Ni in the Fe–Ni layer decreases from surface to interior exhibiting a gradient distribution. Geomagnetic shielding factor (SF) of Fe–Ni laminated composite can reach as high as 22.6, which is about seven times of that of pure Fe substrate. Mathematical equation of SF for laminated structure was derived according to magnetic circuit and resistance theory. The theoretical expression reveals that parameters such as the thickness and magnetic permeability of the shield material play an important role in the magnetic shielding behavior and the theoretical calculation results of SF coincide well with our experimental values.

KEY WORDS: Fe–Ni laminated composite; Initial permeability; Magnetic shield; Shielding factor

1 Introduction

Geomagnetic field exists in any place of the earth and its magnetic field intensity is very low with a magnitude ranging from 2.5×10^{-5} to 6.5×10^{-5} T at the Earth's surface [1]. In some cases of sensitive electrical and high-accuracy electronic sensors, their tolerances to environmental magnetic field are very low, and even the field like geomagnetic field may cause disturbing and even the

sensor becomes disabler [2]. Therefore, it is necessary to provide magnetic protection against the geomagnetic field so as to ensure their normal functions in an Earth environment. The intensity of geomagnetic field fluctuates with no regularity as time goes by, which can be divided into the mean field intensity and fluctuating value. Therefore, the geomagnetic field shield includes static magnetic shielding and low frequency magnetic shielding [3].

Magnetic shielding can be achieved through shunting effect of magnetic materials with high magnetic permeability. As a traditional magnetic shielding material, permalloy has high magnetic permeability and excellent shielding property. However, it is also highly sensitive to stress and microstructure, and even a knock during assembling process could worsen its magnetic properties and shielding effectiveness. The magnetic property of amorphous soft magnetic alloy is not affected by machining. Through structural design, this alloy was reported to produce highly effective magnetic shield [4–6]. Structural design [7, 8] and effectiveness calculation of magnetic shield [9, 10] are the two main issues in the magnetic

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

X. Ma · Q. Zhang (✉) · X. Chen · G. Wu (✉)
School of Material Science and Engineering, Harbin Institute of Technology, Harbin 150001, China
e-mail: zhang_tsiang@hit.edu.cn

G. Wu
e-mail: wugh@hit.edu.cn

X. Chen
Department of Applied Science and Technology, Politecnico di Torino, 10129 Turin, Italy

shielding field. One interesting structural design is to use laminated composite as magnetic shielding material, which can be prepared by several different approaches, such as combining sheets of polymer and soft magnetic metal under pressure or alternatively depositing films of oxide and soft magnetic metal. By adjusting the thickness of each layer, the shielding effectiveness of laminated composite can be tailored [11, 12].

In this study, we manufactured a special laminated composite, composed of two layers of high-magnetic-permeability Fe–Ni alloy (permalloy) on the surface and one layer of pure Fe in the interior. The shielding factor of this laminated composite was determined experimentally and theoretically. Meanwhile, the influencing factors of SF were discussed and the connotative magnetic shielding mechanism was revealed.

2 Experimental

Commercial electromagnetic pure iron (DT4E) in the form of cold-rolled plate was chosen as the substrate material with a thickness of 0.5 mm. The pretreatment processes including alkaline degreasing, sulfuric acid excitation, and water washing before electroplate were conducted. The plating solution was composed of nickel sulfate (250–350 g/L), nickel chloride (30–60 g/L), and boric acid (30–40 g/L). And the process conditions included temperature (45–60 °C) and cathodic current density (1–2.5 A/dm²). Ni layers were deposited on the two sides of pure Fe substrate to form Ni/Fe/Ni diffusion couple. According to heat treatment regime of perm alloy and DT4E, the diffusion heat treatment was established to obtain preferable magnetic property. The Ni/Fe/Ni couple was heated up to 1,200 °C for 1 h, cooled to 880 °C, and then kept at 880 °C for 4 h in vacuum. The heating rate was 10 °C/min, while the rate of heating and cooling around 880 °C should be very slow, and then specimens were cooled in furnace. The Fe–Ni laminated composite obtained was marked by Fe–Ni/Fe/Fe–Ni furnace cooling. In addition, the Fe–Ni laminated composite was further heat-treated by air quenching from 600 °C and which was marked by Fe–Ni/Fe/Fe–Ni air cooling.

The metallographic specimens were prepared with polishing and chemical etching by 3% nital after cutting from the Fe–Ni laminated composite. The Fe–Ni layer/Fe interface in cross section was observed using optical microscopy (OM, ZEISS-40MAT). Energy dispersive spectroscopy (EDS, S-4700) was used to measure the Ni element content distribution. Six specimens were bonded side by side using organic glue. After grinding cross section, the phases were identified by X-ray diffraction (XRD, D/MAX200, CuK α , 40 kV, 100 mA). The pure iron square

tube (20 mm $\times$ 20 mm $\times$ 80 mm) was prepared by mechanical bending and arc welding. With nickel electroplating and diffusion heat treatment, the square tube of Fe–Ni laminated composite was obtained for magnetic shielding measurement. The intensity of magnetic field was measured using the hall probe of gauss meter (Lake Shore 421). The geomagnetic shielding factor (SF) is expressed as H_0/H_S , where H_S is the magnetic field with shield present and H_0 is the magnetic field in the same point without shield. The measured direction was parallel to the cross section of square tube.

3 Results and Discussion

3.1 Microstructure

Figure 1 shows the overall cross-sectional and local oblique-sectional morphology of Fe–Ni laminated composite separately. In the initial Ni-coated Fe specimen, Fe grains exhibit elongated structure and fine combination exists between Ni coating and the Fe substrate with a clean and flat interface. Then the cold rolled structure in Fe substrate turned into annealed structure with equiaxial grains after heat treatment, meanwhile Fe–Ni alloy layer was formed on the surface and interlocking interface was developed in between.

Generally speaking, inter-diffusion between Fe and Ni generates the gradient elemental distribution in the Fe–Ni layer, which was examined through EDS linear scanning, and the result is presented in Fig. 2. The Ni content in the Fe–Ni layer gradually decreased from the surface to the interior, accordingly the Fe–Ni alloy layer could be divided into surface layer (8 μ m, Ni 70–80 at.%) and transition layer (17 μ m, Ni < 70 at.%). However, in reality, Fe–Ni inter-diffusion did not occur uniformly. The boundary diffusion took place faster than the volume diffusion, which resulted in the interlocking interface structure. To further observe interface structure, we increased the observing area by polishing the Fe–Ni/Fe/Fe–Ni-laminated composite obliquely (Fig. 1b) rather than perpendicularly, and the result is shown in Fig. 1d. More details were revealed from the morphological observation in the enlarged interfacial zone, and a lot of grains were surrounded by the fast boundary diffusion paths which restricted them from growing up.

XRD analysis was carried out to identify the phase composition in Fe–Ni laminated composite, as shown in Fig. 3. From the XRD pattern, only ferrite and Fe–Ni solid solution phases were detected and apparently the ferrite phase has much higher content than the Fe–Ni solid solution phase by comparing their intensity.

Fig. 1 Schematic showing OM specimens preparation and metallographic morphology of Fe–Ni laminated composite: **a, c** Cross section; **b, d** oblique section

Fig. 2 Ni element distribution in the surface layer of Fe–Ni/Fe/Fe–Ni laminated composite

Fig. 4 Geomagnetic shielding factor of different structures and cooling conditions

Fig. 3 XRD pattern of Fe–Ni laminated composite on cross section

3.2 Geomagnetic Shielding Property

Geomagnetic shielding factor (SF) of substrate and Fe–Ni laminated composite are plotted separately in Fig. 4. The SF of Fe–Ni laminated composite reaches 22.6, about seven times of the value of pure Fe substrate. In the case of furnace cooling, the SF of Fe–Ni laminated composite (Fe–Ni/Fe/Fe–Ni furnace cooling) is only 9.7, whereas in the case of air cooling (through further air quenching at 600 °C), the SF of composite (Fe–Ni/Fe/Fe–Ni air cooling) arrives at 22.6.

Figure 5 shows the relative initial permeability of Fe–Ni alloy with different Ni content under different cooling conditions. Compared with pure Fe, Ni alloying treatment would improve the initial permeability effectively with

Fig. 5 Initial permeability of Fe–Ni alloy under different cooling conditions [3]

Fig. 6 Schematic diagram of magnetic shielding and equivalent magnetic circuit

both cooling conditions. Especially in the range with (50–90) at.% of Ni, the formation of ordered phase Fe–Ni₃ is believed to play an important role in the magnetic property. When cooling from high temperature, disordered Fe–Ni₃ would turn into ordered Fe–Ni₃, which would worsen the magnetic property of Fe–Ni alloy. Suitable fast cooling treatment can effectively control the degree of Fe–Ni₃ ordering and therefore improve the initial permeability property. Taking these into account, if we consider Fe–Ni laminated composite as several layers of Fe–Ni alloys, the improvement of geomagnetic shielding factor through Ni alloying and air quenching can be well understood.

3.3 Shielding Factor Calculation

Square shield is put in static magnetic field with the magnetic field direction being parallel to the cross section of shield, as shown in Fig. 6. The intensity of outside magnetic field is H_0 , and the intensity of magnetic field in the shield is H_s . So, shielding factor (SF) can be expressed

as H_0/H_s . The calculation of SF is similar to the equivalent circuit method by considering relevant components into magnetic resistance elements.

The magnetic resistance of the shielding area is R_s . The shield is considered to be composed of several magnetic conductive layers. Each magnetic conductive layer has its individual resistance denoted as R_{mi} , which sums to R_m . According to the equivalent magnetic circuit theory [13], when the thickness of the shield is much less than the size of the shielding area, the SF can be expressed as:

$$SF = 1 + \frac{R_s}{R_m}. \quad (1)$$

Meanwhile, in a parallel circuit, total resistance R_m can be written as

$$R_m = \frac{1}{\frac{1}{R_{m1}} + \frac{1}{R_{m2}} + \cdots + \frac{1}{R_{mn}}} = \frac{1}{\sum_{i=1}^n \frac{1}{R_{mi}}}. \quad (2)$$

Thus, the SF becomes

$$SF = 1 + \sum_{i=1}^n \frac{R_s}{R_{mi}}. \quad (3)$$

The magnetic resistance R can be expressed as [14]

$$R = \frac{Hl}{BS} = \frac{l}{\mu S}, \quad (4)$$

where μ is the magnetic permeability in H/m, S is the cross-sectional area of magnetic circuit in m², and l is the length of magnetic circuit in m.

From Eq. (4), it can be obtained that

$$\frac{R_s}{R_{mi}} = \frac{2}{a} \mu_{ri} d_i, \quad (5)$$

where a is the length of side of shield area in m, μ_{ri} is the relative initial permeability of the i th layer, and d_i is the thickness of the i th layer.

Combining Eq. (3) and Eq. (5), the SF of the n -layer magnetic shield can be expressed as:

$$SF = 1 + \frac{2}{a} \sum_{i=1}^n \mu_{ri} d_i. \quad (6)$$

In the case with a single layer of pure Fe substrate, the SF can be expressed as:

$$SF = 1 + \frac{2}{a} \mu_r d. \quad (7)$$

In the case with Fe–Ni laminated composite, the shield can be divided into Fe–Ni/Fe/Fe–Ni three-layer structure at the macroscopic level and the Fe–Ni layers can be further divided into infinite laminated structure. Accordingly, the SF can be written as:

Fig. 7 Divided Fe–Ni alloy layers and initial permeability of each layer

Table 1 Thickness and initial permeability of each layer in Fe–Ni laminated composite and Fe substrate

Shield layer	Thickness (μm)	Initial permeability μ_i	
		Furnace cooling	Air cooling
Fe substrate	500	50	50
Fe–Ni/Fe/Fe–Ni			
Ni ₇₅ layer (70–80%)	8	1.5×10^3	8×10^3
Ni ₆₀ layer (50–70%)	6	1.5×10^3	3.5×10^3
Ni ₃₅ layer (25–50%)	6	2.0×10^3	2.0×10^3
Ni ₁₅ layer (0–25%)	5	100	100
Pure Fe	450	150	150

SF = 1

$$+ \frac{2}{a} \left(\sum \mu_{\text{r-FeNi}} d_{\text{FeNi}} + \mu_{\text{r-Fe}} d_{\text{Fe}} + \sum \mu_{\text{r-FeNi}} d_{\text{FeNi}} \right). \quad (8)$$

In this study, the thickness of the Fe–Ni laminated composite is 500 μm in total, which includes two layers of Fe–Ni alloy (25 μm) and the remaining Fe substrate (450 μm), as shown in Fig. 7. Fe–Ni alloy layer can be divided into several layers with different Ni composition ranges. For example, from the surface to the center, the first (surface) layer includes the Ni content from 70 to 80 at.%, which can be seen as a layer with 75 at.% Ni, named Ni₇₅. The Ni content of second layer is from 50 to 70 at.%, as the Ni₆₀ layer. The third layer with (25–50) at.% Ni is named Ni₃₅. The Ni content range of last layer is (0–25) at.%, named Ni₁₅, which has low initial permeability.

The relative initial permeability of each layer in Fe–Ni laminated composite is shown in Fig. 7b. According to the relationship between the initial permeability and Ni element content (Fig. 5), the initial permeability of pure Fe, Ni₁₅, and Ni₃₅ layers are not related to the cooling condition of heat treatment, which are 150, 100, and 2.0×10^3 , respectively. However, the initial permeability of Fe–Ni alloy with an Ni content from 50 to 90 at.% is strongly

Table 2 Computed and measured values of SF

Shield layer	Computed SF	Measured SF
Fe substrate	3.5	3.3
Fe–Ni/Fe/Fe–Ni		
Furnace cooling	14.5	9.7
Air cooling	27.3	22.6

related to the cooling condition. The initial permeability of Ni₇₅ layer increases from 1.5×10^3 under furnace cooling to 8.0×10^3 under air cooling. The initial permeability of Ni₆₀ layer under furnace and air cooling are 1.5×10^3 and 3.5×10^3 , separately. In addition, the initial permeability of cold-rolled Fe substrate is lower than that of pure Fe after annealing heat treatment, which was set at only 50 in the current calculation.

The thickness and the initial permeability of each layer in the Fe–Ni laminated composite and pure Fe substrate in single layer shield are shown in Table 1. The length of a side of shield area (a) is 20 mm.

According to the layer division method, Eq. (8) becomes

$$\text{SF} = 1 + \frac{2}{a} \left[2 \times (\mu_{\text{Ni75}} d_{\text{Ni75}} + \mu_{\text{Ni60}} d_{\text{Ni60}} + \mu_{\text{Ni35}} d_{\text{Ni35}} + \mu_{\text{Ni15}} d_{\text{Ni15}}) + \mu_{\text{r-Fe}} d_{\text{Fe}} \right]. \quad (9)$$

Given the thickness d and the relative initial permeability μ_i , the computed values of SF of the substrate and Fe–Ni laminated composite are obtained by Eq. (9), as shown in Table 2.

It is indicated that the computed value of SF of Fe–Ni/Fe/Fe–Ni structure is higher than the measured value. The value of relative initial permeability for computing is obtained in literature, which is measured on the Fe–Ni alloy with different Ni contents through the different optimal heat treatment. However, in this study, Fe–Ni alloy layers are formed with gradient Ni element distribution after certain diffusion heat treatment, which is not the

optical heat treatment process for each Fe–Ni layer. The actual magnetic properties (included initial permeability) of Fe–Ni alloy layer will be lower than the value in literature. So, the measured value of SF is lower than the computed value. It is necessary to measure the actual initial permeability of each layer for computing the value of SF. The layer with certain Ni content is chosen to replace the Fe–Ni layer to adjust the composition of the Fe–Ni layer, as shown in Fig. 7a. The value of thickness and initial permeability of each Fe–Ni alloy for computation can be taken as approximate value, which can bring the computing error of SF.

3.4 Magnetic Shield Mechanism

Fe–Ni alloy layers are formed on the surface of pure Fe, which have very high magnetic permeability. The Fe–Ni laminated composite presents Fe–Ni/Fe/Fe–Ni three layered structure and infinite laminates in micro-level, which can shunt the magnetic field in parallel to achieve excellent shielding effectiveness. Compared with single layer (pure Fe substrate), Fe–Ni laminated composite has higher shielding factor due to high permeability of Fe–Ni alloy and parallel shunting of each layer.

As can be seen from the computed formula of SF (Eq. (8)), the total value of SF is obtained with the addition of magnetic shield coefficient of each layer. It is indicated that the roles in magnetic shielding of each layer are the same and there is no mutual coupling relation, which is consistent with mechanism discussions. The thickness of pure Fe is 450 μm , while the total thickness of Fe–Ni alloy layer is 50 μm , which only constitutes 10% of the total volume. However, the contribution of Fe–Ni alloy layer in magnetic shielding under air cooling condition has reached 74.8%, which shows that the magnetic permeability of shield is the key impact factor of magnetic shielding.

In summary, in order to improve the shielding effectiveness of laminated composite, the thickness and magnetic permeability of shield should be increased. When the total thickness of shield remains unchanged, improving the magnetic permeability of shield becomes the main method. In this study, adjusting Ni element content of the surface layer and optimizing heat treatment process can increase magnetic permeability. Another effective approach to improve the shielding effectiveness is by increasing the percentage of high-permeability components in the shield.

4 Conclusions

- (1) Ni layers were deposited on the surface of pure Fe substrate and Fe–Ni laminated composite with Fe–Ni/

Fe/Fe–Ni structure was formed by diffusing heat treatment. The geomagnetic SF arrived at 22.6, seven times higher than that of the Fe substrate.

- (2) Through magnetic circuit theory, mathematical formula of SF of laminated composite is obtained. According to the thickness and initial magnetic permeability of each layer, computational value of SF is obtained, which is slightly higher than the experimental value.
- (3) The Fe–Ni laminated composite exhibits excellent magnetic shielding effectiveness by shunting magnetic field with each layer in parallel and there are no mutual coupling relations within these layers.
- (4) The thickness and magnetic permeability of shield are the major factors in static magnetic field shielding. Improving magnetic permeability and increasing the thickness of shielding case can improve magnetic shielding effectiveness effectively.

References

- [1] Earth's magnetic field (from Wikipedia, the free encyclopedia, 2014), http://www.en.wikipedia.org/wiki/Earth's_magnetic_field. Accessed 28 June 2014
- [2] S. Koroglu, P. Sergeant, N. Umurkan, Simul. Model. Pract. Theory **18**, 206 (2010)
- [3] X. Chen, Master Thesis, Harbin Institute of Technology, 2010 (in Chinese)
- [4] R. Kannan, S. Ganesan, T.M. Selvakumari, Optoelectron. Adv. Mater. **6**, 383 (2012)
- [5] Y. Okazaki, M. Lixin, Y. Ohya, J. Mater. Process. Technol. **181**, 66 (2007)
- [6] G. Haneczok, R. Wroczynski, P. Kwapulinski, A. Chrobak, Z. Stoklosa, J. Rasek, J. Mater. Process. Technol. **209**, 2356 (2009)
- [7] S.L. Zhao, J. Chen, Y.L. Wang, Acta Metall. Sin. **48**, 977 (2012) (in Chinese)
- [8] K. Yamazaki, Y. Hatsukade, S. Tanaka, A. Haga, IEEE. Trans. Magn. **44**, 4187 (2008)
- [9] N. Umurkan, S. Koroglu, O. Kilic, A.A. Adam, Expert Syst. Appl. **37**, 3195 (2010)
- [10] E. Bulic, A.R. Sinnigoj, B. Cestnik, IEEE. Trans. Electromagn. C. **51**, 263 (2009)
- [11] C.D. Yu, P. Li, Y.F. Wang, L. Tang, in *2011 International Conference on Mechatronics and Materials Processing*, Guangzhou, China, 18–20 November 2011
- [12] J.H. Lee, J.W. Jang, S.H. Shon, S.G. Lee, M.S. Park, Mol. Cryst. Liq. Cryst. **470**, 107 (2007)
- [13] Y.X. Yuan, Mater Thesis, Beijing University of Technology, 2005 (in Chinese)
- [14] K.J. Yang, *Electromagnetic Compatibility Principle and Design Technique*, 2nd edn. (Post & Telecom Press, Beijing, 2011), pp. 41–47