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Effect of Annealing on Magnetic Properties of NiFe/Cu Composite Wires

Z.J Zhao[1], X.P Li[1,2], H.L. Seet[1], C. Chua[1] and L. Lu[1]

[1] Department of Mechanical Engineering, [2] Division of Bioengineering,
National University of Singapore Singapore 119260
Fax: 65- 6874 5114, email: mpezz@nus.edu.sg

DC Joule-heat treatment technique is used to improve the efficiency of giant magneto-impedance (GMI) response of ferromagnetic materials. The investigation on the effect of DC heating time and cooling rate under an optimal current density on MI response is performed on NiFe/Cu composite wires, which is known for its high magnetic permeability. The obtained results indicated an initial drop in MI ratio, followed by an increasing trend with increasing annealing time. However, beyond 4 minutes of heating time, MI response stagnated and a plateau was observed. The cooling rate also affected the magnetic properties of composite wires. Slower cooling rate improved the MI response.

Keyword: GMI, Composite Wires, Electroplating, Joule annealing

I. INTRODUCTION

Since GMI effect was firstly discovered in Co-based amorphous wires in 1992 [1], it had attracted many researchers' interest in GMI and its application studies [2-5]. The GMI effect has not only been observed in homogeneous soft magnetic materials, such as amorphous wires, ribbons and thin films [2-3], but also in some inhomogeneous materials, such as composite wires and sandwiched thin films [4-5]. In contrast to the homogeneous materials, the GMI effect in composite structure materials is not restricted by the change of the skin depth in the material under a magnetic field. Normally, their MI ratios are much larger than those of samples with the same dimensions and of similar ferromagnetic materials. A study on the GMI effect of composite wires with a $Ni_{80}Fe_{20}$ layer electrodeposited on copper indicated that the stress condition of the electroplated ferromagnetic materials of the composite wire affects the soft magnetic properties of the material and therefore affects the GMI effect of the composite wire. Therefore, the GMI effect of the composite wires may be enhanced by improving its soft magnetic properties through heat treatment which releases the residual stresses in the ferromagnetic coating layer. In this study, a DC Joule annealing method has been developed for heat treatment of electroplated NiFe/Cu composite wires. The results showed that the GMI effect of electroplated NiFe/Cu composite wires can be greatly enhanced. In this study, the influence of annealing time, cooling rate and other heat process parameters on the magnetic properties of the composite wires were investigated.

II. EXPERIMENTAL DETAILS

Composite wire samples of 20 μm diameter copper core coated with a layer of $Ni_{80}Fe_{20}$ of thickness 1.5 μm and 8 cm in length were produced by electroplating at a constant temperature of 55°C. The plating current density was $2A/dm^2$. The pH value of the plating electrolyte solution was kept constant at 3.4. The surface uniformity, thickness and composition of the plated layers were observed using SEM/EDX.

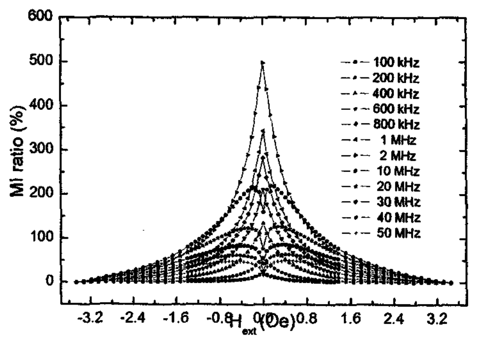
All the composite wire samples, each 15 mm in length, were annealed using a DC Joule annealing technique, in which in the environment of argon gas, the composite wire has a DC current passing through it for certain time and then cools down using Ar air flow. The average annealing current density was kept constant at 7.2×10^8 A/m^2. Magneto-impedance (MI) measurements on the samples before and after annealing were carried out using a precision impedance analyzer (HP4294A). The RMS value of the ac driving current was kept constant at 20 mA, and its frequency was varied from 100 kHz to 50 MHz. The relative change of the magneto-impedance ratio was defined as

$$\frac{\Delta Z}{Z}=\frac{Z(H_{ext})-Z(H_{max})}{Z(H_{max})}\times 100\%$$

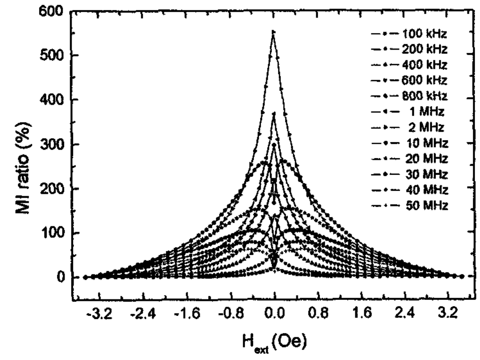
where $Z(H_{ext})$ and $Z(H_{max})$ are the impedance values of a composite wire in MI effect testing under an arbitrary and maximum intensity of external magnetic field H_{ext}, respectively. The external magnetic field for the MI effect tests were generated by a Helmholtz Coil.

III. RESULTS AND DISCUSSION

It has been showed that the optimum annealing current density is 7.2×10^8 A/m^2 when using DC Joule heating method for NiFe/Cu composite wires [7]. In this case, the residual stress is almost released.



(a)



(b)

Fig 1.MI ratio in variation with external magnetic field for electroplated wire (a) before; (b) after the DC Joule annealing at 7.2×10^8 A/m^2 for 5 minutes.

GMI effects in electroplated composite NiFe/Cu wires before and after DC Joule annealing can be seen from Fig. 1, where (a) and (b) show the MI effect curves tested under different ac driving frequencies for the same wire before and after annealing at 7.2×10^8 A/m^2 for 5 minutes, respectively. Fig. 1(a) shows that in the wire before DC Joule annealing, the MI ratio in variation with the external magnetic field depended on the driving frequency of the ac current in the GMI effect test. At the DC driving frequency of 2 MHz, the MI ratio reached the maximum of 497%. For the wire after annealing, Fig. 1(b) shows also that the MI ratio versus the external magnetic field depended on the driving frequency of the ac current in the GMI effect test. At the ac driving frequency of 2MHz, the maximum MI ratio was 551%, which was an 11% increase, as compared to the maximum MI ratio in the wire before annealing.

To study the influence of annealing time on the GMI effect of the composite wires, 6 samples are used and each sample is annealed at current density of 7.2×10^8 A/m^2 and at different annealing time (30s, 1, 2, 3, 4, and 10 minutes). The maximum MI ratio in variation with annealing time was shown in Fig. 2. It can be seen from the graph that after annealing for 30s and 1 minute, MI ratio drops below the initial MI ratio obtained before annealing. As the annealing time further increases, MI ratio starts to show positive increment. At annealing time of 4 minutes, the increment in MI ratio is 12%. As the annealing time increases beyond 4 minutes, the increment in MI ratio plateaus thus, indicating that MI ratio increases with constant rate. The transition from an increasing rate of MI ratio to a constant increment of MI ratio is speculated to be at 4 minutes.

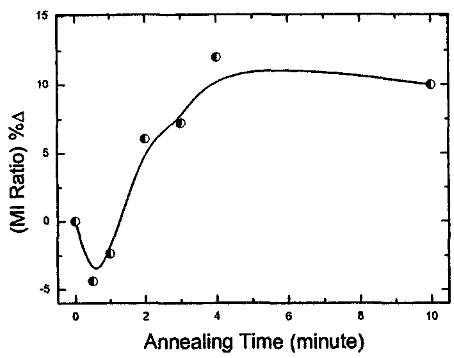


Fig 2. The percentage increment in the MI ratios with different annealing time

Before undergoing the DC Joule annealing, the plated layers of the composite wire samples contain residual stresses induced by the electrodepositing process. During the initial annealing at shorter annealing time, it was conjectured that there were tremendous inertia for the magnetic domains to rotate from their initial local anisotropy orientations to the circumferential anisotropy as induced by the annealing current. As a result, a larger crystalline magnetic anisotropy, *k*, was needed to rotate the domains, which were frozen in their initial directions, along the easy axis to the circumferential direction. This magnetic hardening also led to a slight drop in the MI ratio.

With increasing annealing time, the residual stress can be almost released. After this critical annealing time, there is no observed significant effect. The plateau can be seen in Fig. 2..

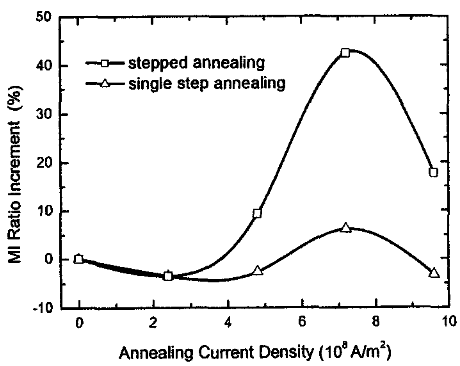


Fig 3. The percentage increment in the MI ratios of single step annealed composite wire and stepped annealed wire.

During the annealing, there are two different kinds of process in DC Joule annealing of the composite wires, single step annealing and stepped annealing. The stepped annealing involved annealing of a composite wire using an increasing average annealing current density from 2.4 to 9.6 $\times 10^8$ A/m^2 at the step of 2.4×10^8 A/m^2 and the subsequent measurement of the MI ratio of the wire. In the single step annealing, 5 composite wires of the same plated layer composition and thickness were used to test the effects of 4 levels of annealing current densities on the MI ratios of the wires. As shown in Fig. 3, in both the single step annealing and stepped annealing, the MI ratio of the annealed wire increased with increasing annealing current density, before it reached the maximum. However, stepped annealed wires had much higher MI ratio increments compared to the single step annealed wires. The MI ratio increments for wires annealed at the current density 7.2×10^8 A/m^2 was 42% for stepped current annealing and 6% for single step annealing. Hence, stepped current annealing can be concluded to be the better technique in achieving higher MI ratio. As a possible reason, it could be thought that it was easier for the electroplated material to release its internal stresses after the smaller current density annealing.

For the DC Joule annealing method, the cooling rate in annealing was also investigated. Three composite wire samples of the same plated layers were annealed at an annealing current density of 7.2×10^8 A/m^2 for 1 minute. Subsequently, for the first sample, the annealing current was stopped immediately, and for the second and third samples the current was reduced gradually to zero during 30 and 60 minutes, respectively. It was found that the MI ratio of the annealed wire increased almost linearly with the increase in the cooling time, as shown in Fig. 4. This can be explained by the better stress minimization of lower cooling rate in the annealing processes.

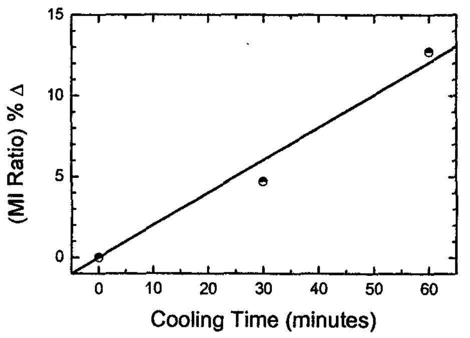


Fig 4. Effect of the cooling time in the DC Joule annealing on the percentage increment in the MI

IV. CONCLUSIONS

The influence of DC joule annealing parameters on the magnetic properties of electroplated FeNi/Cu composite wires has been investigated. There is a minimum annealing time to release the residual stress. Stepped annealing was found to be better than single step annealing and the MI ratio increment was found to increase almost linearly with the cooling rate in the annealing.

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