# Effects of magnetic permeability and resistivity on magneto-impedance in Fe–Cu–Nb–Si–B alloy ribbons

**Wanjun Ku†, Fuding Ge† and Jing Zhu‡**

† Central Iron and Steel Research Institute, Beijing 100081, People's Republic of China
‡ Department of Materials Science and Engineering, Tsinghua, Beijing 100084, People's Republic of China

Received 29 October 1996, in final form 18 March 1997

**Abstract.** The giant magneto-impedance (MI) effect and magnetic permeability of $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ alloy ribbons were measured as a function of the annealing temperature. When the ribbons had been annealed at the optimum temperature ($T_a$ = 843 K) they exhibited both a large MI and excellent soft magnetic properties. The MI was also calculated on the basis of classical electromagnetic theory. It was found that a large change in the effective magnetic permeability, caused by the application of an external magnetic field in an excellent soft magnetic sample, was crucial for the MI effect. Furthermore, the effect of the resistivity on the MI was also investigated. When the resistivity decreases, the eddy current losses increase and the frequency at which the variation in the complex impedance exhibits its maximum moves to a low value; thus the sample exhibts a large MI effect.

## 1. Introduction

Large magnetic-field-induced variations in the complex impedance, namely the magneto-impedance (MI), of Co–Fe–Si–B wires (ribbons) [1–4] and Fe–Cu–Nb–Si–B wires (films) [5, 6] have attracted attention in recent years. According to the classical electromagnetic theory, the impedance ($Z$) of a sample depends on its effective transverse magnetic permeability ($\mu_m$), and MI effects result from the change in $\mu_m$ due to the application of an external magnetic field ($H_{ex}$). In general, the more excellent the soft magnetic properties the more remarkable the change in $\mu_m$; thus the excellent soft magnetic properties in these alloy ribbons are important for the MI [7].

It is known that the resistivity can influence the impedance and magnetic permeability of the sample; therefore, it also influences its MI. For $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ alloy wires, using the classical eddy-current theory, Knobel *et al* [6, 8] found that the large MI was associated with the reduction in resistivity, but they did not consider the effects of micro-eddy currents generated by the movement of domain walls on the effective permeability. In fact, for superior soft magnetic materials, the effects of micro-eddy currents on the MI and magnetic permeability can not be neglected [9].

Therefore, in this paper, we first studied a relationship between the magnetic permeability, which represents the soft magnetic properties of the samples, and the MI in $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ alloy ribbons. To achieve different soft magnetic properties, these ribbons were annealed at various temperatures. For consideration of the effects of micro-eddy currents on the effective magnetic permeability ($\mu_m$), the relationship between the resistivity and the MI was also investigated from the theoretical point of view. The MI($R, X, |Z|$) was defined as the following:

$$\mathrm{MI}(R, X, |Z|) = (R, X, |Z|_{(H_{ex})} - R, X, |Z|_{(H_{ex}=0)}) \times [R, X, |Z|_{(H_{ex}=0)}]^{-1} \times 100\% \qquad Z = R + \mathrm{i}X.$$

## 2. Experimental procedures

Ribbon samples of $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ alloys 15 mm wide and about 25 $\mu$m thick were prepared by the conventional single-roller melt-spinning method. The as-cast state was confirmed to be amorphous by x-ray diffraction. Rectangular samples were cut into lengths of 15 mm along the transverse direction and widths of 3 mm along the longitudinal direction of the ribbons. The amorphous alloy ribbons were then wound into toroidal cores of 20.2 mm inner diameter and 20.6 mm outer diameter for measuring the magnetic permeability. To achieve different magnetic properties, both the cores and the rectangular samples were annealed at various temperatures in the range 733–893 K for 1 h in a vacuum of about $10^{-4}$ Torr. After they had been annealed, the samples were in crystalline phases which were also identified by x-ray diffraction. The experimental arrangements were as in figure 1. We adopted the four-terminal method to measure the impedance. $H_{ex}$, applied by a solenoid, was parallel

0022-3727/97/131842+04$19.50 

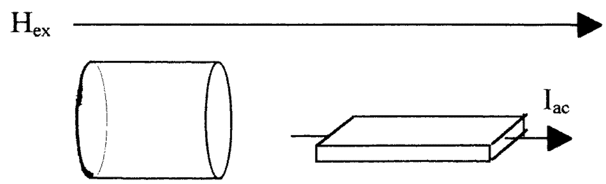


**Figure 1.** The schematic arrangement for measuring the effective magnetic permeability and impedance under an external magnetic field ($H_{ex}$). The AC driving current is also shown.

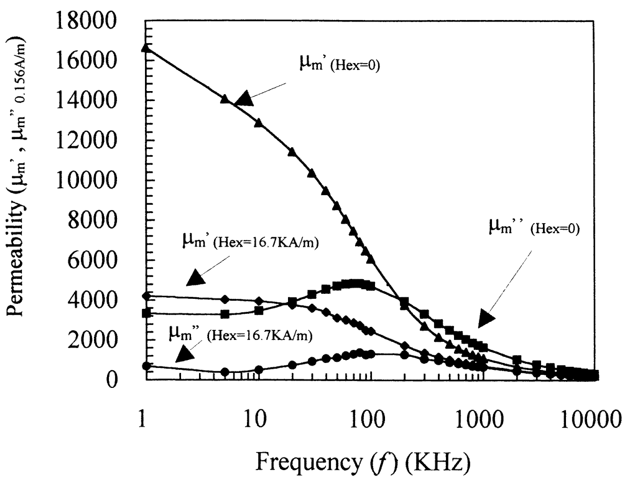


**Figure 2.** The frequency dependence of the magnetic permeability ($\mu_m$) of the ribbons annealed at 833 K. $\mu_m = \mu'_m + i\mu''_m$, $\mu'_m$ and $\mu''_m$ are the real and imaginary parts of the permeability respectively.

to the AC driving current ($I_{ac} = 10$ mA) with frequency varying from 5 Hz to 13 MHz and kept in the sample plane for measuring the impedance. $H_{ex}$ was also applied along the transverse direction of the core for measuring the effective magnetic permeability in the same frequency range. It should be noted that the different geometry of the permeability and MI samples will have led to different demagnetizing fields in the two measurements. So, the effects of the external magnetic field on the permeability samples were different from those on the MI samples. Both the magnetic permeability (under 0.156 A m$^{-1}$) and the impedance were measured by an impedance analyser (HP4192A).

## 3. Results and discussion

The magnetic properties of $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ alloy had already been extensively studied [10]. It is known that, when the alloy is annealed at the optimum temperature, a homogeneous ultra-fine grain structure of BCC FeSi grains of size several tens of nanometres embedded within the residual amorphous matrix forms. Owing to their small size, the grains are exchange coupled and thus the local magneto-crystalline anisotropy is randomly averaged out by this sort of exchange interaction, so that superior soft magnetic properties are presented. However, the soft magnetic properties of the alloy are degraded due to precipitation of $Fe_2B$ when the alloy is annealed at high temperature. Our own experiments also confirmed these results.

Figure 2 shows the frequency dependence of $\mu_m$ with $H_{ex} = 0$ and $H_{ex} = 16.7$ KA m$^{-1}$ of the sample annealed at 833 K. From figure 2, it can be seen that $\mu_m$ decreases to a very low value and the characteristic frequency ($\omega_\tau$) is shifted from 70 to 150 kHz by the application of $H_{ex}$. Figure 3 shows the change of $\Delta\mu_m/\mu_m$ with frequency; it clearly shows that a large $\Delta\mu_m/\mu_m$ is manifested at a very low frequency and that it decreases with increasing frequency.

The MI has a close relation to the change in $\mu_m$. Following Panina *et al* [9], the impedance of a ribbon (film) of thickness $2a$ can be written

$$Z = R_{dc}\, \mathrm{i}ka \coth(\mathrm{i}ka)$$

$$k = (1+\mathrm{i})/\delta_m \qquad \delta_m = \frac{c}{2\pi}\left(\frac{\rho}{\mu_m f}\right)^{1/2} \tag{1}$$

where $\mathrm{i} = \sqrt{-1}$, $R_{dc}$ is the DC resistance of the ribbon, $\delta_m$ is the skin depth of the material, $c$ is the speed of light, $\rho$ is the resistivity and $\mu_m$ is the effective magnetic permeability.

Using equation (1), MI($R$, $X$, $|Z|$) can be written in the form

$$\begin{aligned} \mathrm{MI}(R, X) = {} & \{[\mu_1 \sinh(2\mu_1) \pm \mu_2 \sin(2\mu_2)]_{H_{ex}} \\ & \times [\cosh(2\mu_1) - \cos(2\mu_2)]_{H_{ex}=0}\} \\ & \times \{[\cosh(2\mu_1) - \cos(2\mu_2)]_{H_{ex}} \\ & \times [\mu_1 \sinh(2\mu_1) \pm \mu_2 \sin(2\mu_2)]_{H_{ex}=0}\}^{-1} - 1 \end{aligned} \tag{2}$$

where

$$\begin{aligned} \mu_{1,2} = {} & -\frac{2\pi a (f/\rho)^{1/2}}{c}\left[\left(\frac{|\mu_m| - \mu_m}{2}\right)^{1/2}\right. \\ & \left. \pm \frac{\mu''_m}{[2(|\mu_m| - \mu'_m)]^{1/2}}\right] \end{aligned} \tag{3}$$

where $|\mu_m| = (\mu'^2_m + \mu''^2_m)^{1/2}$ and $\mu'_m$ and $\mu''_m$ are the real and imaginary parts of the effective magnetic permeability ($\mu_m$).

Equation (2) is the relationship between the MI and $\mu_m$. With the experimental $\mu_m$ measured under an external magnetic field ($H_{ex}$), it is easy to calculate the MI from equation (2).

For the sample annealed at 833 K, using equation (2) and the resistivity which was measured to be about 150 $\mu\Omega$ cm, the MI effects of the alloy were calculated and compared with the experimental data. Both the calculated results and experimental data are shown in figure 4. Because of the de-magnetizing field effect, the external magnetic field of 5.57 kA m$^{-1}$ chosen for measuring the MI was different from that of 16.7 kA m$^{-1}$ used for measuring effective magnetic permeability. It can be seen that the experimental and theoretical cures are qualitatively similar but they show quantitative differences, particularly at lower frequencies. It is interesting to note that at a certain frequency ($f_m$), MI($R$), MI($X$) and MI($|Z|$) have the same value, and that MI($|Z|$) has its maximum at precisely this frequency.

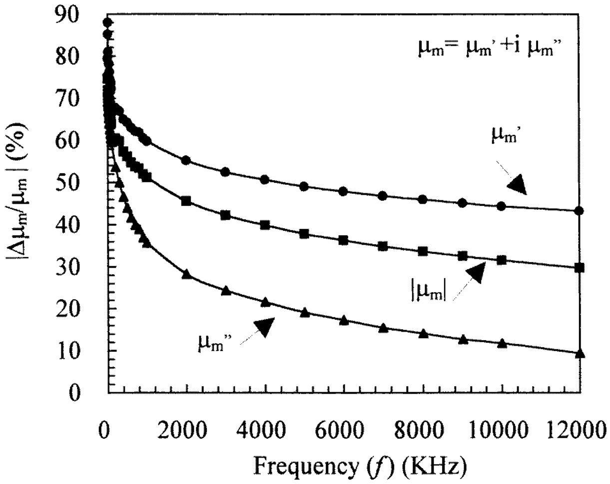


**Figure 3.** The frequency dependence of $\Delta\mu_m/\mu_{(mH_{ex}=0)}$ ($\Delta\mu_m/\mu_{m(H_{ex})} - \mu_{m(H_{ex})}$, $\mu_m = \mu_m' + i\mu_m''$) for the ribbons annealed at 833 K.

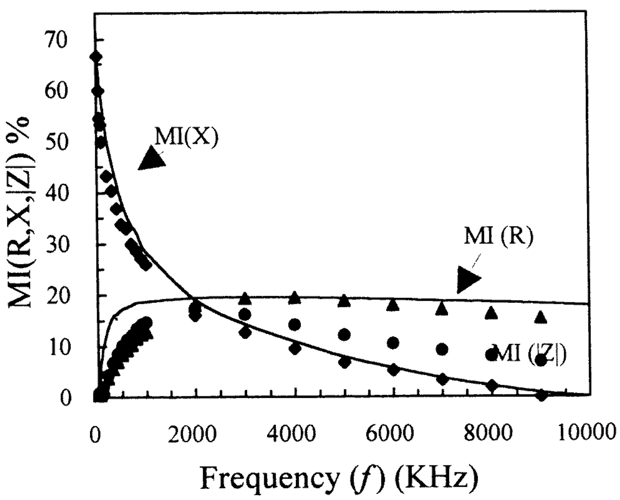


**Figure 4.** The frequency dependence of MI($R$, $X$, $|Z|$) with the external magnetic fixed at 5.57 kA m$^{-1}$ for the ribbons annealed at 833 K. Theoretical curves are shown as full lines and experimental data are shown as full points.

Figure 5 shows the relationship between the peak of MI($|Z|$) and the effective magnetic permeability as well as the resistivity ($\rho$) for various annealed samples. The frequency for measuring $\mu_m$ was fixed at 1 kHz. From figure 5, it is obvious that the peaks both of MI($|Z|$) and of $\mu_m$ had their maximum values when the sample was annealed at 843 K. This suggests that a large change in the effective permeability, which is caused by the application of $H_{ex}$, is crucial for the MI in the excellent soft magnetic sample.

From figure 5 it also can been seen by comparing MI($|Z|$) and the resistivity of the sample annealed at $T_a$ = 783 K with those of the sample annealed at $T_a$ = 863 K that the decrease in the resistivity is certain to be helpful for increasing of MI($|Z|$). In the following, considering the effects of the classical and microscopic eddy current on the effective magnetic permeability, we discuss the relationship between the resistivity and the MI from the theoretical point of view.

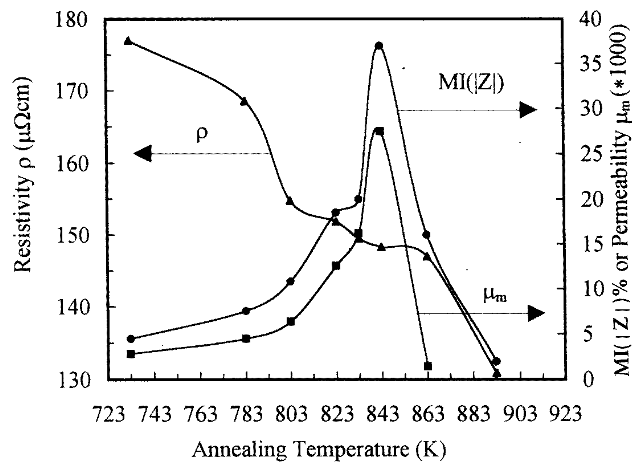


**Figure 5.** The maximum of MI($|Z|$), the effective magnetic permeability ($\mu_m$) and the resistivity as functions of the annealing temperature. The external field for measuring the MI was fixed at 5.57 kA m$^{-1}$.

When only the effect of the classical eddy current on the effective permeability is considered, the effective permeability for a film (ribbon) of thickness $2a$ can be written [11]

$$\begin{aligned} &\mu_m = \mu_m' + \mathrm{i}\mu_m'' \\ &\mu_m', \mu_m'' = \left(\frac{\omega_w}{\omega}\right)^{1/2} \\ &\quad\times \frac{\mu_i}{2}\,\frac{\sinh[2(\omega/\omega_w)^{1/2}] \pm \sin[2(\omega/\omega_w)^{1/2}]}{\cosh[2(\omega/\omega_w)^{1/2} + \cos[2(\omega/\omega_w)^{1/2}]} \\ &\omega_w = \frac{c^2\rho}{2\pi a^2 \mu_i} \end{aligned} \tag{4}$$

where $\mu_i$ is the static permeability. It follows from equation (4) that the characteristic frequency which is determined by the skin effect, $\omega_w$, is proportional to the resistivity. When the frequency of the driving current, $\omega$, is equal to $\omega_w$, $\mu_m' = \frac{2}{3}\mu_i$, $\mu_m'' = \frac{2}{5}\mu_i$ and $\mu_m'' = \frac{3}{5}\mu_m'$, respectively.

When the effect of the domain dynamics on the effective magnetic permeability is considered, taking stripe-domain structure as the example, to a first approximation we assume that the domain dynamics is limited by the wall motion rather than by the magnetization rotation. In a relaxation-type mechanism of the wall motion, the effective permeability for a film (ribbon) with thickness $2a$ can be written [11]

$$\begin{aligned} \mu_m = \mu_m' + \mathrm{i}\mu_m'' &= \frac{\mu_i}{1 - \mathrm{i}\omega/\omega_r} \\ \omega_r &= \frac{9\pi\sigma_{wall}\rho}{8\mu_0^2 M_s^2 a^2} \end{aligned} \tag{5}$$

where $\sigma_{wall}$ is the wall energy, $\mu_0$ is the permeability of free space, $M_s$ is the saturation magnetization and $a'$ is a parameter related to the inclusions which damp the wall motion. When the frequency equals the relaxation frequency, $\omega_r$, $\mu_m' = \mu_m'' = \mu_i/2$. It also can be seen that $\omega_r$ is proportional to the resistivity.

In order to simulate the effective permeability from a theoretical point of view and compare it with the

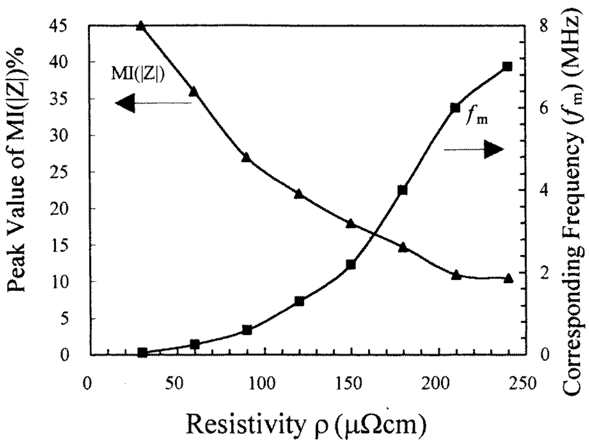


**Figure 6.** The resistivity dependences of the peak value of MI($|Z|$) and the corresponding frequency ($f_m$).

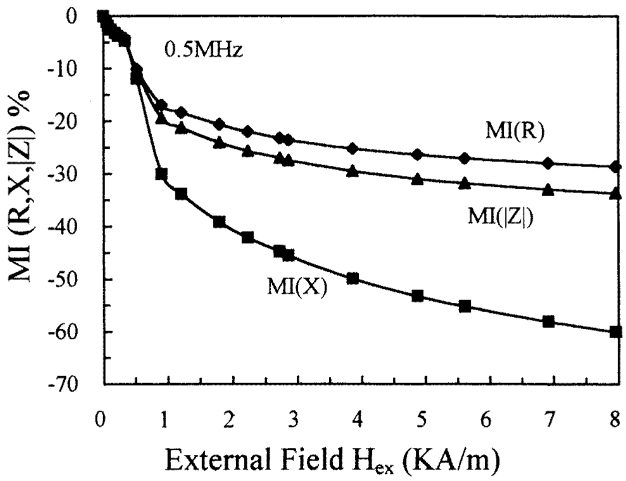


**Figure 7.** The field dependence of MI($R, X, |Z|$) for the ribbons annealed at 843 K.

experimental data in figure 2, we consider the effects both of the classical and of the micro-eddy current. Using equations (4) and (5), on the basis of the experimental static magnetic permeability determined from figure 2, the static permeability $\mu_i = 17\,000$ under zero field and $\mu_i = 4000$ under the external field of 16.7 kA m$^{-1}$, we simulated the effective permeability and the results were in good agreement with the experimental data. Hence, on the basis of the change in effective permeability with resistivity and equation (2), the relationship between the MI and the resistivity can be obtained. The results are shown in figure 6. In figure 6 the maximum of MI($|Z|$) and its corresponding frequency ($f_m$) are shown as functions of the resistivity. It can be seen that with decreasing resistivity the maximum of MI increases but the corresponding frequency decreases.

The decrease in the resistivity will lead to an enhancement of the eddy-current losses and thus the real part of the impedance, $R$, increases; at the same time the relaxation frequency moves to a low value, thus a large MI($|Z|$) peak value exhibiting a low frequency ($f_m$) can be achieved.

The field dependence of MI($R, X, |Z|$) of the sample annealed at 843 K with the AC frequency fixed as 0.5 MHz is shown in figure 7. From figure 7 it can be seen that MI($R, X, |Z|$) increases with the external field. MI($R$) of 18%, MI($|Z|$) of 20% and MI($X$) of 30% were obtained under an external magnetic field of 1 kA m$^{-1}$ in these ribbons.

## 4. Conclusion

In this paper, the MI effects of $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ alloy ribbons have been measured as a function of the annealing temperature. Both the largest MI and excellent magnetic properties exist at $T_a = 843$ K. A large change in the effective permeability of the excellent soft magnetic sample, caused by the application of the external magnetic field, is crucial for the MI effect. Furthermore, the relation between the resistivity and the MI has also been presented. When the resistivity decreases, the eddy-current losses increase and the frequency at which MI($|Z|$) exhibits its maximum is shifted to a low value; thus the sample shows a large maximum of MI($|Z|$) at low frequency.

## Acknowledgments

This work was supported by the Foundation of the Ministry of Metallurgical Industry and the National Nature Science Foundation of the People's Republic of China.

## References


[1] Mandal K and Ghatak S K 1993 *Phys. Rev.* B **47** 14 233
[2] Mohri K, Kohzawa T, Kawashima K, Yoshida H and Panina L V 1992 *IEEE Trans. Magn.* **28** 3150
[3] Velazquez J, Vazquez M, Chen D-X and Hernando A 1994 *Phys. Rev.* B **50** 16 737
[4] Beach R S and Berkowitz A E 1994 *Appl. Phys. Lett.* **64** 3652
[5] Sommer R L and Chien C C 1995 *Appl. Phys. Lett.* **67** 3346
[6] Knobel M, Sanchez M L, Gomez-Polo C, Marin P, Vazquez M and Hernando A 1996 *J. Appl. Phys.* **79** 1646
[7] Panina L V, Mohri K, Bushida K and Noda M 1994 *J. Appl. Phys.* **76** 6198
[8] Knobel M, Sanchez M L, Marin P, Gomez-Polo C, Vazquez M and Hernando A 1995 *IEEE Trans. Magn.* **31** 4009
[9] Panina L V, Mohri K, Uchiyama T, Noda M and Bushida K 1995 *IEEE Trans. Magn.* **31** 1249
[10] Herzer G 1991 *Mat. Sci. Eng.* A **133** 1–5
[11] Liao S B 1988 *Ferromagnetism* vol III (Beijing: Science Press) (in Chinese)