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Effect of Joule-Heating Annealing on Giant Magnetoimpedance of $Co_{64}Fe_4Ni_2B_{19-x}Si_8Cr_3Al_x$ (x = 0, 1 and 2) Melt-Spun Ribbons

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ABSTRACT

In this work, we have studied the influence of dc joule-heating thermal processing on the structure, magnetoimpedance (MI) and thermal properties of $Co_{64}Fe_4Ni_2B_{19-x}Si_8Cr_3Al_x$ (x = 0, 1, and 2) rapidly solidified melt-spun ribbons. The nanocrystallization process was carried out by the current annealing of as-spun samples at various current densities. As-spun and joule-heated samples were studied by X-ray diffraction (XRD), differential scanning calorimeter (DSC), and magnetoimpedance (MI) measurements. DSC results revealed that by the replacement of B by Al the first and second crystallization peaks are overlapped with each other and the initial nanocrystallization temperature is decreased with the increase in Al content of the alloy. Also it was shown that the replacement of B by Al atoms can improve soft magnetic properties confirmed by magnetoimpedance ratio (MIR%) results for the amorphous joule-heated ribbons. Furthermore, increase in dc joule current density increases the MI ratio first, however; after formation of crystalline phases, it decreases.

Keywords: *Co-based alloy, Joule-heating annealing, giant magnetoimpedance.*

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1. Introduction

The discovery of giant magnetoimpedance (GMI) effect in soft magnetic materials has caused a large interest due to perspective application as the magnetic sensors [1-5]. The giant magnetoimpedance (GMI) effect consists of the large change of both real and imaginary parts of the impedance upon the application of static magnetic field for the ferromagnetic samples when is subjected to a small alternating current as $I = I_0 e^{jwt}$. A theoretical model based on the skin depth effect was suggested to explain the magnetoimpedance effect. The magnetoimpedance is proportional to the transverse magnetic permeability and can be written as [6]:

$$Z=(1-i)L(2lc)^{-1}(2\pi\rho w\mu_T)^{1/2} \qquad \text{(eq. 1)}$$

where L is the ribbon length, l is the ribbon width, at which the skin depth (δ) becomes smaller than the sample thickness, the magnetic penetration depth (δ) is related to the transverse magnetic permeability (μ_T),

$$\delta=c(4\pi^2 f\sigma\mu_T)^{1/2} \qquad \text{(eq. 2)}$$

where c is the speed of the light, σ is the electrical conductivity, and f is the angular frequency. The maximum GMI is generally found in the alloys with the lowest magnetostriction which corresponds to a maximum transverse permeability. Some authors reported that such a high permeability of amorphous alloys does not necessary lead to a high GMI value, and the observed large effect was due to the presence of transverse magnetic anisotropy induced by the application of external magnetic field during the annealing process [8-10]. One of the useful and handyways to induce additional transverse magnetic anisotropy in amorphous ferromagnetic ribbons is DC joule heating. Joule heating is a method that allows a sample to be heated directly by the action of a DC current flowing along the sample axis for a certain time. During joule heating, the DC magnetic field generated by the DC current allows a thermal treatment under the self-generated external circular magnetic field [11-14].

It is shown that the Co-based amorphous alloys are well-known for their favorable ultra soft magnetic properties in amorphous state [15,16]. Various works have reported the effect of composition and structure on magnetoimpedance response of Co-based ribbons. Further, the addition of Al in Co-based amorphous alloy is reported to increase soft magnetic properties specially permeability and decrease coercivity [17-19]. The aim of this work is to investigate the structural and magnetoimpedance effect of joule-heated amorphous CoFeNiBSiCr melt spun ribbons with different Al content.

2. Experimental

The arc-melted ingots of master prealloys of nominal composition $Co_{64}Fe_4Ni_2B_{19-x}Si_8Cr_3Al_x$ (x = 0, 1, 2 and 3, hereafter referred to as Al_0, Al_1 and Al_2 samples) were rapidly quenched using a single roller melt-spinning technique at a wheel surface speed of 35 m/s under pure argon gas (99.999%) atmosphere. The melt was ejected from a quartz crucible by flowing Ar gas at a constant pressure of 0.1 bar. Selected ribbons have been submitted to DC joule heating with different electrical current values I (0-0.8 A) for 0.5 h under 0.001 mbar vacuum. The structure of as-spun and joule heated ribbons with x=2 in different currents was examined by X-ray diffraction using an X-Pert XRD-Philips diffractometer with Cu-Kα radiation to evaluate structural changes occurring during current annealing. The average crystallite sizes of the samples were also determined from the full width at half maximum of the strongest reflection peak using the Williamson-Hall method [20] after applying the standard correction for instrumental broadening. The crystallization kinetics and transformation temperatures of the samples were investigated using a DSC under pure argon gas (99.999%) atmosphere at a constant heating rate of 10 °C/min. The average size of the ribbons used for the Joule-heating annealing and GMI measurements was 25 μm thickness, 30 mm length and 1.1mm width. To measure the MI ratio (MIR), a computer controllable system including a function generator (AGILENT-33220A) as a current source and a digital oscilloscope (TEKTRONIX-TDS2022B) for voltage measurements were employed. The required DC axial field, H, for investigating the magnetic field dependence GMI, is provided by a solenoid, generating a maximum field Hmax=120 Oe. The applied field was arranged to be vertical to the earth's ambient magnetic field. The GMI ratio was defined as [6]:

$$\frac{\Delta Z}{Z} = 100 \times \frac{Z(H)-Z(H)max}{Z(H)max} \quad \text{(eq. 3)}$$

where H_{max} is the maximum bias longitudinal magnetic field.

3. Results and Discussions

XRD patterns for the samples with x=2, for as-spun and joule-heated samples is reported in Fig. 1. One observes that the material is amorphous until I=0.4 A. For further increase in the current density more than 0.4 A, some peaks appear in the XRD patterns which indicate the precipitation of Co, Fe_2B and Fe_3B phases. The average crystallite sizes of Co phases for A_2 samples after current annealing at 0.5 and 0.7 A is about 23 and 45 nanometers; respectively. The magnitudes of MIR are decreased with the increasing in current density and formation of Fe_2B and Fe_3B hard phases.

Fig. 2 shows DSC curves for all of the as-spun samples with different Al content obtained at a constant heating rate of 10 °C/min. For the Al_0 sample, two exothermic peaks are detected at temperatures about 566 °C and 591°C, respectively. The first peak is related to the primary crystallization of the nanocrystalline phase, i.e. Co phase and the second one attributed to the formation of iron boride phases based on XRD results (Fig. 4). The first and second peaks for the Al_1 and Al_2 samples are overlapped and one exothermic peak is only appeared, i.e. 558 °C and 546 °C, respectively. The decrease in crystallization temperature by adding Al to Fe-based amorphous alloys has reported in previous studies [21-23]. In fact, the primary and second crystallization temperatures are merged together by adding Al to the alloy and it is observed Fe_2B, Fe_3B and Co phases are formed simultaneously in Al_2 alloy at current density above 0.4 A (Fig. 1).

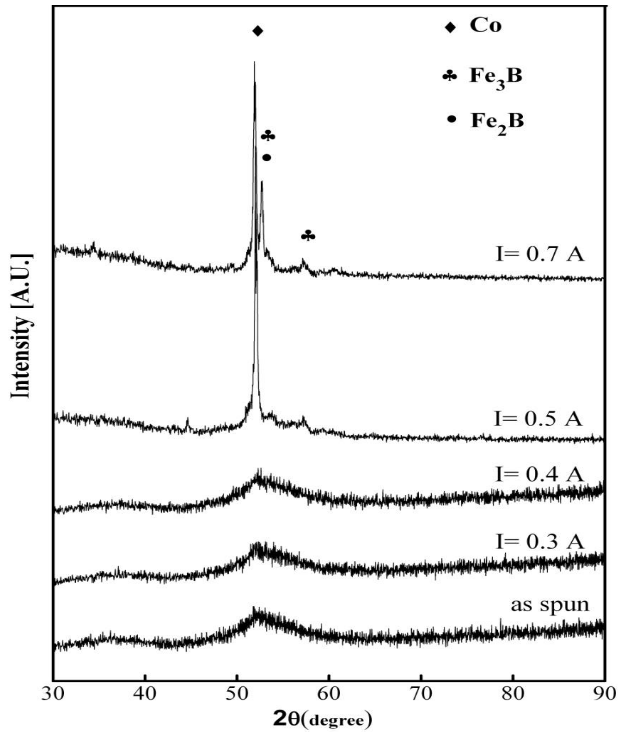

Fig. 1- X-ray diffraction pattern for as cast and different current densities joule heated samples with composition $Co_{64}Fe_4Ni_2B_{18}Si_8Cr_3Al_2$.

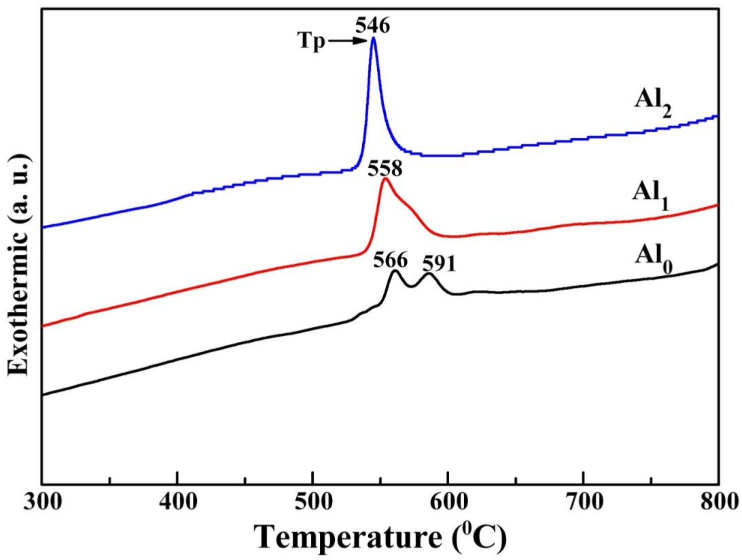

Fig. 2- DSC scan curves of $Co_{64}Fe_4Ni_2B_{19-x}Si_8Cr_3Al_x$ (x = 0, 1, and 2) rapidly solidified melt-spun ribbons.

The evolution of MI response as a function of applied field, measured at f=5 MHz and in the DC current range 0.3≤I≤0.7 A, is reported in Fig. 3 for the joule heated samples together with the as- spun ribbon with x=0. The as-spun sample shows the single peak behavior, it implies that the sample has easy longitudinal axis magnetization (longitudinal magnetic anisotropy), such that the transversal magnetization is dominated by rotational processes and the impedance displays a monotonous decrease from H_{ex}=0. However, all the joule heated samples display a maximum in the GMI (two peak behavior) in the MIR curves as a function of the magnetic field. The maximum value of MIR for the sample with x=0 is observed in the sample treated with I=0.6 A. The values of the transversal anisotropy field H_K (the point where the impedance has its maximum value) versus DC current are showed

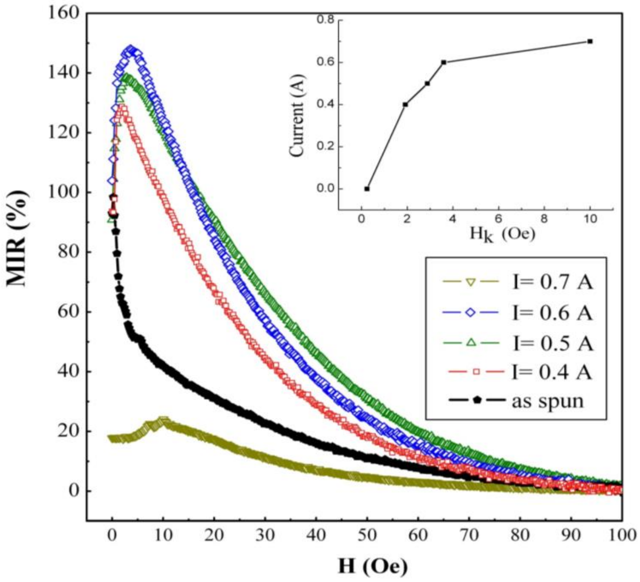

Fig. 3- MI profiles measured at f = 5MHz for as cast and different current densities joule heated samples with x=0. The inset shows the anisotropy field H_K.

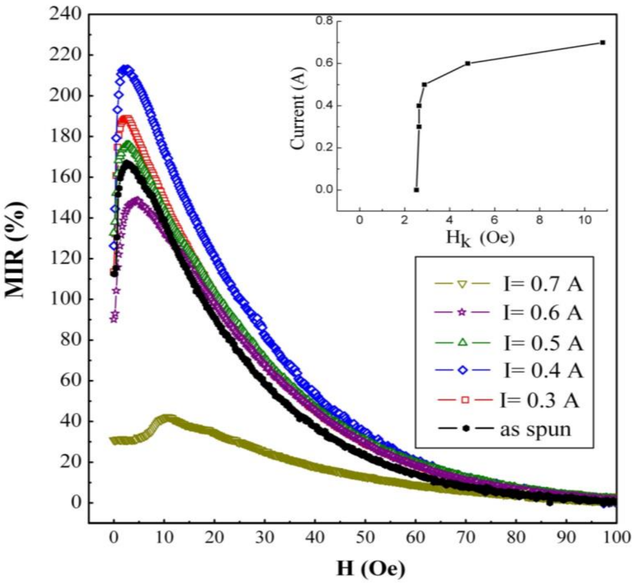

Fig. 4- MI profiles for as cast and different current densities joule-heated samples with the composition of $Co_{64}Fe_4Ni_2B_{18}Si_8Cr_3Al_1$. The condition is same as in Fig. 3.

in the inset of Fig.3. The H_K values increase with the increase in the DC current value. Joule heating leaves a preferred direction of magnetization in the sample generally by the rearranging atoms on a local scale in such a way as to favor magnetization in a given direction [1]. An annealing temperature sufficiently high for atomic mobility, some atoms orient themselves relation to the direction of the magnetization so that magnetic anisotropy energy is minimized. Once the temperature is reduced to a level at which significant diffusion can no longer occur and the field is removed, the frozen-in atomic directional ordering may be sufficient to override other anisotropies and hold the magnetization in the direction that it had during joule heating. Finally, the magnetoimpedance ratio is seen to be intensely reduced in the high level of DC current possibly indicating the beginning of the crystallization process [3,17].

Fig. 4 shows the DC magnetic field dependence of MIR profile at frequency f=5 MHz for both as spun and joule heated ribbons with x=1. The values of the transversal anisotropy field H_K are also showed in the inset of Fig. 4. It can be seen that all of the samples (as spun and joule heated) have transverse anisotropy however the value of the transverse anisotropy in the joule heated samples is higher than that of as-spun ribbon such that the higher DC current gives rise to a higher induced transverse magnetic anisotropy. Results show the maximum value of MIR, MIR_{max}, for the as-quenched sample with x=0 is 150%, however, for Al_1 joule heated sample is 218 % in the joule current of 0.4 A.

The field dependence of MIR measured at f=5 MHz for the as-cast and joule heated Al_2 ribbons is presented in Fig. 3. In addition H_K values of samples are reported in the inset of Fig. 5. It can be seen that upon the application of a DC joule heating, the maximum MIR reached the value of 220% in I=0.4 A. This value is much higher than that of as spun sample and the other samples with x=0 and 1. This result may correspond to the effect of Al on the magnetic moment configuration of ferromagnetic elements, i.e. Co, Fe, and Ni [12]. On the other hand, in previous paper [17] we showed that the replacement of B by Al gave rise to the decrease in electrical resistivity. The reduction of resistivity can improve the GMI effect with the decrease in the skin effect [17,21].

The relation between structure and magnetoimpedance effect in as-cast and joule-

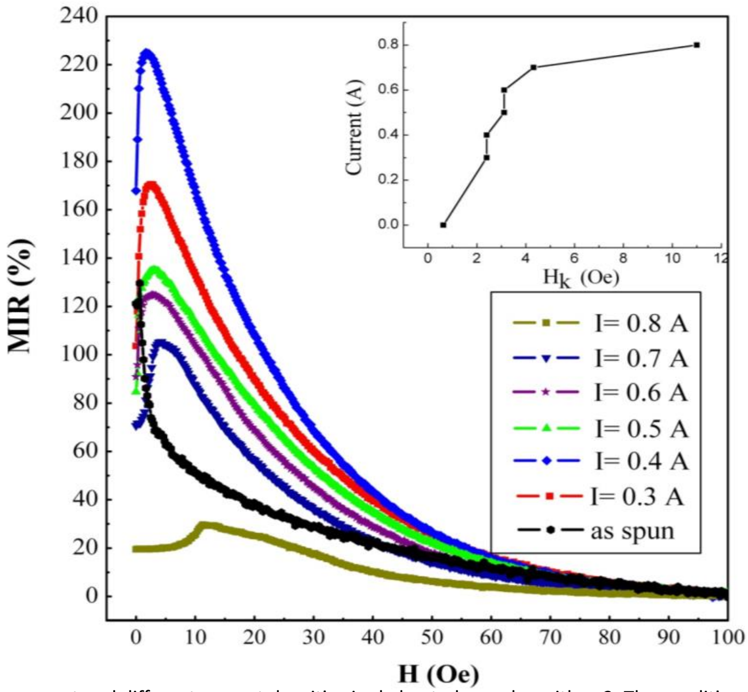

Fig. 5- MI profiles for as cast and different current densities joule heated samples with x=2. The condition is same as in Fig. 1.

heated ribbons shows that MIR value first increases in DC joule heated ribbons while the decrease in the MIR value occurs after formation of crystalline phases. Based on XRD results, the amorphous structure is not changed by the increase in current density up to 0.5 A (Fig. 1). The observed increase in MI response for the samples annealed up to 0.5 A is related to the stress relief and relaxation of amorphous structure. Further, the magnitudes of MIR are decreased with the increase in current density and formation of Fe_2B and Fe_3B phases. As mentioned in introduction section, MIR is influenced by μ_T and electrical resistivity.

4. Conclusions

The effect of dc joule heating on the GMI effect and structure in $Co_{64}Fe_4Ni_2B_{19-x}Si_8Cr_3Al_x$ (x = 0, 1, and 2) melt spun ribbons have been investigated and the following are concluded:

1- The dc joule annealing was efficient in inducing transverse anisotropy in all studied samples. 2- A significant increase in MI ratio has been observed after dc joule heating. A maximum MI ratio of 220% is observed in the sample with x=2 treated in joule current of 0.4 A.

3- It was indicated that replacement B by Al can improve MI ratio in dc joule-heated samples.

4- Al addition to the $Co_{64}Fe_4Ni_2B_{19}Si_8Cr_3$ melt-spun ribbon decreases the crystallization temperature.

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