Thermo-magnetic memorization effect in amorphous ferromagnetic ribbons

R. Sato Turtelli and A. Hengeltraub

Depto. de Física do Estado Sólido e Ciências do Materiais, Instituto de Física "Gleb Wataghin", UNICAMP, Caixa Postal 6165, Campinas, 13081, SP, Brasil

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Abstract The results of experiments done on soft magnetic amorphous alloy ribbons of Co_{70.4}Fe_{4.6}Si_{15}B_{10} are presented and discussed. They give the behaviour of the initial ac permeability as a function of temperature for several values of the amplitude and frequency of the driving field. A frequency memorization effect, already reported, is seen to be dependent not only on the frequency but also on the amplitude of the field applied during the previous thermal treatment. The kinetics of domain wall motion driven by temperature and applied field is suggested as the mechanism responsible for the memorization effect.

1. Introduction

Soft ferromagnetism is observed in certain amorphous alloys. Cobalt rich amorphous alloys with zero magnetostriction and high permeabilities are excellent materials for transformer cores and magnetic heads, due to their high resistivities.

The initial value of the permeability of such alloys depends on the quenching rate and on the presence of an external applied field.

In a previous paper a frequency dependent memory effect related to the thermal history of the ac magnetic permeability in the as quenched Co_{70.4}Fe_{4.6}Si_{15}B_{10} alloy was reported. This effect was discussed in terms of a model for the time response of the magnetic permeability based on the domain structure of amorphous materials. In this work we present several new results related to the frequency dependent thermo-magnetic memorization effect (FDTMME). They lead us to consider that it is basically due to the kinetics of the domain walls (DW) motion.
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2. Experimental

Samples of the amorphous alloy Co$_{70.4}$Fe$_{4.6}$Si$_{15}$B$_{10}$ were produced by melt-spinning. Their dimensions are 1.5 mm wide, 20 $\mu$m thick with a length of a few centimeters cut from a long ribbon. The initial ac permeability, was measured with the samples inside two co-axial coils. The driving coil, formed by 40 turns, is 5 cm long. The pick-up coil is 1 cm long and contains 50 turns. The signal from the pick-up coil was recorded through a lock-in amplifier according to the scheme of fig. 1. The first series of measurements of the initial ac permeability were performed with the temperature varying from room values up to 410°C, well above the Curie temperature $T_C = 386°C$, with a rate of 6°C/min, for the as cast annealed samples. The frequency and amplitude of the driving field were varied. The frequency values were such that the skin depth was larger than the sample thickness. The second series of measurements of the initial ac permeability were done at room temperature. The samples were previously annealed, for 20 min, at 400°C, to allow for irreversible structural relaxation. They were then heated up to a certain fixed value of the temperature, which was kept constant for 3 minutes, with and without an applied ac field and quenched to room temperature by placing the sample on a copper block. Measurements of the initial ac permeability were performed for different values of the frequency of the ac applied field.

Fig. 1 - Experimental setup.
3. Results

The behaviour of the root-mean-square initial magnetic ac permeability (from now on referred to simply as permeability) \( \mu(\omega) = \mu'(\omega) + i\mu''(\omega) \) as a function of the temperature for various frequencies of the driving field for as cast samples is shown in fig. 2.

![Fig. 2 - Initial ac magnetic permeability \( \mu \) in aq. Co_{70.4}Fe_{4.6}Si_{15}B_{10} as a function of the temperature \( T \) for different values of the driving field frequency \( f \). \( S \) is the value of the sensitivity of the lock-in amplifier. The arrows indicate the direction of temperature variation.](image)

The effect of frequency memorization is shown in figs. 3, 4 and 5. In order to avoid interference of irreversible structural relaxations, the temperature range was swept in two successive cycles. Measurements were made at different settings
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Figs. 3, 4, 5 – Thermal histeresis of the ac magnetic permeability $\mu$ in aq-
$Co_{70.4}Fe_{4.6}Si_{15}B_{10}$ for driving fields of frequency $f$ and lock-in amplifier sensi-
tivity $S$. The arrows indicate the direction of temperature variation.

of the sensitivity $S$ of the lock-in amplifier and at two values of the frequency $f$ of
the driving field, which has an effective amplitude of $10$ A/m.

Fig. 6 shows the permeability as a function of the temperature for a sample
which had previously undergone various complete cycles of permeability measure-
ments with driving fields of amplitude $H_{pp} \approx 8$ A/m, peak to peak, and frequency
$500$ Hz. The plotted results were obtained with driving fields of $500$ Hz with
different values of the amplitude.

One sample was annealed at $T_a = 200^\circ$C for $t_a = 10^4$ min and the permeability
was measured at $500$ Hz, $H_{pp} = 8$ A/m, during three temperature cycles, as shown
in fig. 7. Similar results are shown in fig. 8 for a sample that had undergone a
cycle $\mu \times T$ with $f=500$ Hz and $H_{pp}=1.5$ A/m.
A second series of measurements produced the results shown in Figs. 9, 10 and 11.

4. Discussion

The first studies of the variation of permeability with temperature, given in fig. 3 and 4, indicated that the second cycle (curves 3 and 4) was reproducible. The same results were obtained on repeated measurements. A dependence on frequency is evident. However, as fig. 5 shows, when two cycles were performed at 20 kHz (results are those of fig. 4, of which only curves 1 and 4 are reproduced in fig. 5) followed by a third cycle at 500 Hz (curves 5 and 6), the behaviour was different from the one obtained with the same procedure and shown in curves 3 and 4 of fig. 3. This was interpreted as a frequency memorization effect. Can this effect occur at different frequencies? It is dependent on the amplitude of the driving field? Trying to answer, at least partially, those questions a few cycles of measurements of the permeability as a function of the temperature were made at different frequencies with 10 A/m effective amplitude for the driving field on as cast samples and are given in fig. 2. Any sample submitted to a second cycle will yield basically the same results as given in the curves with decreasing temperature.

The cycle with $H_{pp} = 8$ A/m and $f = 500$ Hz, curves 1 and 2 of fig. 6, is different from the corresponding cycle, curves 3 and 4 of fig. 3, which was obtained with a higher value of $H_{pp}$. The next cycles, with $f = 50$ kHz and $H_{pp} = 0.5$ A/m, seemed to show a FDTMME, however this is questionable since cycle 5,6 is similar to 3,4 in spite of including temperature values above $T_C$. Nevertheless, it should be noted that the behaviour of the permeability in one cycle depends on the value of $H_{pp}$ in the previous one. To see this observe the sequence of cycles 3, 4; 5, 6 and 7, 8.

When an as cast sample was annealed, with no applied field, at $T_a = 200^\circ$C for $10^4$ min, the first part of the first cycle $\mu \times T$ exhibited substantially smaller permeability values than the second part, fig. 7. Another feature is the sudden rise in the value of the permeability near $230^\circ$C, in curve 1.
Fig. 6 - Various cycles of $\mu \times T$ measurements were made at the indicated amplitudes and frequencies of the driving field. The sample was subjected to several such cycles, at $f = 500$ Hz, $H_{pp} = 8$ A/m, before the shown results were obtained. The numbers indicate the order at which the measurements were made.

Fig. 7 - Cycles of $\mu \times T$ obtained from a sample annealed for $10^4$ min at $T_a = 200^\circ$C. The measurements were made with a field of $H_{pp} = 8$ A/m and $f = 500$ Hz.
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Fig. 8 - The $\mu \times T$ cycles were obtained from a sample that had gone previously through one cycle with $H_{pp} = 1.55 \text{ A/m}$ and $f = 500 \text{ Hz}$.

Fig. 9 - $\mu$ measured at room temperature as a function of the annealing temperature $T_a$. The temperature was kept at $T_a$ for 3 minutes then quenched to room values.
Fig. 8 contains the results of several cycles of $\mu r T$, with $f=500 \text{ Hz}$, for various values of $H_{pp}$, from a sample that had been through a previous cycle similar to 5, 6 with $H_{pp}=1.5 \text{ A/m}$. It is quite evident that the behaviour depends strongly on the excitation intensity. A sudden increase of the permeability, at about $340^\circ \text{C}$ was observed when $H_{pp}$ was increased to $8 \text{ A/m}$, curve 1. When the amplitude was lowered back to $1.5 \text{ A/m}$, a sudden decrease in the permeability at about $280^\circ \text{C}$ was measured, curve 3. A sudden increase is also seen in curve 7, at about $210^\circ$. There seems to be an interplay between the thermal agitation and the driving field that determines critical points, where $\mu$ undergoes sudden changes. The position of the critical points is probably determined by both the temperature and $H_{pp}$.

Finally figs. 9, 10, 11 show the results of a study of the dependence of the permeability, at room temperature, with thermal treatment with and without an ac driving field. Larger permeability values were obtained with higher annealing temperatures, with ac applied fields, for higher values of the field frequency. This is due to the fact that by quenching of the sample, the state of isotropy, reached at higher temperatures with an applied field, is memorized.

### 5. Final Remark

Further experiments are in progress in order to understand more deeply the kinetics of domain wall motion driven by the ac field and by temperature. Samples with non-zero magnetostriction are also being measured. The possible influence of oxidation on the sample surface upon wall motion is also being analysed through measurements in an inert atmosphere.

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Fig. 10 - $\mu$ measured at room temperature as a function of the annealing temperature $T_a$. The temperature was kept at $T_a$ for 3 minutes, with an applied field $H_a$, then quenched to room values.

Fig. 11 - $\mu$ measured at room temperature as a function of the frequency $f_a$ of the field applied during thermal treatment for 3 minutes at $T_a = 380^\circ$C.
References


Resumo

São apresentados e discutidos novos resultados de medidas feitas em fitas amorfá das liga magnética "soft" Co70.4Fe4.6Si15B10. Eles consistem na variação da permeabilidade magnética inicial ac em função da temperatura, para vários valores da amplitude e da frequência do campo aplicado. Verifica-se que um efeito de memorização de frequência, já publicado anteriormente, depende não só da frequência como também da amplitude do campo magnético aplicado durante o tratamento térmico anterior. Sugere-se que a dinâmica do movimento de paredes de domínio, devido à temperatura e ao campo aplicado, seja responsável pelo efeito de memorização.