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MAE MEASUREMENTS USING A 4-POINT METHOD

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A new method for measuring Magnetic After Effect (MAE) in amorphous materials is here presented. MAE was observed as the decrease of the real and imaginary parts of the complex impedance with time after a sudden change in the applied magnetic field. Real and imaginary parts of the impedance of the sample in the form of a magnetic wire were obtained using a four-point technique with a lock-in amplifier.

Keywords: MAE measurements, amorphous wires, four points technique

1 THEORY

The Magneto impedance (MI) was discovered years ago in amorphous samples and has a great interest due to its possible application in magnetic sensors [1-3]. MI effect originates in the skin effect as a consequence of the changes in the penetration depth induced by the static external field through modification of the transverse permeability. The skin depth is defined as:

$$\delta = \left(\rho / \pi\mu_{\varphi} f\right)^{1/2} \quad (1)$$

where ρ is the resistivity of the material, μ_{ϕ} the circular permeability and f the frequency of the ac current flowing through the wire.

The impedance of the sample depends on the penetration depth according to [4]:

$$Z = R_{dc} ka \frac{J_0(ka)}{J_1(ka)} \quad (2)$$

where J are Bessel functions, $k=(1-j)/\delta$ and R_{dc} is the electrical resistance.

When the frequency is high enough the skin effect plays an important role reducing the effective section of the sample and then increasing the impedance. So, the change of impedance is a consequence of the modification of the skin depth penetration via the external field. The MI ratio can be defined as:

$$MI(\%) = \frac{Z(H) - Z(H_{\max})}{Z(H_{\max})} \times 100 \quad (3)$$

The Magnetic After Effect (MAE) analyses the evolution of the MI effect. In that sense, by studying the isochronal spectrum of after effect processes in these wires, different temperature activated processes can be distinguished as well as diffusive processes.

Measurements in the real part of the impedance are taken after removing a 10 Oe field strength beginning in the first second after switching off the field. Due to the exponential dependence of after effect processes, next measurements are taken every double time step. With this data MAE ratio can be defined as:

$$MAE(\%) = \frac{R(t_1) - R(t_2)}{R(t_1)} \times 100 \quad (4)$$

where t_1=1s always, so that the MAE ratio is normalized taking always the first second, and t_2=2, 4, 8, 16, 32, 64 and 128 s.

2 EXPERIMENTAL

As a general scope the technique works as follows. Two contacts carry the driving AC current provided by the Lock-in amplifier while the other two measure the modulus and phase of the voltage drop in the sample. Currents of 0.3 mA of amplitude and frequencies from 1kHz to 100 kHz were used in an amorphous wire of composition $Co_{68.15}Fe_{4.35}Si_{12.5}B_{15}$ and 130 μm in diameter. The main advantage of this technique is that the impedance of the measuring wires are eliminated with the 4-point method.

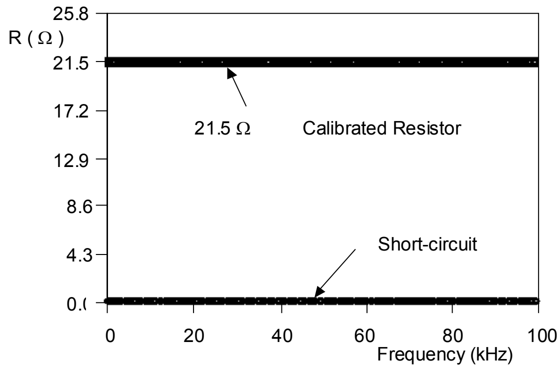

Fig. 1. Short-circuit resistance and 21.5 Ω –calibrated resistor

As can be seen in Fig. 1, the resistance of a short-circuit of copper is measured. Error in data is less than 1%, showing the ability of measuring in all the range of frequencies presented here without the influence of any parasitic impedance. Besides, the values of a 21.5 Ω – calibrated resistor are also shown, where the precision of measurements is related to the second decimal in the used frequency range from 1 kHz to 100 kHz.

Being deeply convinced of the suitability of this 4-point technique by calibrating our equipment, resistance

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measurements are fulfilled on the object of our study: an amorphous wire of composition $Co_{68.15}Fe_{4.35}Si_{12.5}B_{15}$ and 130 μm in diameter. The frequency dependence of the resistance is shown in Fig. 2 and leads to the same result described mathematically by the theory of an AC current flowing through a cylindrical conductor [4] represented here by equations (1) and (2).

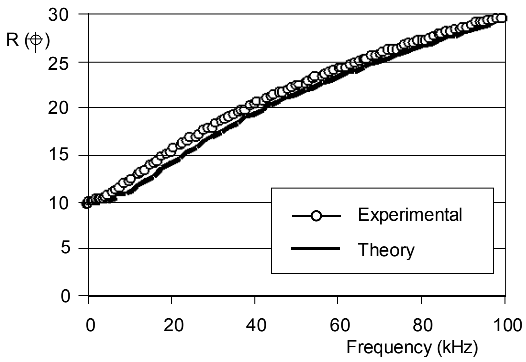

Fig. 2. Resistance of the amorphous wire versus frequency (room temperature).

The MAE measuring process is described as follows: a magnetic field of 10 Oe is applied axially to the sample during 5 seconds and then suddenly removed. Straightaway, resistance and induction values are measured by the lock-in amplifier every time step, beginning in the first second after removing the field. So, we have measurements at 1, 2, 4, 8, 16 s, and so on. This process is fulfilled at constant temperature inside a cryostat, which allows us to repeat it for temperatures ranging from 77K to 450K in steps of 5 K.

4 RESULTS AND DISCUSSION

In a first step, different measurements of MAE have been done for a fixed frequency of 25kHz, which is believed to give a significant amount of skin depth, varying the driving current. It has been found that a maximum MAE in current is close to 0.3 mA. So, with this current, a frequency sweep between 1kHz and 30MHz (Fig. 3) has been done in order to look for a maximum of MAE in frequency, finding that the maximum MAE is close to 2% in a frequency range from 25 kHz to 100 kHz.

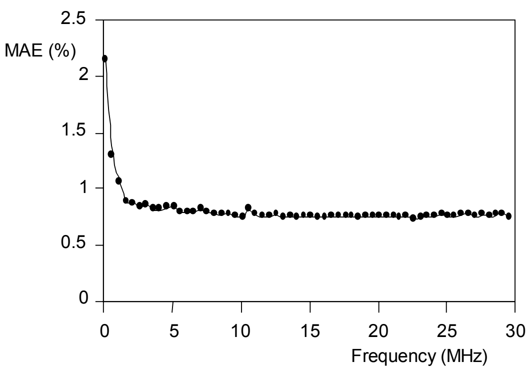

Fig. 3. MAE versus frequency at 300 K

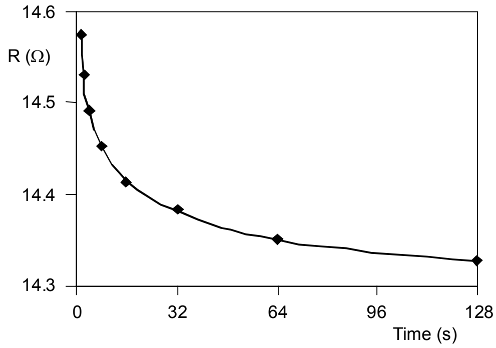

Fig. 4. Resistance of the amorphous wire after removing the magnetic field at 300 K.

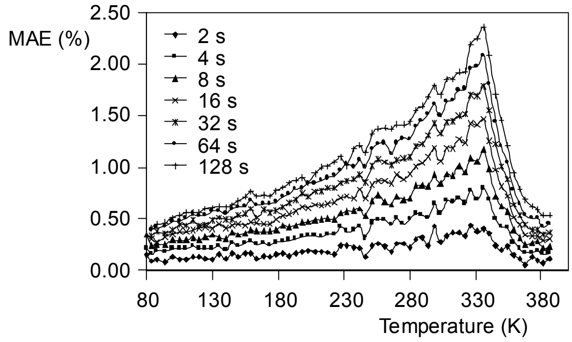

Fig. 5. MAE in resistance at 0.3 mA and 37.5kHz (isochronal spectrum)

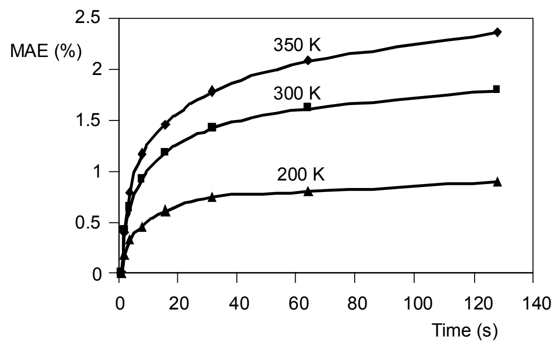

Fig. 6. Isothermal spectrum of MAE

In Fig. 4 the evolution of the resistance of the sample in time is shown at constant temperature of 300 K and a frequency of 37.5 kHz. The MAE response is related to frequencies around kHz, when domain wall movements and relaxation phenomena take place, and decreases fast at higher frequencies. The decrease of the resistive part of the impedance is related to a decrease of the permeability. It is usual to find peaks of MAE close to critical temperatures. In this case, this is the temperature where crystallization starts and the wire tends to be no longer amorphous. By measuring these evolutions in temperature, the stability and accuracy of magnetic sensors based on amorphous materials are well described.

When the MAE ratio is ploted as a function of the temperature (Fig. 5) for every time-step used, a so called isochronal spectrum, it shows a peak of 3% in around 350 K, very close to the maximum of circular permeability [5].

At higher temperatures the permeability reflects a general decrease. This is due to a magnetic decoupling between ferromagnetic grains and the amorphous matrix [6]. Rapid quenching at room temperature influences the temperature of the maximum.

As far as we are concerned, the shape of the isochronal curves suggests that the dynamic of the process is not purely of Debye type because they are not joined at the end of the temperature plot. The wide temperature region where the relaxation is present indicates that the most probably cause of these relaxation phenomena is a combination of reorientation of atom pairs and long range diffusion [7].

In order to show a detailed behaviour of MAE ratio with temperature, it has been represented the MAE for three different temperatures in Fig. 6 following equation (4) with the same initial time of t_1=1 s. As it is seen, the relaxation of the impedance presents the highest level at temperatures close to 350 K while in others presents a lower level. The time dependence is nearly exponential. These are perpendicular cuts of Fig. 5, which are shown here for clarity. MAE in the imaginary part, which is not shown here due to the high noise it has, also presents the highest level close to the same temperature.

MAE sets the limit of 1-3% precision in technical applications where these wires have been implemented, such as magnetic sensors.

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