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AC CONDUCTIVITY OF NON MAGNETIC METALLIC ALLOYS

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Summary
AC and DC conductivity measurements on AA3003 aluminum alloy are considered using several inductive methods and the well-known 4-wire method. Samples with conductivity from 2.70×10^7 to 2.95×10^7 S/m are produced by cold rolling and subsequent recrystallization. Conductivity obtained varies from 1 to 10% relative to initial conductivity (0% recrystallization). Reference materials are used to calibrate standard eddy current impedance diagram equipment, in the range 5-15 kHz. Besides impedance equipment, other two methods are used in order to compare sensitivity to small conductivity changes: force between flat circular coil to sample and transmission between coils at either sides of the sample. In both cases senoidal current are applied to circular flat coils placed at prescribed distance from sample. Measurements are compared with numerically simulated behavior for each physical system, accordingly with Maxwell equations. A procedure for Non-destructive measurement of AC conductivity is proposed and validated.
Key words: Electrical conductivity recrystallization

I Introduction

Eddy current method has proven to be very sensitive to small variations in relative conductivity. In order to use inductive method for measurements of absolute variations of conductivity, calibrated samples with small increments within the interval of interest are needed. An alternative to several calibrated samples is to use the temperature coefficient to obtain the desired conductivity controlling the reference sample temperature. In order to produce samples with small conductivity variations, cold rolled samples are recrystallized from 0% to 100%. This gives rise to samples with conductivity from 2.70×10^7 to 2.95×10^7 S/m. DC conductivity of the samples is determined by the so called "4 wire method" following standardized procedures[1] in order to obtain reference samples.

II Experimental procedures

Tree methods are used for obtaining measurements related with conductivity of the samples: the force method, the transmission method and impedance instrument with reflection coil method. In these tree methods, harmonic current of controlled amplitude are use to obtain average force, in the first method, transmitted amplitude and phase variations, in the second method and finally, impedance variations in both amplitude and phase, in the third method. To avoid the need of many calibrated samples, the approach developed is based in numerical simulation of the physical situation by means numerical method applied to Mawell equations with axial symmetry.

III Numerical simulation

Equation 1 is obtained from Mawell equations for harmonic time dependency and axial symmetry (cylindrical coordinates). E_θ is the complex azimuthal component of the electric field. J_s is the source current density.

$$\left(\frac{E_\theta}{r^2}-\frac{\partial^2 E_\theta}{\partial r^2}-\frac{\partial^2 E_\theta}{\partial z^2}-\frac{\partial E_\theta}{r\partial r}\right)=-i\mu\sigma\omega E_\theta - i\mu\omega J_s \qquad (1)$$

From equation 1 two equations in differences are easily obtained for real and imaginary component of electric field and current density. Mesh parameter (h) is set according with $\boldsymbol{h = \delta/5}$ where $\boldsymbol{\delta}$ is the standard depth of penetration[2].

Procedure

Samples are made from AA3003 H14 aluminum alloy cold rolled to 70% of width reduction. Then samples are subjected to thermal treatment in order to produce a gradual variation in recrystallization from sample to sample, from 10% to 100% recrystallization. The degree of recrystallization is measured by metallographic methods. DC resistivity is measured by the 4-wire method[3]. Resistivity[4] profile with recristalización for DC measurements is verified and also correlated to hardness measurements.

AC resistivity is measured by means of impedance diagram equipment. The calibration of this equipment is performed using a reference material with known resistivity and temperature coefficient. Small temperature variations (less than 15 ºC) are enough to sweep resistivity changes produced in recrystallized samples.

Transition through wall and force methods is also used in order to compare experimental sensitivity between methods and also to compare with numerical simulations.

Figures 1 to 4 shows experimental results. Relative sensitivity of the employed methods is compared with numerically simulated data.

The force method

When a flat circular coil with harmonic current through it is paced near a conductor, a repulsive force develops between coil and conductor. This force has a high dependence with distance and poor dependence on sample resistivity.

Modeling the force between coil and sample

Numerical solution to equation 1 for the direct problem (known source and known spatial electromagnetic properties distribution) allows modeling the force between sample and coil.

Lorentz force is obtained integrating equation (2)

$$d\vec{F} = \vec{B}\times d\vec{l}\, I \qquad (2)$$

Where dl is the line element of the coil, I is the current (free current) and B the magnetic flux density. Due to system symmetry, B field has only components in the direction of z and r. So, z component of force applied to the coil is given by

$$F_z = \int B_r I\, dl \qquad (3)$$

B_r is the *r* component of ***B***, which is complex. Experimental method measures the average force between coil and sample. So force has to be averaged. I is the phase reference, so I is chosen to be real. Integrating along the circumference and taking the time average of the real part of the force, the result is

$$\langle F \rangle = \pi RIB_{r0} \cos\varphi \qquad (4)$$

Where $\langle F \rangle$ is the average force, R is the coil radius, B_{r0} is the amplitude of the radial component of **B** and φ is the phase lag between I and **B**. The phase lag satisfies the relation

$$\cos\varphi = B_{rRE} / B_{r0} \qquad (5)$$

Where B_{rRE} is the real component of B_r. So, the average force is

$$\langle F \rangle = \pi RIB_{rRE} \qquad (6)$$

By other side, in cylindrical coordinates and harmonic time dependence, the following relation holds

$$B_r = -\frac{i}{\omega}\frac{\partial E_\theta}{\partial z} \qquad (7)$$

From this relation it is obtained that

$$B_{rRE} = \frac{1}{\omega}\frac{\partial E_{\theta IM}}{\partial z} \qquad (8)$$

Finally it is obtained that the averaged force is

$$\langle F \rangle = \frac{\pi RI}{\omega}\frac{\partial E_{\theta IM}}{\partial z} \qquad (9)$$

This is readily calculated from de numerical solution of equation (1).

Modeling of the transmission method

The electromotive force V induced in a secondary coil placed symmetrically at the other side of the sample is obtained once equation 1 is numerically solved. So $V = 2\pi RE_\theta(r,z)\,\Big|_{\substack{r=R\\ z=d}}$.

The field is evaluated for r = R and z = d, where d is the distance from coil to simple and R is the radius of the secondary coil.

III Experimental results

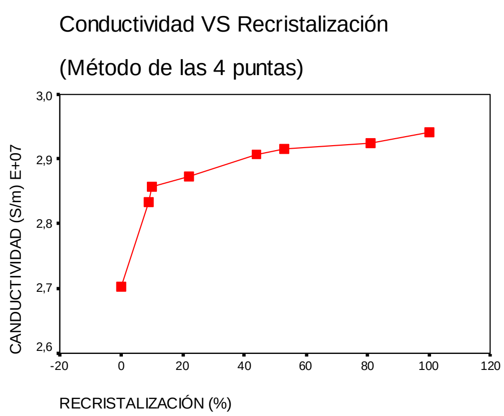

Figure 1. Conductivity variation versus probe recrystallization. Initial variation in resistivity of the simples was less than 0,1%.

Figure (1) shows that a change of approximately 10% of the initial conductivity is developed when recrystallization varies from 0% to 100%.

Figure (2) corresponds to the values of the electromotive force induced in the secondary coil as a function of the conductivity of the sample. Coil used has 500 turns and is air cored. Frequency is 5.0 kHz. Distance from coil to simple is hold fixed.

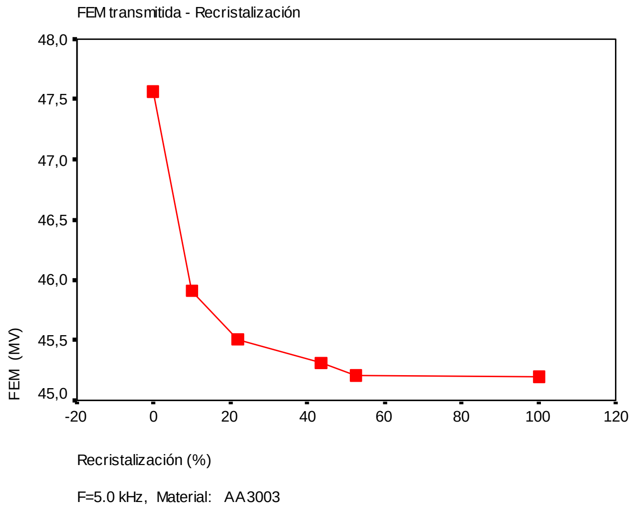

Figure 2. Relative induced emf variations as a function of probe conductivity in the transmission method

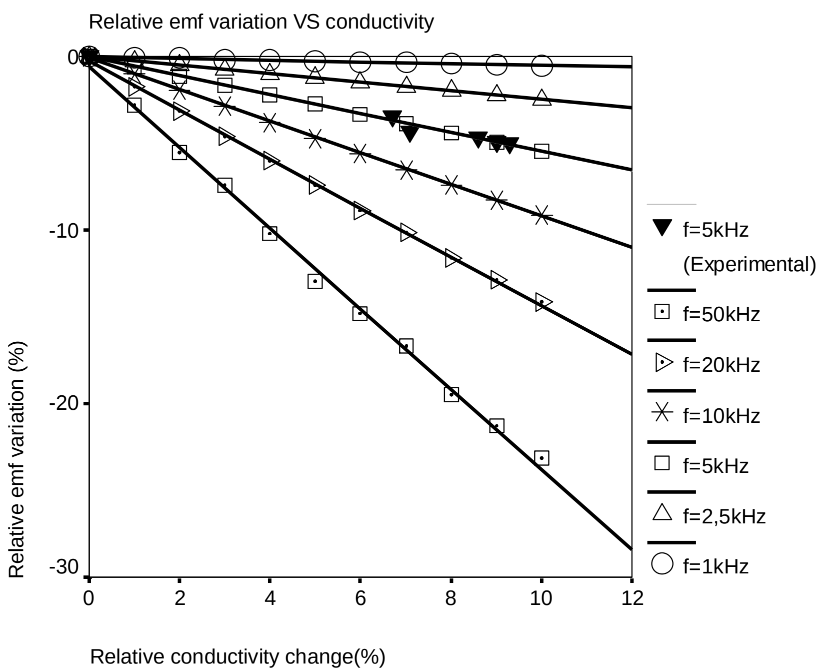

Figure 3.- Relative variation of electromotive force as a function of the relative variation of conductivity. All points except solid triangles are obtained numerically from equation 1.

Figure (4) shows the calibration curve for the impedance diagram equipment. Reference material is AA6063(T5). Calibration is performed calculating the corresponding conductivity to a given temperature. Equipment probe is placed and removed in order to avoid probe heating. Lift-off curve of the resistive part of the impedance diagram is considered for the calibration.

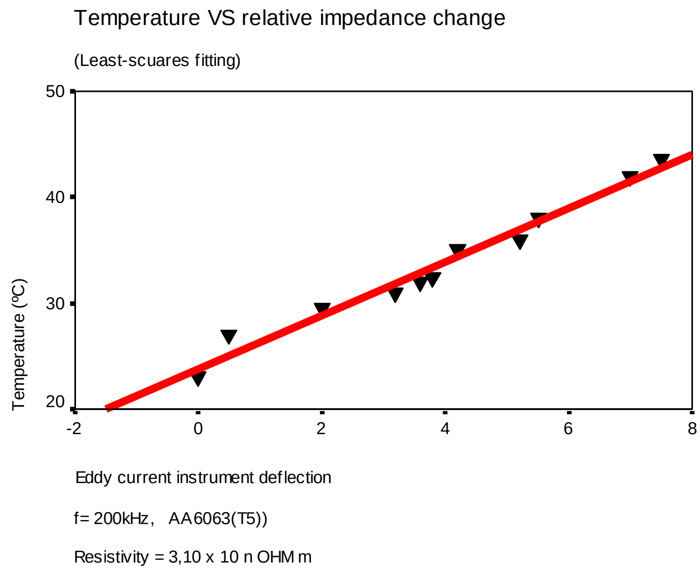

Figure 4.- Impedance diagram Eddy current equipment calibration. Temperature variation required for a given deflection is shown in order to calibrate the equipment for absolute measurements of AC conductivity. Minimum square fittings m = (2,6 ± 0,1) ºC/division. With temperature coefficient α=0,0043K^{-1} , sensitivity obtained is 0,0341×10^{-8} Ωm/division. f=200kHz .

Figure 5 shows the relationship between recrystallization and the current intensity required for keeping repulsive force at a given constant value. f = 5.0 k Hz.

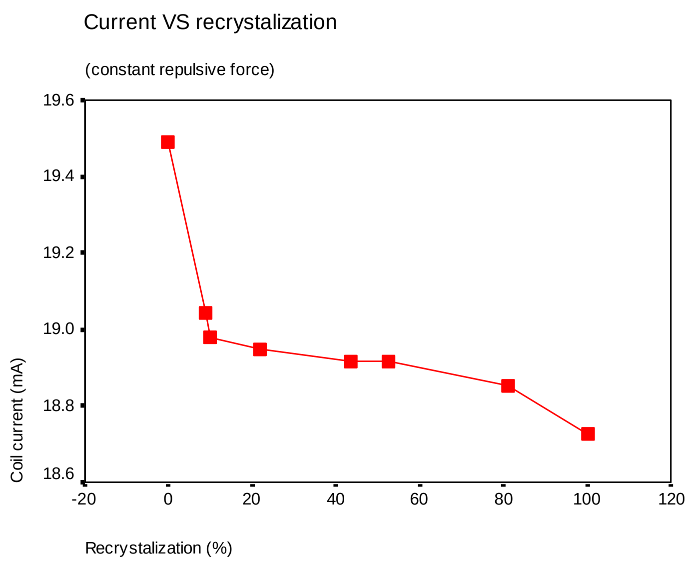

Figure 5.- Relationship between recrystallization and the current intensity required for keeping repulsive force at a given constant value. f = 5.0 k Hz.

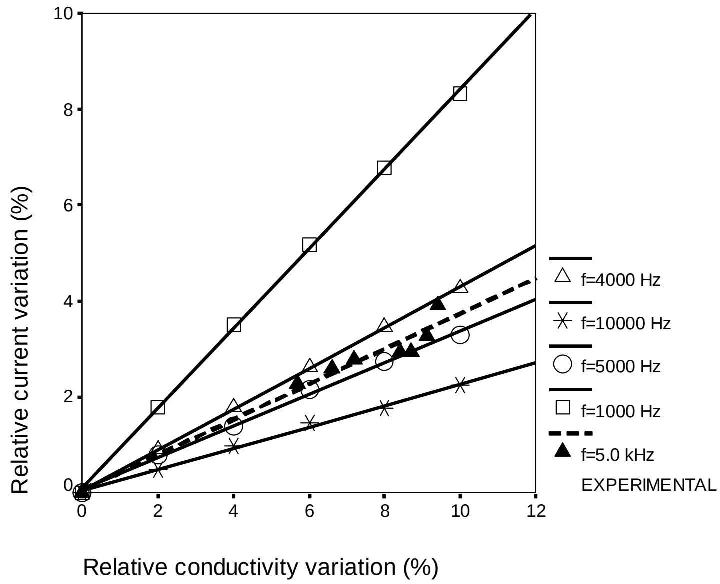

Figure 6.- Force method. Simulated relationship between recrystallization and the current intensity required for keeping repulsive force at a given constant value for various frequencies (solid lines).. Disrupted line corresponds to experimental measurements for f = 5.0 k Hz.

Figure 6 shows the simulated relationship between recrystallization and the current intensity (relative variations) required for keeping repulsive force at a given constant value for various frequencies (solid lines). Disrupted line corresponds to experimental measurements for f = 5.0 k Hz.

Finally, figure 7 shows a comparison between DC and AC resistivity as a function of recrystallization. DC values are obtained by the 4-wire method and AC values are obtained by Eddy current impedance diagram equipment, calibrated with a reference material of known resistivity and temperature coefficient. f = 200 k Hz.

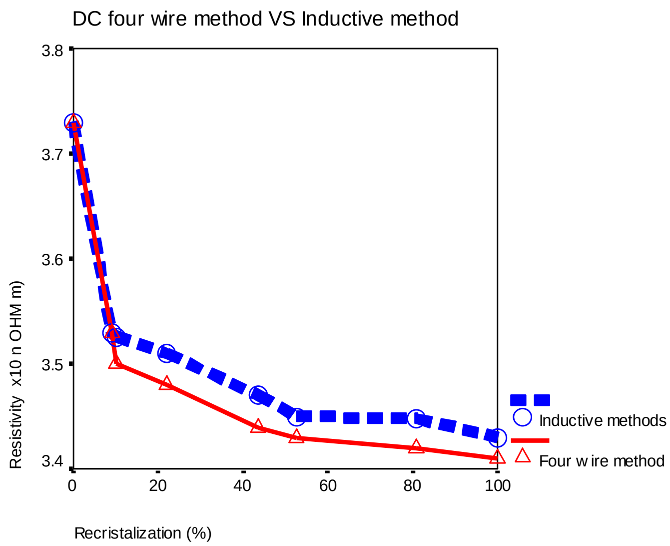

Figure 7.- Comparison between DC and AC resistivity as a function of recrystallization. DC values are obtained by the 4-wire method and AC values are obtained by Eddy current impedance diagram equipment, calibrated with a reference material of known resistivity and temperature coefficient. f = 200 k Hz.

V Conclusions

Simulated results are in good agreement with experimental values. For inductive methods AC results are also in good agreement with the values obtained by the DC method employed.

Comparison between absolute measurements and relative variations, give rise to a theoretical basis for non-destructive measurement of AC resistivity, by means of inductive procedures.

Results also reflects that sensitivity to resistivity changes is better for impedance diagram instrument based methods than for the average force methods, this last method is more adequate for proximity measurements like non determination of conductive layer thickness over a conductive substrate.

Sensitivity dependence on frequency is also established from simulated and measured results.

VI References

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