Characterization of field-dependent elastic modulus and damping in pure nickel and iron specimens using a new experimental system

A. L. Morales, A. J. Nieto, J. M. Chicharro, P. Pintado & R. Moreno
Department of Applied Mechanics and Project Engineering, University of Castilla – La Mancha, Spain

Abstract

The main objective of this work is to characterize the dependence on the applied magnetic field of both the Young's modulus (ΔE-effect) and the specific damping capacity (ΔΨ-effect) in pure nickel and iron specimens. The high quantity of direct and indirect information they provide requires very precise and accurate results, which can be achieved by means of a recently developed experimental set-up. The experimentally measured ΔE- and ΔΨ-effects in pure nickel and iron are in good agreement with magnetic domain theory and they show better magnetoelastic behaviour of nickel in comparison to iron.
Keywords: magnetoelasticity, elastic modulus, damping, iron, nickel.

1 Introduction

The main objective of this work is to characterize the dependence on the applied magnetic field of both the Young's modulus (ΔE-effect) and the specific damping capacity (ΔΨ-effect) in pure iron and nickel specimens.

This kind of research in these metals has been previously developed by Chen *et al.* [1], but applied to torsional stress and measuring magnetostriction. In this work we will stress the samples axially and will focus our attention into the two significant magnetoelastic effects previously mentioned.

The reason for measuring these magnitudes lies in the high quantity of direct and indirect information they can provide: directly, both of them show the influence of the magnetic field and stress in acousto-elastic measurements and

WIT Transactions on Engineering Sciences, Vol 64,
www.witpress.com, ISSN 1743-3533 (on-line)
doi:10.2495/MC090131

performances of magnetic materials; indirectly, the ΔE-effect provides significant details about anisotropy and domain structure [2] and the ΔΨ-effect can also be used as a tool for probing internal stress in ferromagnetic materials [3]. Thus, more precise and accurate results regarding these magnitudes can be valuable for researchers.

Before we start presenting the achieved results it is advisable to properly define the magnitudes we desire to characterize in this work. Regarding the ΔE-effect, when tension is applied to any ferromagnetic sample, two different types of deformations appear: elastic (ε_{ll}), fully described by Hooke's law, and magnetoelastic (ε_{ml}), an additional strain caused by the constitution of its magnetic domains [4]. Hence, the Young's modulus for a specific applied magnetic field will be called E_H, so the complete ΔE-effect is described in terms of the ratio

$$\frac{\Delta E}{E}=\frac{E_S-E_D}{E_D}=\frac{\varepsilon_{ml}}{\varepsilon_{ll}} \tag{1}$$

with E_D and E_S being the demagnetized and saturated Young's moduli, respectively. The ΔΨ-effect requires a more careful explanation. If we take into account the fact that macroscopic and microscopic eddy currents only influence damping of ferromagnetic materials for frequencies on the order of 300kHz or higher [4], the full damping will be given by magnetomechanical hysteresis losses. This term depends on both the amplitude of the oscillation and the applied external magnetic field, but it is independent of frequency. So, the specific damping capacity for a specific magnetic field and stress will be called $\Psi_{H,\sigma}$, which lets us describe the ΔΨ-effect for a constant stress σ in terms of the ratio

$$\frac{\Delta\Psi_{\sigma}}{\Psi_{\sigma}}=\frac{\Psi_{S,\sigma}-\Psi_{D,\sigma}}{\Psi_{D,\sigma}} \tag{2}$$

with $\Psi_{D,\sigma}$ and $\Psi_{S,\sigma}$ being the demagnetized and saturated specific damping capacity for such stress σ.

2 Experimental set-up

Pure crystalline bars of iron and nickel were obtained from the Godfellow Corporation. Their purities, sizes and other relevant data can be found in Table 1.

Table 1: Information about the tested specimens.

Material	Purity (%)	Length (mm)	Diameter (mm)	Density (kg/m3)
Iron	99.99	100	6	7874
Nickel	99.90	110	10	8912

The field-dependent elastic modulus and specific damping capacity of these materials were obtained by means of a novel experimental system for automatic measurement based on laser Doppler vibrometry, which also makes it possible to include stress-dependence studies. This experimental system, which is depicted in the sketch of the fig. 1, was developed by Morales and recently published in [5].

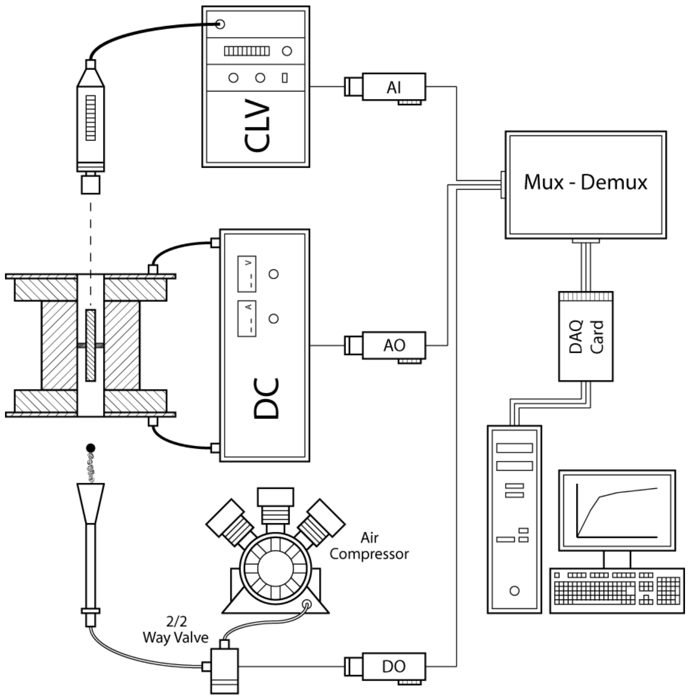

Figure 1: Sketch of the experimental system developed by Morales *et al.* [5].

Basically, the ferromagnetic samples are magnetized by a solenoid in whose inner space the specimen is placed. This solenoid combines both a straight coil and a pair of Helmholtz coils, which compensate for the inhomogeneity of the straight component. In order to generate the magnetic field necessary to achieve the desired magnetization throughout the sample, a dc supply feeds the appropriate current intensity. The exciting system is responsible for generating an automatic free longitudinal oscillation in the specimen: it consists of a barrel in which a lead pellet is placed, while a 2/2 way valve and a relay regulate the necessary compressed air flow for the shot. On the other hand, the basis of the measuring system is a Polytec compact laser vibrometer based on LDV technology (laser Doppler vibrometry) which points a 70MHz He-Ne laser beam on the vibrating surface. Finally, input and output signals are handled with National Instruments acquisition devices, which are controlled by a generic laptop using a Matlab environment. More details of this experimental set-up are given elsewhere [5].

Indeed, some minor features have been enhanced for the measurements shown in this work. They are listed below:

i. A new data acquisition device with a higher sample rate has been used in order to improve the signal resolution and to obtain a more accurate estimation of the material damping within a short portion of the signal (in which the stress is considered constant). In particular, we have used a National Instruments USB-6289 (mass term), which is able to measure 625kS/s.
ii. The Hilbert transform has been implemented in the software in order to obtain the instantaneous amplitude of the time response of the specimen, i.e., its envelope. Using this method instead of the less sophisticated one, which was based on peak detection, we have increased the accuracy of the experimental system, especially regarding damping measurements.

Next, the results about the ΔE- and ΔΨ-effects in pure iron and nickel will be shown and discussed, always taking into account the eventual influence of stress on them.

3 Experimental results

3.1 ΔE-effect

Although it is known that elastic modulus can be stress-dependent in ferromagnetic materials due to its inherent magnetomechanical coupling [4], the definition of the ΔE-effect stated in section 1 did not include any reference to such stress-dependence effects. This fact is due to the reduced level of stresses that is induced to the ferromagnetic specimen during our tests, always lower than 1.0MPa.

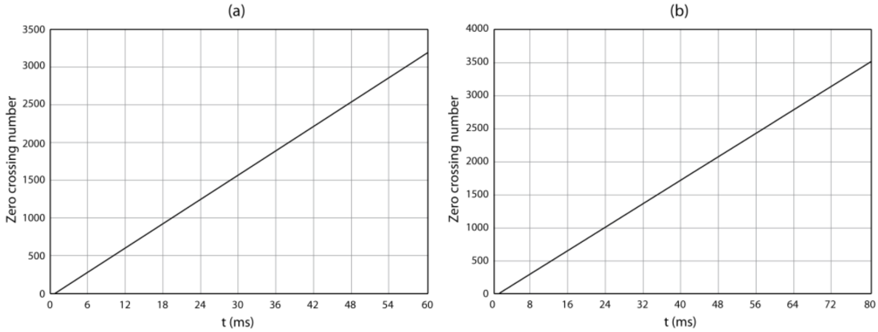

Figure 2: Zero crossing number vs. time for the time responses of iron (a) and nickel (b) (solid line: experimental results; dashed line: fitted curve).

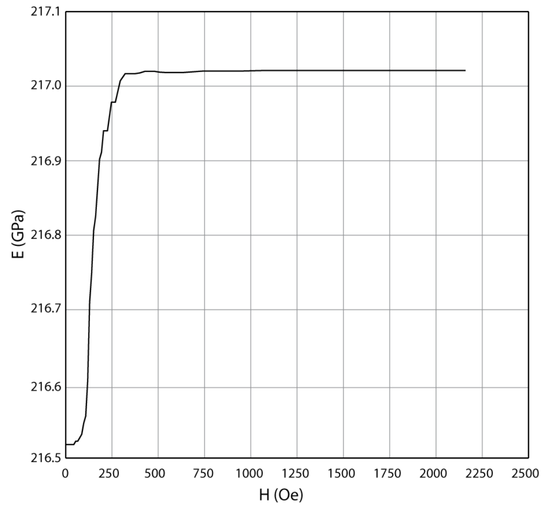

Figure 3: ΔE-effect in pure iron.

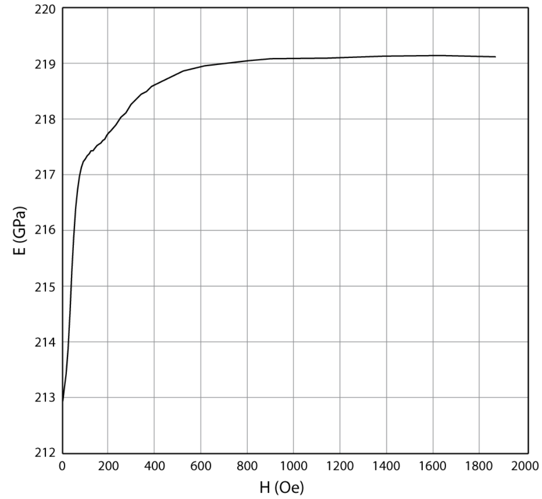

Figure 4: ΔE-effect in pure nickel.

Anyway, such hypothesis can be demonstrated by looking at fig. 2, which shows the zero crossing number distribution along the time, i.e., how frequent the time response of the vibration crosses zero. If the trend of the zero crossing number is linear, it means that the frequency of vibration is not dependent of the strain and therefore neither is the Young's modulus. In fig. 2 we can see that the linear fitting curve is perfectly superimposed to the experimental zero crossing number for the time responses in iron and nickel. The factor R^2, which measures the goodness of the fitting process, is on the order of 0.999999 in both cases, i.e., practically the unit.

Next, figs. 3 and 4 show the ΔE-effect in iron and nickel, respectively. In both cases, two zones can be detected: an initial stage of rapid growth that belongs to the low magnetic field range (less than 250Oe in iron and 150Oe in nickel), and the second stage of slow growth until saturation. These results agree with the magnetic domain theory. Low magnetic fields lead to easy displacements of domain walls, whereas high ones imply the saturation of the sample in a single magnetic domain and the appearance of an upper limit that corresponds to the value of the Young's modulus if the material were nonmagnetic [6].

Table 2 shows the more significant numerical results regarding the ΔE-effect. It is clear that higher variations in elastic modulus via application of magnetic field are achieved in nickel.

Table 2: ΔE-effect results for pure iron and nickel.

Material	ΔE (GPa)	ΔE (%)
Iron	0.50	0.23
Nickel	6.21	2.93

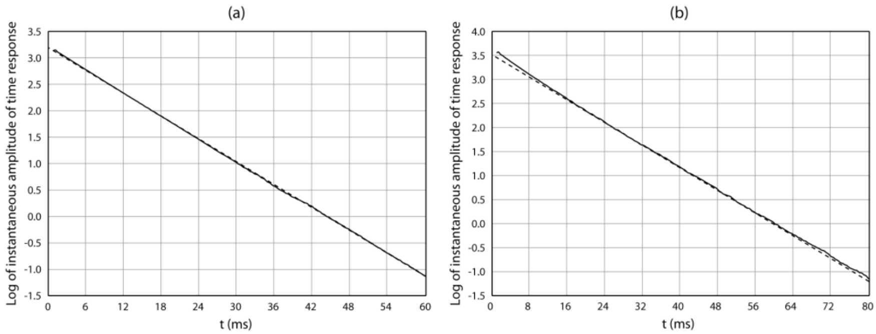

Figure 5: Logarithm of instantaneous amplitude vs. time of iron (a) and nickel (b) (solid line: experimental curve; dashed line: fitted curve).

3.2 ΔΨ- effect

Unlike in the case of the ΔE-effect, the ΔΨ-effect is highly dependent on stress. So, while measuring damping in ferromagnetic materials, this effect must be taken into account. In particular, the specific damping capacity of the material was measured within short portions of the time response where the stress or strain could be assumed constant (±10% of variation). This procedure is detailed in Morales' recent work [5], although the initial idea is due to Atalay and Squire in their work [7].

Similarly to fig. 2, fig. 5 tries to demonstrate the influence of stress on the material damping. In this case we plot the natural logarithm of the instantaneous amplitude of the time response along the time, which is directly related to the logarithmic decrement simply by dividing the slope of the curve by the oscillation frequency of the signal. So, if the material damping is dependent on the strain of the time response, the curve must not fit properly to a line. In fig. 5 we can see that the linear fitting curve is not as exact as in the case of the elastic modulus. In particular, the factor R^2, which measures the goodness of the fitting process, is now on the order of 0.9999 and 0.999 in iron and nickel respectively. This fact demonstrates the stress-dependence of the specific damping capacity, but such influence is expected to be minute in our range of stress.

Next, figs. 6 and 7 show the ΔΨ-effect in iron and nickel, respectively. Again one observes two different zones in the specific damping capacity curve: an initial rising stage that corresponds to the low applied magnetic field range (less than 250Oe in iron and 150Oe in nickel), and the second declining stage until saturation. This special trend can be again explained thanks to the magnetic domain structure of ferromagnetic materials. In the first stage of magnetization the damping increases as domain boundaries move irreversibly, whereas the second declining stage starts when the applied field is strong enough to suppress domain walls (by means of domain rotations) and make the specimen behave like a non-magnetic material [6].

Table 3 shows the more significant numerical results regarding the ΔΨ-effect. It is clear that higher variations in specific damping capacity are achieved in nickel.

Another way of studying the influence of stress on the ΔΨ-effect consists of estimating the exponent n of the Lazan's expression for mechanical losses [8]:

$$\Delta W = J\sigma^n \tag{3}$$

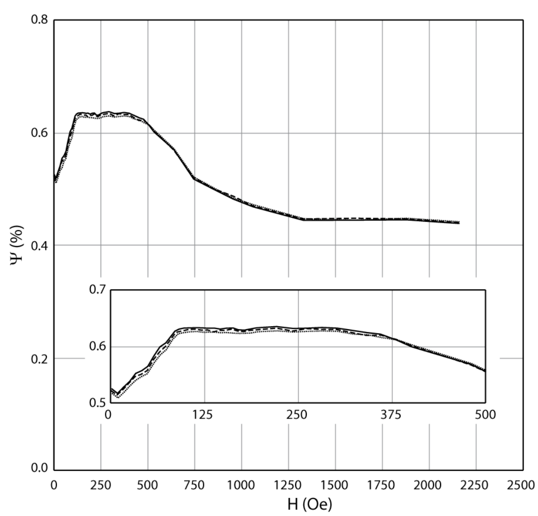

Figure 6: ΔΨ-effect in pure iron (solid line: 0.75MPa; dashed line: 0.50MPa; dotted line: 0.25MPa).

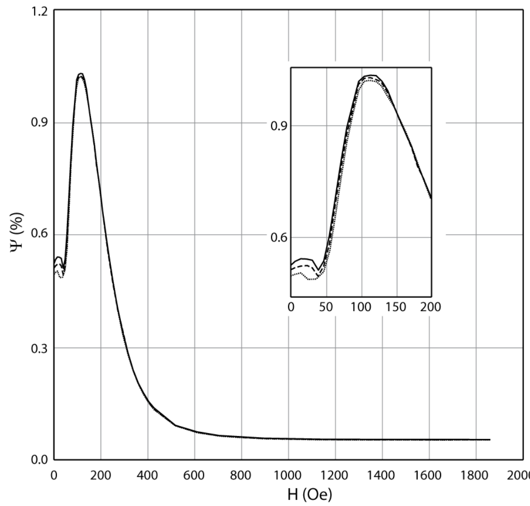

Figure 7: ΔΨ-effect in pure nickel (solid line: 0.75MPa; dashed line: 0.50MPa; dotted line: 0.25MPa).

Table 3: ΔΨ-effect results for pure iron and nickel.

Material	ΔΨ (%) (increasing stage)	ΔΨ (%) (decreasing stage)	ΔΨ (%) (total)
Iron	0.109	-0.201	-0.092
Nickel	0.507	-0.976	-0.469

When ferromagnetic materials are considered, parameters J and n are not constant but they depend on both stress and magnetic field [9, 10]. Indeed:

$$\Psi_{H,\sigma} = \frac{\Delta W_{H,\sigma}}{W_{H,\sigma}} = \frac{J_{H,\sigma}\sigma^{n_{H,\sigma}}}{\dfrac{\sigma^2}{2E_H}} = 2E_H J_{H,\sigma}\sigma^{n_{H,\sigma}-2} \tag{4}$$

This expression means that the specific damping capacity of the material becomes independent of stress when the exponent n is equal to 2.

The evolution of the exponent n of Lazan's expression for iron and nickel can be seen in fig. 8. Regarding iron, such exponent stays almost constant in a value of 2, which means that the specific damping capacity is the same for the three tested stresses and any variation is mainly due to measurement uncertainties. Regarding nickel, the exponent n seems to be slightly higher than 2, which means that little differences exist between the specific damping capacities of the three cases considered. In any case, the higher the applied magnetic field is, the smaller the dependence on stress is, because high magnetic fields make the sample saturate and behave like a non-magnetic material [6].

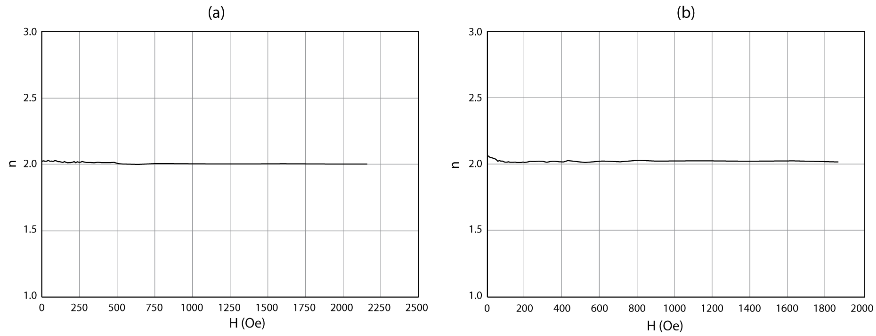

Figure 8: Field-dependence of exponent n for iron (a) and nickel (b).

4 Conclusions

In conclusion, the results shown have been obtained via a new experimental system which offers significant capabilities such as lack of interaction with the sample, non-destructive automatic and fast characterization, high accuracy and resolution in magnetic field, and the possibility of including stress-dependence studies.

In particular, qualitative and quantitative results show better magnetoelastic behaviour of nickel in comparison to iron since they offer higher ΔE- and ΔΨ-effects. Furthermore, all results are in good agreement with magnetic domain theory.

Finally, the influence of stress on magnetoelastic results have been studied for three different values: 0.25MPa, 0.50MPa and 0.75MPa. Regarding ΔE-effect, results support the hypothesis of considering the elastic modulus independent of stress within our range of work. Regarding ΔΨ-effect, results agree with the predicted stress-dependence but the stresses studied are so close that differences result minute.

Acknowledgement

This work was supported by the Consejería de Educación y Ciencia (Junta de Comunidades de Castilla–La Mancha, Spain) under Project PCI08-0082 "Análisis y diseño de elementos activos para el control de vibraciones".

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