AIP Advances

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Cite as: AIP Advances **13**, 035103 (2023); https://doi.org/10.1063/9.0000531
Submitted: 03 October 2022 • Accepted: 09 February 2023 • Published Online: 02 March 2023

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Note: This paper was presented at the 67th Annual Conference on Magnetism and Magnetic Materials.
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ABSTRACT

In this article we evaluate the possibility of using glass coated magnetic microwires as an alternative to optical fiber devices in structural health monitoring in the railway industry. The effect of applied stress on hysteresis loops of $Fe_{71.80}B_{13.27}Si_{11.02}Nb_{2.99}Ni_{0.92}$ and $Co_{65.34}Si_{12.00}B_{10.20}Cr_{8.48}Fe_{3.90}Mo_{0.08}$ microwires has been studied and analyzed. An interpolation function has been obtained relating the coercitivity H_c with the applied stress.

I. INTRODUCTION

In the last years, the railway industry has been one of the leading sectors in the research of alternatives to reduce the costs associated with maintenance. The components of railway tracks suffer huge amounts of pressure that could compromise railway safety and must be revised, repaired and renew frequently according to strict criteria. In the case of the sleeper, the maximum stress allowed by the different authorities is in the order of ~100 MPa[1] before substitution. Currently, the main testing procedures are based on visual inspection or *in situ* measurements, making maintenance procedures economically inefficient.

With the development of industry 4.0, researchers have been studying the fabrication of smart-sleepers capable of monitoring the sleeper structural stress in real-time.[2] Current technology makes extensive use of expensive optical fiber based instruments.[2,3] Thus, making it difficult to extend its use to big extensions of railway lines.

Magnetic microwires fabricated by the Taylor-Ulitovsky method[4–6] appear in this context as an alternative for smart-sleeper technology. The microwires obtained using this technique are characterized by their small cross section (the metallic nucleus diameters, d, can be varied from 0.2 to 50 μm), environment insulation thanks to the glass-coating and high sensitivity to external stimuli.[7] These properties, along with their cheap fabrication costs have motivated the studies of these microwires as well as their applications for structural measurements in concrete structures similar to concrete sleepers.[8]

The presence of biocompatible and flexible glass coating is suitable for many technological applications, however is also the source of additional magnetoelastic anisotropy.[9] Thus, rather different thermal expansion coefficients of metallic alloy and glass are the main source of rather strong internal stresses.[10–13] The internal stresses, σ_i, magnitude to great extent determined by the ratio, ρ, between the metallic nucleus diameter, d, and total microwire diameter, D ($\rho = d/D$): low ρ values (thick glass-coating) are associated with high σ_i values.[12,13] Due to technological constraints, in submicrometric wires prepared by Tayor-Ulitovsky technique the glass-coating thickness, as a rule, is much thicker than the metallic nucleus diameter.[10,11]

Stress dependence of the coercivity, H_c, is one of the parameters frequently used for stress monitoring.[7] Previously, the effect of applied stress, σ, on magnetic properties of glass-coated microwires has been evaluated in several publications.[7,14,15] The $H_c(\sigma)$ is affected by both chemical composition of microwires as well as by the σ_i value linked to the ρ ratio.[14] In Co-rich microwires with negative magnetostriction coefficient, λ_s, the coercivity, H_c, is not the most stress-sensitive parameter. Whereas in magnetic microwires with $\lambda_s > 0$ and rectangular character of hysteresis loops, the substantial $H_c(\sigma)$ dependence is reported.[7,14,15] Generally, H_c is less sensitive to applied stresses in microwires with low ρ ratio (i.e. with high internal stresses).[14] Additionally, the character of $H_c(\sigma)$ dependence in Fe- and Co-rich microwires with $\lambda_s > 0$ is rather different.[14] This difference must be attributed to the dependence of the magnetostirction coefficient on chemical composition.

In this work we show the possibility of glass coated magnetic microwires of working as railway monitorization devices. This is done by measuring the effect of longitudinal stress on the hysteresis loops of several Co- and Fe-rich microwires with different compositions.

II. EXPERIMENTAL METHOD

For this work, we employed two glass coated microwires of Co-rich and Fe-rich alloys respectively with different diameters fabricated by the Taylor-Ulitovsky method. This way, the microwire is fabricated by introducing the alloy ingot inside a glass tube while surrounded by an inductor, as shown in Fig. 1. At high enough temperature, the alloy melts as well as the glass, then a glass capillary is formed and pulled out of the softened glass, which is caught by the rotating pick-up spool. Rapid melt quenching rate is achieved by a stream of coolant (water or oil). When a high enough quenching rate is achieved, in our case by using water as coolant, the amorphous structure is obtained. The microwire continues drawing and forming an amorphous structure until the alloy ingot is consumed, forming a continuous microwire with a total length of about 1 Km/g of precursor alloy used in the fabrication process.

Considering previous knowledge, for the present studies in order to evaluate the applications of glass-coated microwires in the railway monitorization devices, as a first approach, we selected one Co-rich (with low $\lambda_s > 0$) and one Fe-rich microwire with (with high $\lambda_s > 0$) with intermediate d and ρ values.

This family of microwires is characterized by its chemical composition, metallic nucleus diameter d and the total diameter D. The atomic composition (% at) and diameters of the microwires used in this work where the following: $Fe_{71.80}B_{13.27}Si_{11.02}Nb_{2.99}Ni_{0.92}$ (d = 15.9 μm and D = 24.5 μm) and $Co_{65.34}Si_{12.00}B_{10.20}Cr_{8.48}Fe_{3.90}Mo_{0.08}$ (d = 17.5 μm and D = 22.2 μm).

Measurements of the hysteresis loops of both microwires where carried using the fluxmetric method as previously discussed elsewhere[16] and schematically represented in Fig. 2. In this method, the magnetization of the microwire is obtained using a pick-up coil of N turns that measures an electromotive force ε related with the change of magnetic flux ϕ as described in Eq. (1).[17]

$$\varepsilon = -N\frac{d\phi}{dt} \tag{1}$$

Then the sample magnetization can be obtained by integrating ε as follows:

$$M = \frac{1}{N\mu_0 A_s}\int \varepsilon dt \tag{2}$$

where As is the sample cross-section. The hysteresis loops are represented as the normalized magnetization, M/Mo, versus the applied magnetic field, H, where Mo is the magnetic moment of the sample at the maximum magnetic field amplitude, Ho. In order to study the evolution of the hysteresis cycles, the microwires where introduced inside the pick-up coil protected by a ceramic capilar while leaving both ends outside the coil. One of the ends of the microwire was fixed to a dynamometer while a longitudinal force T was applied on the opposite one. Applied stress on the metallic nucleus σ_m can

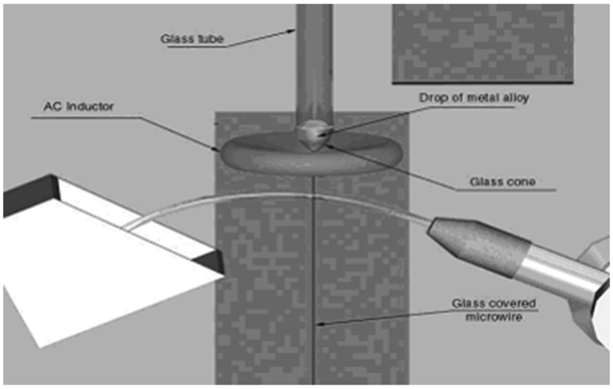

FIG. 1. Representation of the fabrication of a microwire by the Taylor-Ulivtosky method.

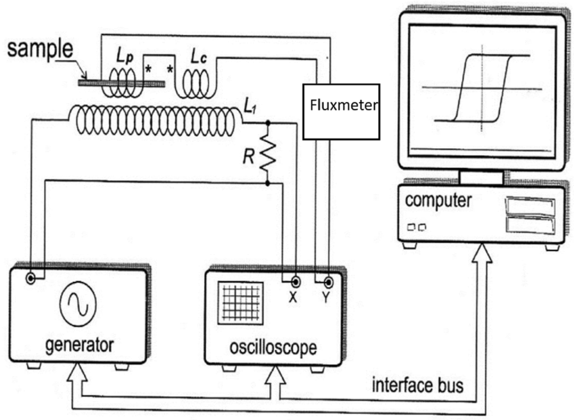

FIG. 2. Scheme of the fluxmetric method set up used for the measurement of the hysteresis cycles.

be derived from the applied force by using Eq. (3) as previously described elsewhere[18]

$$\sigma_m = \frac{K \cdot T}{K \cdot S_m + S_{gl}} \tag{3}$$

Where S_m is the area of the metallic cross-section, S_{gl} corresponds to the glass cross section and $K = E_m/E_{gl}$, being E_m and E_{gl} the Young modulus of the metallic core and glass coating respectively. The quotient between Young modulii was fixed to $K \sim 2$ for both microwires attending to the typical values given by Domone *et al.*[19] of $E_m \sim 130$ MPa and $E_{gl} \sim 70$ MPa for these twomaterials.

III. RESULTS

We measured the hysteresis loops of both microwires by applying an external magnetic field H between ±150 A/m and ±400 A/m for the Co-rich and Fe rich microwires, respectively. The recorded hysteresis loops were averaged with the help of the oscilloscope until the resulting cycle formed a stable image on the screen. This process was repeated while applying different forces to the microwires resulting in internal stresses estimated using Eq. (3).

The resulting hysteresis cycles are represented in Figs. 3(a) and 4(a). As tensile stress, σ, is applied, the coercive field H_c of both microwires experiments an increase passing from ~40

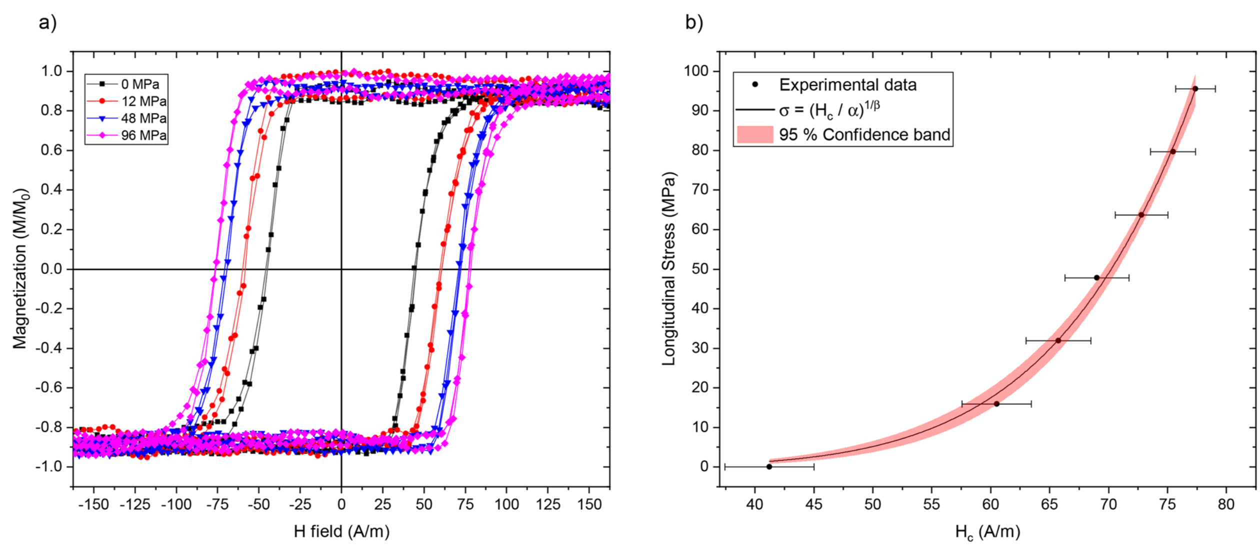

FIG. 3. Magnetic response to applied stress of the $Co_{65.34}Si_{12.00}B_{10.20}Cr_{8.48}Fe_{3.90}Mo_{0.08}$ microwire: (a) Hysteresis loop evolution. (b) Microwire calibration function and associated confidence band.

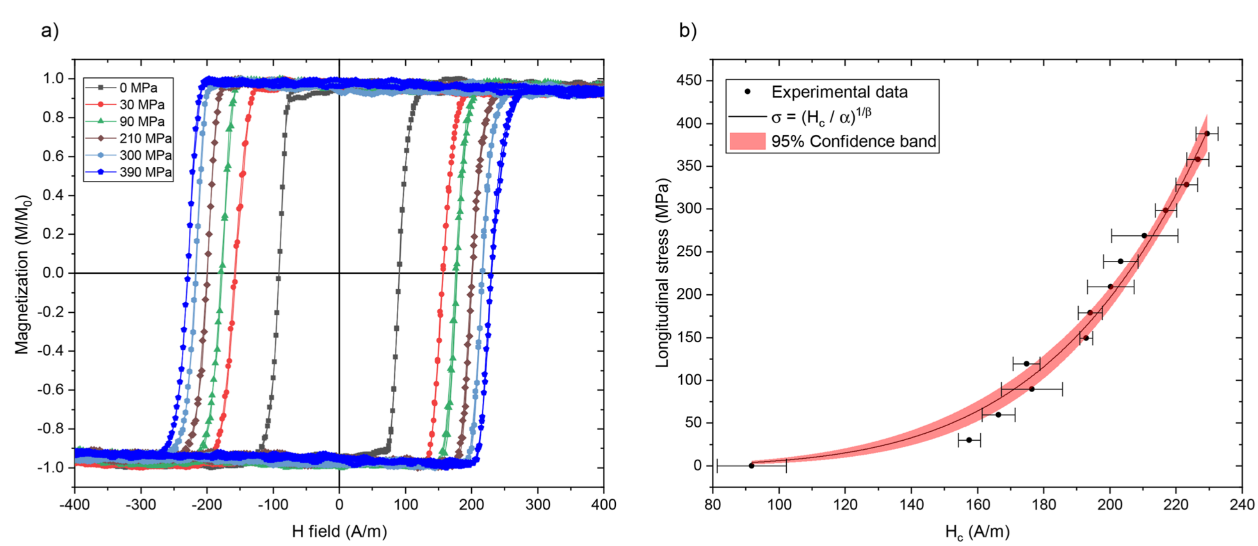

FIG. 4. Magnetic response to applied stress of the $Fe_{66.99}FeB_{19.64}Si_{6.45}Nb_{5.79}Ni_{1.13}$ microwire: (a) Hysteresis loop evolution. (b) Microwire calibration function and associated confidence band.

TABLE I. Fitting parameters obtained for both microwires.

Alloy	α (Am^{-1} MPa^{-1})	β
$Co_{65.34}Si_{12.00}B_{10.20}Cr_{8.48}Fe_{3.90}Mo_{0.08}$	39 ± 1	$150 \cdot 10^{-3} \pm 6 \cdot 10^{-3}$
$Fe_{71.80}B_{13.27}Si_{11.02}Nb_{2.99}Ni_{0.92}$	70 ± 4	0.20 ± 0.01

to ~100 A/m for the Co-rich microwire and from ~90 to ~230 A/m for the Fe-rich one. This results in an increase of the coercitive field $H_c(\sigma_{max})/H_c(\sigma = 0) \simeq 250\%$ for both microwires while the pressure applied to the Fe-rich microwire was four times bigger than the applied to the Co-rich one.

Having observed a good response, we studied the evolution of the H_c with the applied pressure for both microwires in order find a function capable of evaluating the stress at the metallic core by measuring the coercitive field. By taking as starting point the relation $H_c \sim \sigma^a$ used by Corte-León *et al.*[7] we proposed the following interpolation function:

$$\sigma = \left(\frac{H_c}{\alpha}\right)^{(1/\beta)} \quad (4)$$

The fitting of the data of both microwires is shown in Figs. 3(b) and 4(b) where a successful fitting with narrow confidence bands has been achieved with the parameters presented in Table I. Attending to the results, both microwires could be used for sleeper structural health monitorization.

For the monitorization of concrete sleepers in the railway industry the $Co_{65.34}Si_{12.00}B_{10.20}Cr_{8.48}Fe_{3.90}Mo_{0.08}$ microwire arises as perfect candidate as it has the highest sensitivity for the range of 0 to 100 MPa. It also presents a lower coercitive field, making easier the implementation of these microwires in industrial application as power consumption will be lower in order to power the magnetic field that would scan the coercitive field.

The $Fe_{71.80}B_{13.27}Si_{11.02}Nb_{2.99}Ni_{0.92}$ microwire presents also high sensitivity for the stress range of concrete sleepers health monitoring but also could be used for monitorization of systems with higher pressure thresholds as it is able to reach ~400 MPa. Although this microwire has higher magnetic field requirements that imply a higher power consumption than the Co-rich microwire, the fact that the alloy does not contain Co makes it cheaper from the alloy fabrication perspective. Further study would be needed in order to see it the lack of critical materials use in the fabrication process could compensate for the higher power consumption.

IV. CONCLUSIONS

The effect of applied stress in the hysteresis cycles of $Co_{65.34}Si_{12.00}B_{10.20}Cr_{8.48}Fe_{3.90}Mo_{0.08}$ and $Fe_{66.99}Si_{6.45}Nb_{5.79}Ni_{1.13}$ has been studied. We have been able to obtain an interpolation function that relates the amount of stress in the metallic core of both microwires with their coercitive field for stresses ranging up to 400 MPa. Also the use of these microwires has been proposed as an alternative for structural health monitoring in the railway industry as both are able to fulfill the pressure range requirements.

Future experiments will be conducted to explore the effect of temperature and pressure over time in these alloys to study the stability of the hysteresis cycles. We shall study as well new annealing conditions searching for enhancement in the microwires response. Finally, it is intended to embed these microwires in concrete structures like it has been done in other works[8,20–22] in order to test the microwires in an environment closer to their intended use as health monitorization devices for railway concrete sleepers.

ACKNOWLEDGMENTS

This work was supported by the EU under "INFINITE" (HORIZON CL5-2021-D5-01-06) proyect, by the Spanish MCIU PGC2018-099530-B-C31 (MCIU/AEI/FEDER, UE), by the Government of the Basque Country under PUE_2021_1_0009 and Elkartek (MINERVA, ZE-KONP and COMPONENS) projects and (under the scheme of "Ayuda a Grupos Consolidados") (ref. IT1670-22), by the Diputación Foral de Gipuzkoa in the frame of Programa "Red guipuzcoana de Ciencia, Tecnología e Innovación 2021" under 2021-CIEN-000007-01 project and by the University of Basque Country under the COLAB20/15 project. The authors thank for technical and human support provided by SGIker of UPV/EHU (Medidas Magneticas Gipuzkoa) and European funding (ERDF and ESF). We wish to thank the administration of the University of the Basque Country, which not only provides very limited funding, but even expropriates the resources received by the research group from private companies for the research activities of the group. Such interference helps keep us on our toes.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

A. García-Gómez: Conceptualization (lead); Data curation (lead); Formal analysis (lead); Investigation (lead); Methodology (lead); Writing – original draft (lead); Writing – review & editing (lead). **P. Corte-León**: Supervision (equal); Validation (equal). **M. Ipatov**: Resources (equal); Software (equal). **V. Zhukova**: Project administration (equal); Supervision (equal); Validation (equal). **J. Gonzalez**: Supervision (equal). **A. Fert**: Supervision (supporting). **A. Alonso**: Conceptualization (equal). **E. Gomez**: Conceptualization (equal). **A. Zhukov**: Funding acquisition (lead); Project administration (lead); Resources (lead); Supervision (lead); Validation (lead); Writing – review & editing (lead).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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