Force sensing utilizing a CoFeSiB microwire: a preliminary experimental study

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***Abstract*— Amorphous materials, and FeSi-based in particular, have peculiar magneto-mechanical properties which promote their use in many applications: from microelectronics to instrumentation and measurement. In this study, we investigate the use of a CoFeSiB microwire for force sensing purposes. We utilize an inductive method and a linear actuator to assess the magnetic sample behavior while applying a controlled tensile force. The results showed a complex behavior of the magnetization saturation and residual magnetization vs the tensile stress; however, after a threshold force value, a linear relationship is observed between the magnetic parameters and the applied force. Therefore, the performance utilizing different readout strategies are assessed, and the results are discussed concerning the recent literature.**

Keywords*— *CoFeSiB microwire, force sensing, magneto-mechanic properties

I. Introduction

In recent years, amorphous materials have become of great interest in many fields, from instrumentation and measurement sector to electronic and microelectronic devices application [1]. These materials can be employed to fabricate micro and nano wires which allow the development of small dimensions and low payload devices. The characteristics of these materials, mainly based on Iiron and silicon, depend on the specific chemical composition, heat treatment, and construction method used for their fabrication. For example, rotating water spinning [2], and Ulitovsky–Taylor methods [3] are widely used to produce CoFeSiB-based microwires. In particular, the latter process results in high mechanical strength and high magnetic permeability of the produced devices. Moreover, environmental conditions, such as applied magnetic field and temperature, have a large influence on their magnetic behavior, hence they are widely used as sensing elements. For instance, CoFeSiB microwires and ribbons are used in fluxgate magnetometers with high reliability and sensitivity [4]. More recently, Baglio et al. [5] developed a sensor based on the temperature influence on the hysteresis loop of a 100 μm CoFeSiB microwire. They further exploited different characteristics of the magnetic cycle for thermal sensing, also concerning a time domain readout [6], [7].

Mechanical stress can affect the magnetic behavior of CoFe-based samples, and thermal treatments are often used to control this feature [8]. For instance, the annealing process is often used to this purpose [9], [10]. In general, the stress applied to ferromagnetic materials interacts with the magnetic domains, thus affecting the overall magnetization of the sample, the permeability of the material, and the hysteresis loop. Moreover, the magnetostriction coefficient plays a key role in the magneto-mechanic relationship in ferromagnetic elements [11].

In FeSi-based amorphous materials, the peculiar magneto-mechanic characteristic relationship, in combination with the high mechanical resistance, low weight and small dimensions of ribbons and microwires made by these materials, promote their use in force and stress sensing devices. In the literature, several studies investigate the relationship between stress and magnetic parameters. The effect of the internal stress on GMI (i.e., giant magnetoimpedance) is studied in [12], [13] for different configurations of CoFeSiB layers and in different operating conditions. Aksenov et al. [14] studied the effects of mechanical stress on a FeSiB microwire with positive magnetostriction, and they obtained that coercivity increases with tensile stress. Novak et al. [15] observed the influence of the stress in the direction of magnetization, and they obtained changes in the properties of domain walls e in the entity of magnetostriction. Lo et al. [16] evaluated the influence of stress in magnetic materials, observing an increase in the coercive field by applying a compression state. Kurita et. al. [17] studied the inductance of a FeSiB ribbon specimen subjected to tensile stress in the range of 0-2 N, and they obtained an equivalent permeability change of 0.19%.

Therefore, the literature presents several studies regarding the magneto-mechanic relationship especially in FeSi-based materials, but their exploitation for sensing purposes still requires a systematic investigation on the transduction methods and parameters. We remark that the sensitivity of the magnetic core to multiple parameters, such as the temperature, the external magnetic field, and the mechanical stress can be utilized for the development of multi sensing devices, especially by applying different strategies for independent readout. Moreover, such sensing elements are possibly suitable in space applications due to their small payload, and in many civil applications due to their high sensitivity and small dimensions.

In this paper, we explore a 120 µm CoFeSiB microwire as sensing element for force sensing. We focus on low frequency utilization, investigating the relationship between the magnetic hysteresis loop and the tensile force applied to the sample. Therefore, we analyze different readout strategies, and we characterize the response of the sensing sample by comparing different transduction methods.

This paper is organized as follows: after a brief introduction (Sec. I), we describe the experimental setup and the method pursued for the investigation (Sec. II). Therefore, we report and discuss the obtained results (Sec. III) and finally we present the conclusions (Sec. IV).

II. METHOD

We aim at investigating the characteristics of the hysteresis loop of an amorphous material sample as a function of the applied tensile force. The sample is a 120 µm diameter microwire made by CoFeSiB. We used an inductive method to supply a time-varying magnetic field and measuring the induced voltage on a secondary winding. As primary winding, we use 1052 coils made by a copper wire wrapped around a 130 mm diameter PVC pipe over 320 mm length. We use an AGILENT 33521A waveform generator set to operate as current source to supply a sinusoidal current into the primary winding, thus generating a magnetic field H as:

$$H = \frac{N_p I}{L_p} \quad (1)$$

In Eq.1, I is the current circulating in the primary coil, N_p and L_p are, respectively, the primary coil turns number and the total length of the primary magnetic circuit. The current I is evaluated by measuring the voltage drop V_p across a shunt resistor R_s = 0.1 Ω. The secondary winding is made by 500 turns of 0.1 mm diameter copper wire, wrapped around a 0.3 mm diameter glass pipe over 50 mm length. The CoFeSiB microwire is then housed inside the glass, hence any mechanical force acting on the sensing element does not affect the geometry of the secondary winding. A picture of the used microwire and of the secondary winding is showed in Fig.1.

We housed the CoFeSiB microwire inside the glass pipe supporting the secondary magnetic circuit. We use a PLA (i.e., PolyLactic Acid) holder to place the secondary winding and the microwire on the primary winding axis. Therefore, we mechanically fix one side of the sensing element to the PLA support. By measuring the open voltage V_s on the secondary winding we can measure, via the Faraday's law, the magnetic flux ϕ as:

$$\phi = \frac{1}{N_s}\int_0^t V_s(\tau)d\tau \quad (2)$$

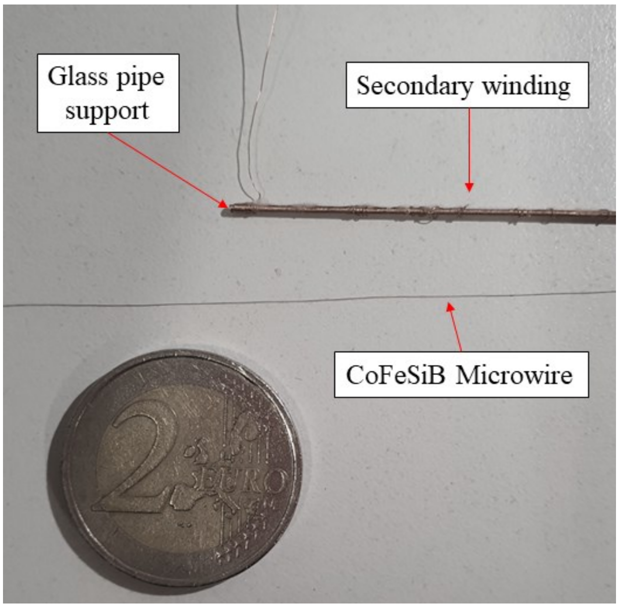


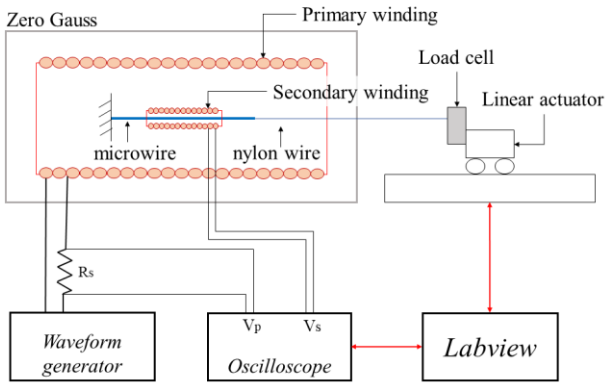
Fig.1. Picture of the used microwire and of the secondary winding.

In Eq. 2, N_s is the number of coils of the secondary winding. In particular, we apply a sinusoidal current *I(t)* to generate a corresponding *H(t)* field. We choose 10 Hz operating frequency as a trade-off to obtain a quick measurement of the hysteresis cycle, and to limit the effect of eddy currents which can alter the measurement with major dynamic effects, as investigated in previous studies [5], [7].

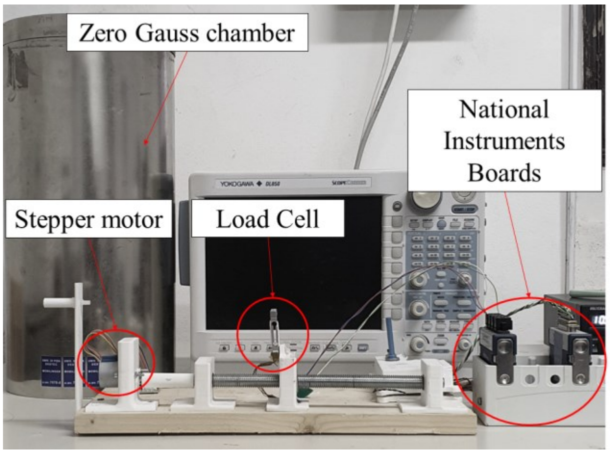
The sensing element is very sensitive to external static magnetic fields (such e.g., the Earth magnetic field), and to the purpose of performing a reliable measurement of the magnetic parameters, we shielded the microwire, the primary and the secondary coils by using a Zero Gauss chamber made by three concentric MuMetal layers, capable of attenuating the external static fields of over 200 times.
Therefore, we use a 0.1 mm diameter nylon wire, fixed to the microwire, to pull the sensing element and apply a controlled tensile force. To this purpose, we employ a linear actuator made by a stepper motor, a mother-screw coupling, and a TAL221 full-bridge load cell for force sensing. The load cell is properly calibrated prior the use. To acquire the signals V_p and V_s, we use a Yokogawa DL850E ScopeCorder equipped with a 720268 1 MS/s 16-bit module. The output of the load cell is acquired by means of a NI9219 board.

By moving the linear actuator, we produce a strain on the microwire and nylon wires, thus a force F is applied along the axis of the sensing element. A feedback control allows applying the desired F and keeping the system in steady state conditions. The setup and the data acquisition are managed by a LabVIEW™ software made on this purpose.
The scheme, and a picture of the employed setup are shown in Fig.2. We would like to highlight that both the microwire and the air inside the glass contribute to ϕ in different manners. In the case of the microwire, the relationship between ϕ and H is expected as ferromagnetic, while in the

case of air as paramagnetic. The overall behavior of the system is



(a)



(b)

Fig. 2. Scheme (a) and a picture (b) of the experimental setup.

therefore, a mix between the two. However, due to the high permittivity of the CoFeSiB, we expect the comprehensive behavior as ferromagnetic and close to the behavior of the microwire.

We operate the system to magnetically saturate the CoFeSiB, and we achieve this with a current peak-to-peak amplitude of around 50 mA. According to the literature [18], [19] we expect the hysteresis loop to rotate and vary both the magnetization saturation and residual flux, thus we expect the V_s signal to vary its amplitude accordingly. An example of the expected outcome is shown in Fig. 3.

The hysteresis cycle variation vs F is depending on the positive or negative magnetostriction coefficient [15], and must be experimentally determined.
Therefore, we monitor the magnetization saturation M, the residual magnetization R, and the peak of the V_s signal i.e., V_s^{max}, calculated as follows:

$$M = \frac{\max(\Phi) - \min(\Phi)}{2} \tag{3}$$

$$R = \frac{\Phi|_{H=0,V_s>0} - \Phi|_{H=0,V_s<0}}{2} \tag{4}$$

$$V_s^{max} = \frac{\max(V_s) - \min(V_s)}{2} \tag{5}$$

In order to set the operating conditions, we estimate the mechanical properties of the microwire to work with minor irreversible deformation on the CoFeSiB sample.

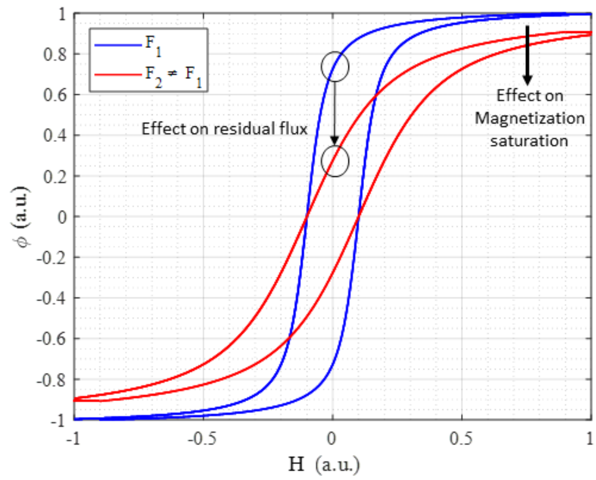
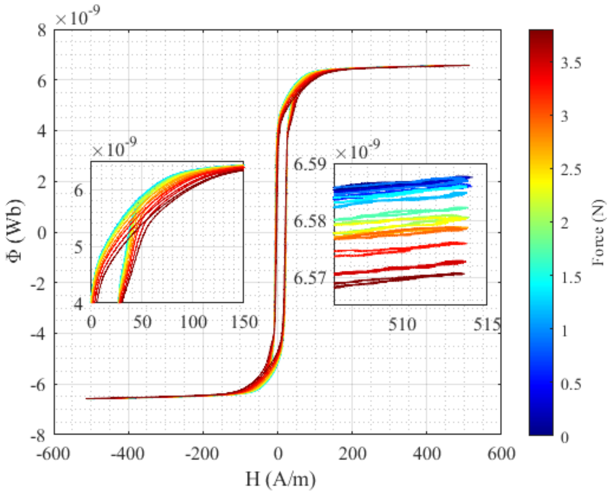


Fig. 3. Schematic illustration of the expected effect on the hysteresys cycle by applying an axial stress on a FeSi-based material.

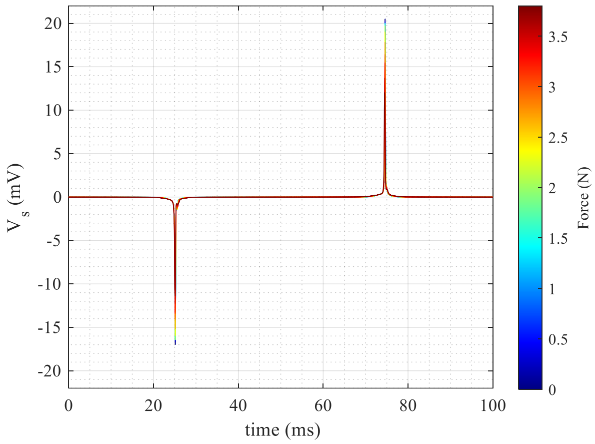
However, the evaluation of the yield stress is an important and difficult point to address andwe refer to the literature to obtain an order of magnitude of such value. As example, Co-based amorphous materials can exhibit up to 4 GPa of tensile stress [20], while in [21] they declared 250 MPa as tensile stress on a FeSi-based ribbon. Hence, the different chemical composition and thermal treatment can significantly vary the mechanical characteristics of such samples. However, several authors [12], [22] applied tensile stress below 450 MPa to CoFeSiB ribbons or microwire samples to assess their magnetic behavior. Therefore, we used a maximum stress of about 350 MPa, never exceeding 4 N of applied force, thus possibly operating in elastic regime. However, we have preliminary applied several 0-4 N and 4-0 N cycles to test and train the microwire and the mechanical chain.
In this work, the uncertainties are calculated in agreement with the GUM [23], and a coverage factor k = 2 is used to provide the extended uncertainty.

III. Results and Discussion

In Fig. 4 we report the obtained ϕ-H and V_s-t cycles for each different applied force.



(a)



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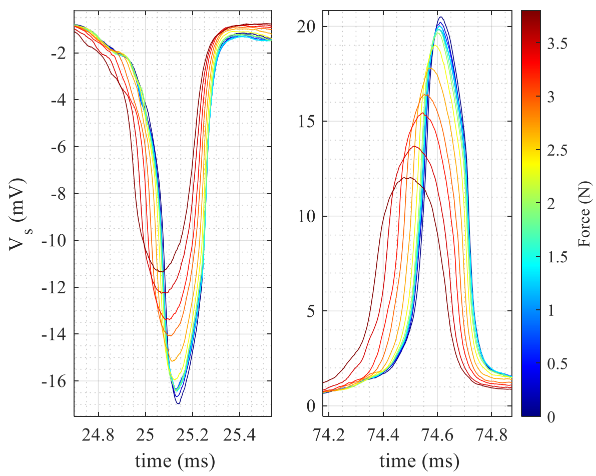


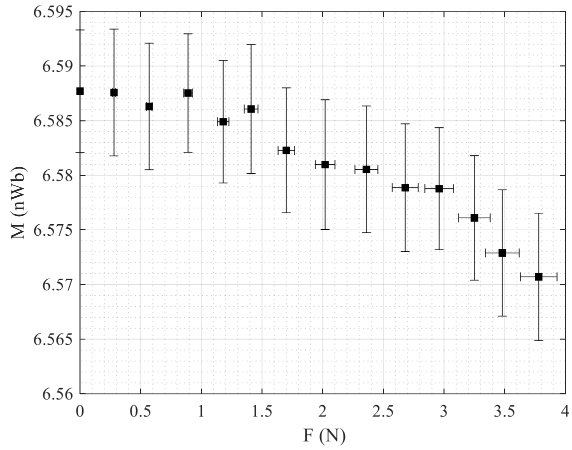
(c)

Fig. 4. ϕ-H loop (a) and Vs – t signal (b) and focus and the negative and positive peak (c).

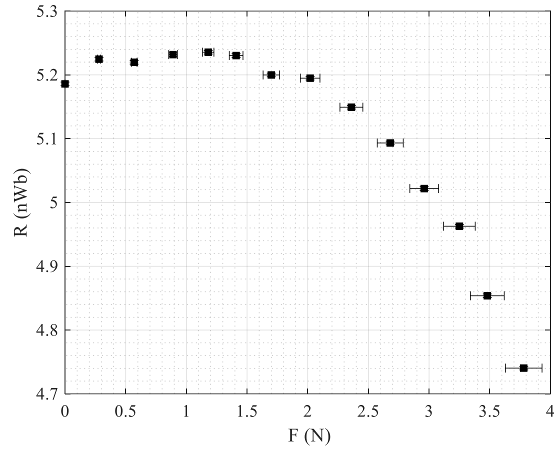
Fig. 4 shows that an increase in stress produces a decrease in saturation magnetization and a clockwise rotation of the hysteresis loop, as highlighted by the inset plots of Fig. 4a. This behavior agrees with the literature in case of positive magnetostriction coefficient [11].

The effect on magnetization saturation and on the hysteretic behavior is consistent with Fig. 4b and 4c, where the signal of the induced voltage produces flatter peaks while increasing F. By using the ZeroGauss setup we expect a symmetric profile of V_s vs t with respect to $V_s = 0$. Hence, the asymmetry observed in Fig. 4b and 4c is possibly given by an offset in the current profile, with negligible impact on the evaluation of the ϕ-H loop characteristics for transduction method assessment.

Fig. 5 shows the relationship of M, R and V_s^{max} against F.



(a)



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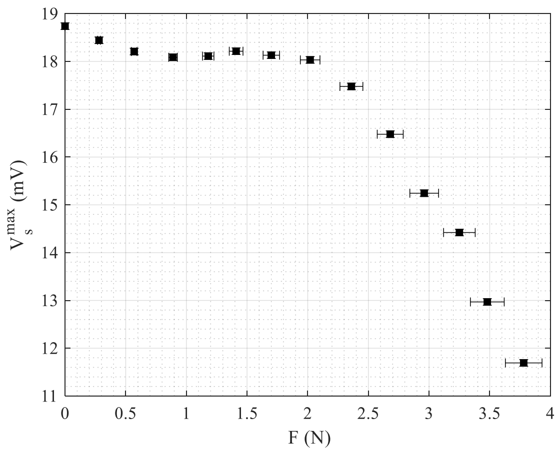

(c)

Fig. 5. Behavior of M vs F (a), R vs F (b) and V_s^{max} vs F (c).

The uncertainties presented in Fig. 5 are mainly due to type-A sources, and for both R and M it results in the order of 0.2 % as relative value. Fig.5a shows that the magnetization saturation is slightly influenced by F; indeed, the results show the compatibility of the results regarding M vs F, and a reliable trend cannot be detected (overall variation in the order of 6.5 nWb/N). This permeability change is in the order of 0.3%, which is consistent with the 0.19% found in [17] while characterizing similar samples.

From Figs. 5b and 5c we notice a flat relationship of R and V_s^{max} with $F < 2$ N. This specific value can be eventually considered as a threshold force F_t = 2 N. This occurrence can indicate a nonlinear behavior of the magnetic parameters with F, or the presence of large play in the system i.e., leading to inaccuracies in estimating the force acting on the sample. However, we infer that the microwire has a non-zero internal stress initial status (i.e., when $F = 0$), which tends to counterbalance the effect of the tensile stress to the CoFeSiB. Therefore, a threshold force (i.e., 2 N in the present case) is needed to produce a major effect on the initial status of the sample.

For $F > F_t$, the system exhibits a significant linear response concerning both R and V_s^{max}. In particular, the sensitivity for $F > F_t$ is -5.75 nWb/N using R as parameter, and 26 mV/N (i.e., around 20% of the signal maximum per newton as shown in Fig. 5c) using V_s^{max}.

The obtained values show high sensitivity in the context of an application for force sensing, which can be exploited for high-precision measurement through a magnetic-based readout. Moreover, the small dimensions and low weight of the sensing element promote its use where geometry and payload are relevant constraints. We achieve such high sensitivity by employing a simple and reliable method based on low frequency measurements concerning other literature methods involving GMI evaluation. For instance, in [13], they achieved a 30% variation of the GMI in a CoFeSiB ribbon. We measured similar sensitivity while using V_s^{max}, and the strategy is simply based on a voltage measurement. Other sensors, such as based on piezoresistivity, can result in a sensitivity (in terms of input variation over force variation) ranging from the order of 1%/N [24] to 100%/N [25], while utilizing complex manufacturing techniques for the development of the device.

Finally, for the application of the proposed method in sensing devices we can reduce the significance of the threshold force by pre-loading the sample, thus improving the range to the desired one. However, attention should be paid not exceeding the yield stress of the CoFeSiB. As further option, heat treatments, such as annealing, can significantly reduce the internal stress [26] and possibly mitigate the effect of the threshold force.

IV. Conclusions

In this paper, we studied the relationship between the force applied to a 120 µm CoFeSiB microwire and its magnetic behavior. To this purpose, we developed a dedicated setup, and we measured the magnetic behavior utilizing an inductive method. From the experiments, it turned out that the magnetization saturation, residual field, and peak of the induced voltage present a monotone trend against the force applied after a force threshold value. High sensitivity is calculated to the last two parameters, thus highlighting the capability of the sensing element for implementation in high-precision force sensors. Further attention should be paid in mitigating the effect of the threshold force, thus properly investigating the physical causes of its occurrence. A dynamic characterization of the sensing element can also help the assessment of the CoFeSiB microwire performance in sensing.

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