## Research articles

# Study of bistable behaviour in interacting Fe-based microwires by first order reversal curves

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## Abstract

Amorphous ferromagnetic Fe-based microwires (MWs) have a magnetic structure consisting mainly of a single longitudinal domain and small closure domains at both ends. A rectangular hysteresis loop is then observed according to the fast domain wall propagation along the microwire. This type of material is a good physical example of the idea of a magnetic relay hysteron as described in Preisach model of hysteresis. The hysteron was defined as a mathematical operator acting on the field and producing rectangular loops whose superposition gives out the hysteresis loop. The hysteron idealization is frequently used to describe and interpret FORC (First Order Reversal Curve) diagrams by comparison with Preisach plane. The central idea of this work is to study the FORCs of a real physical sample that behaves closely to the ideal hysteron, both isolated and interacting with a twofold aim. On one hand, providing a better understanding of FORC measurements, and, on the other, analyzing the magnetization reversal processes in microwires with rectangular hysteresis loops. While for a single microwire the behaviour is that expected for a hysteron, both in the hysteresis loop and in the FORC diagram, the magnetostatic interaction

between two microwires breaks with the ideal behaviour due to the change in the domain wall mobility at the end of the wires.

**Keywords**: FORC-analysis; Hysteron; Bistable ferromagnetic microwires; Classical Preisach Model; Hysteresis; Magnetostatic interaction

# 1 Introduction

Nowadays, First Order Reversal Curve (FORC) analysis is on top of popularity to describe magnetic interactions in ferromagnetic materials [1–5]. The measurement of sets of FORCs provides detailed information from different paths of magnetization, which enables the determination of the Switching Field Distribution (SFD) and interaction fields for all the phases that contribute to the hysteresis loop [6,7].

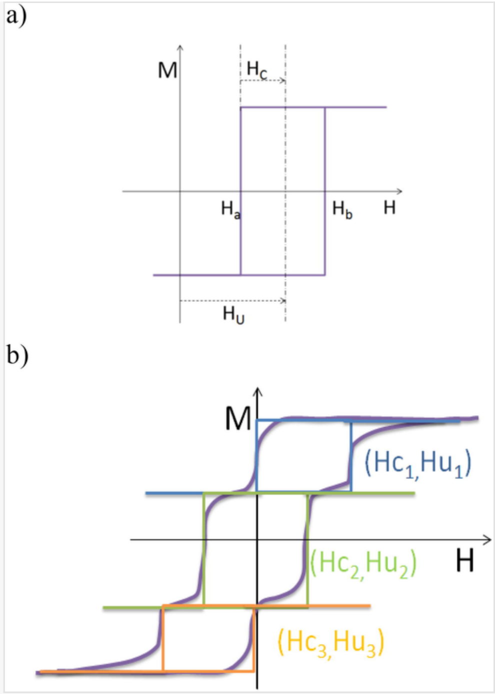
The FORC diagram interpretation is frequently based on its comparison with the Preisach distribution of a set of magnetic hysterons fulfilling Mayergoyz's constraints for the Classical Preisach Model (CPM) [8]. The Preisach model of hysteresis stands out because it encompasses the basic features of hysteresis phenomena in a conceptually simple and mathematically elegant way. In this model, the hysteron is a mathematical operator that acts on the magnetic field and produces a square hysteresis loop characterized by a coercive field $H_c$ (half-width) and an interaction field $H_u$ (horizontal bias) [9–11]. The hysteron's distribution $\rho\left(H_c, H_u\right)$ is represented on the two-dimensional Preisach plane with axes $H_c$ and $H_u$.

Parameters $H_c$ and $H_u$ can be evaluated from the values of "switching up" ($H_b$) and "switching down" ($H_a$) fields by ratio:

$$H_u = \frac{H_a + H_b}{2}; H_c = \frac{H_b - H_a}{2} \tag{1}$$

Fig. 1(a) shows the irreversible loop of a typical hysteron. The main idea of Preisach's model is that the hysteresis loop can be represented as the superposition of a weighted collection of hysterons (see Fig. 1(b)).

Fig. 1




a) The hysteron in Preisach model b) The hysteresis loop build up with different hysterons.

By comparison to the Preisach plane, FORC analysis evidences the magnetic interactions within the sample under test, as well as the existence of different phases, and allows characterizing each magnetic phase. Pike, Roberts et al. [12,13] developed the first experimental application of CPM — the FORC measurements of hard ferromagnetic materials. Later, the FORC analysis has become a useful tool for determining features in the magnetic behaviour of soft magnetic materials [1,14]. Despite the advantages and simplicity of CPM, most physical samples are far from the ideal behaviour described by means of a set of "irreversible bistable hysterons".

The amorphous ferromagnetic Fe-based microwires (MWs) produced by Taylor-Ulitovsky method [15] can be a good physical example of the relay of irreversible hysteron. Among their unique magnetic properties, the magnetic bistability stands out. These glass-coated MWs have a micromagnetic structure consisting of a single longitudinal domain and small closure domains at the ends. A rectangular hysteresis loop is then observed according to the fast domain wall propagation along the microwire [16,17].

In this paper, we propose the comparison of the fundamental concept of one irreversible hysteron and a set of two interacting hysterons, respectively with the results obtained out of FORC measurements for a Fe-based amorphous microwire and a set of two magnetostatically interacting microwires with ideal bistable magnetic behaviour.

## 2 Experimental details and samples, models

In this work, the magnetic behaviour of $Fe_{74}B_{13}Si_{11}C_2$ (diameter of the metallic core $d = 18.8$ μm, outer diameter $D = 28$ μm, length of 5 cm) glass-coated amorphous microwires is studied. The study includes two configurations: 1) one single wire, and 2) an array of two coupled wires (the distance between both metallic nuclei being twice the thicknesses of the glass shell). Hysteresis loops and sets of first order reversal curves (FORCs) were obtained in an AC-inductive magnetometer setup [18] using a 16 mm long pick-up coil. The set-up produces a magnetic field of tunable frequency in the range 0.1–200 Hz, and amplitudes of 0.2–40 kA/m. For the measurements of this paper we have chosen a triangular waveform field with a rate of 5600 $\mathrm{Am}^{-1}$/s and a maximum amplitude field of 180 A/m, both for the hysteresis loops and all the measured FORCs. Such field rate value was chosen to analyze the magnetic behaviour in quasi-static regime.

To obtain a FORC the applied field must be saturating, then decreased to a so-called return value $H_r$ and increased again to saturation. The measured curve from the return field to the saturation field is called a FORC [19]. To analyze the interaction processes in magnetic systems it is better to measure as many FORCs as possible (usually 100–150 curves are enough for analysis). The switching field distribution (SFD), or differential susceptibility, is calculated by differentiation:

$$\mathrm{SFD}(H, H_r) = \left.\frac{\partial M}{\partial H}\right|_{Hr} \tag{2}$$

For systems in which there are no interactions among the magnetic elements, e.g. non-interacting monodomain particles, the SFD curves corresponding to successive FORCs should be superimposed in the range of commonly applied field. On the contrary, magnetic interactions produce a relative shift of these curves. When the magnetic interaction is positive (parallel to the source magnetization, as ferromagnetic exchange), the SFD curves are shifted to the left (in the direction of negative applied fields) for increasing values of $H_r$. In the case of negative interaction (as, for example, demagnetizing field), the shift is to the right (to larger applied fields) [2,6].

To clearly observe these variations, it is typical to plot the FORC distribution defined as

$$\rho\left(H, H_r\right) = -\frac{1}{2}\left(\frac{\partial^2 M}{\partial H \partial H_r}\right) \tag{3}$$

on the $H$-$H_\mathrm{r}$ plane. Frequently, this change of variables is done:

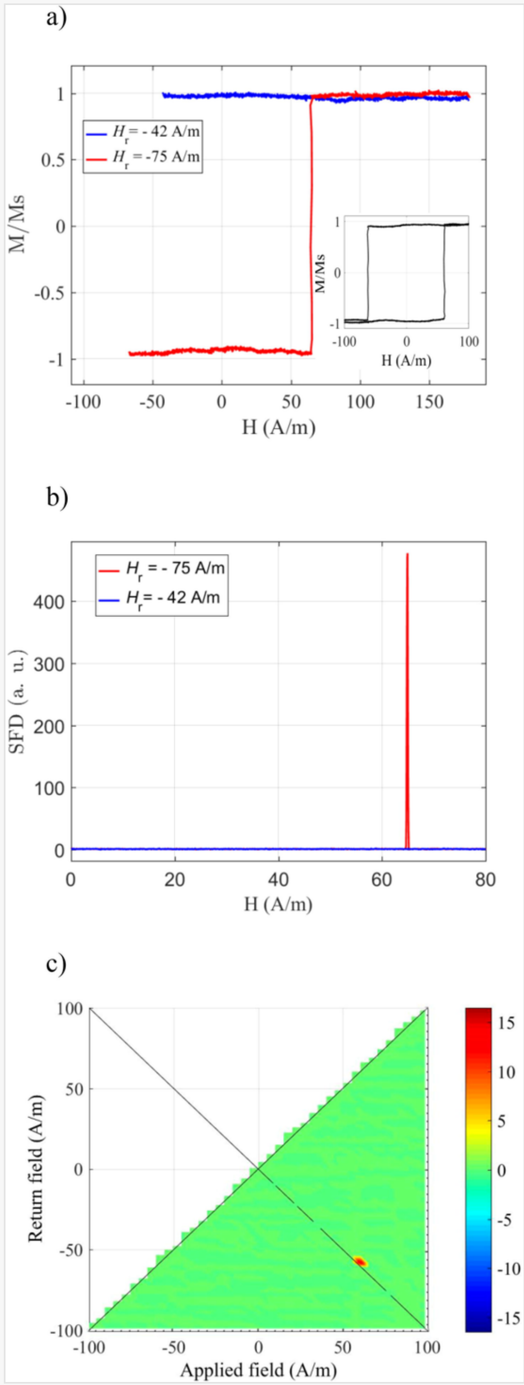
$$H_c = \frac{H - H_r}{2}; H_u = \frac{H + H_r}{2} \tag{4}$$

which practically produces a rotation of the FORC diagram by 45°. This practice is used to look for the correspondence between the FORC diagram and Preisach plane. In this paper we will use the $H$-$H_r$ representation.

# 3 Results and discussion

For a single Fe-based microwire the bi-stability is confirmed by the squareness of the hysteresis loop as shown in Fig. 2. The microwire presented a bi-stable behaviour at amplitudes up to 300 A/m and at frequencies up to 50 Hz. For larger values, the hysteresis loop loses its hysteron look as magnetization rotation appears.

Fig. 2

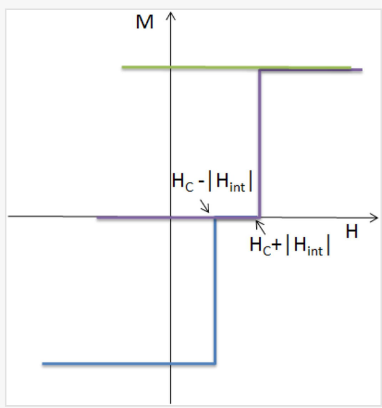



(a) two typical FORCs of an isolated MW; Inset: hysteresis loop of single microwire; (b) SFDs corresponding to the same hysteresis loop; (c) FORC diagram.

For a single MW (Fig. 2 (a)) the plot of the FORC set looks as expected: For $H_r > -H_c$ there is no switching of the magnetization, the curve is flat and the corresponding SFD is null (blue lines in Fig. 2 (b)) at all values of the applied field; for $H_r \leq -H_c$, the FORC starts at negative saturation and there is a Barkhausen jump at $H = -H_c$, which produces a peak in the corresponding SFD (in red). This change produces the only non-zero value in the FORC diagram at point ($H$ = 63 A/m, $H_r$ = −63 A/m), as can be seen in Fig. 2 (c). This is equivalent to a hysteron with $H_c$ = 63 A/m and $H_u$ = 0.

Two equal hysteron-like-microwires were used for analyzing the magnetic behavior for the coupled wires. To simulate the magnetostatic interaction of two parallel microwires, one should consider negative interaction. Then three types of FORCs are predicted, as can be seen in Fig. 3. Notice, that the first switching is produced before the coercive field of the individual MW at $H_{sw1} = H_{C1} = H_C - |H_{int}|$, and the second after it at $H_{sw2} = H_{C2} = H_C + |H_{int}|$. These shifts indicate the demagnetizing field of each microwire upon the other. This would be represented by two hysterons at points ($H_c$, $-|H_{int}|$) and ($H_c$, $|H_{int}|$) on Preisach plane, equivalent to ($H = H_c - |H_{int}|$, $H_r = -(H_c + |H_{int}|)$) and ($H = H_c + |H_{int}|$, $H_r = -(H_c - |H_{int}|)$) on the $H$–$H_r$ FORC diagram. The Preisach distribution, in this case, shows the two peaks of the distribution.

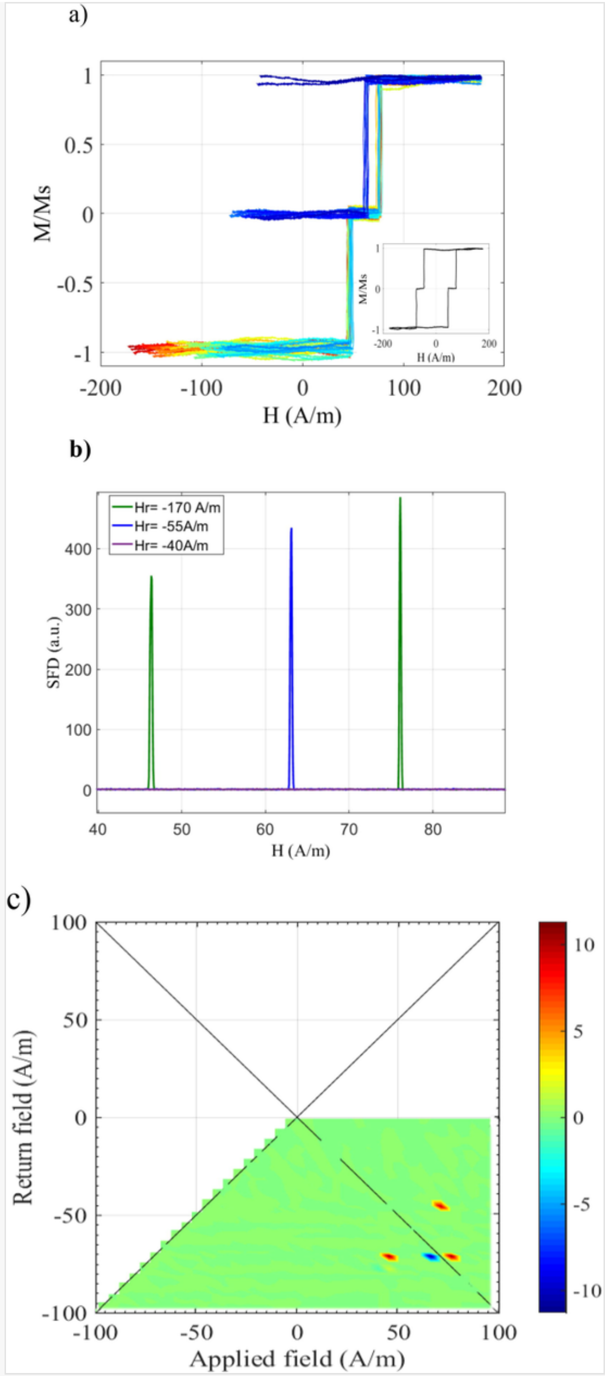
**Fig. 3**




Set of two magnetically interacted irreversible hysterons.

The FORC measurements (Fig. 4) on the system formed by two microwires glued together in parallel disposition show, as expected, three collections of curves (disregarding small fluctuations of the switching field due to random pinning by small defects and thermal activation [20]): (i) For $H_r > -46$ A/m the curves are flat, with both microwires always positively saturated; (ii) for $H_r < -76$ A/m, the FORCs present two switches at symmetrical fields, $Hs_{w1}$ = 46 A/m and $H_{sw2}$ = 76 A/m, indicating that the interaction field value is $H_{int}$ = 15 A/m; (iii) finally, for the intermediate return fields, −76 A/m < $H_r$ <−46 A/m, there is one magnetization switching at $H_{sw3}$ = 63 A/m.

**Fig. 4**




(a) FORCs of an array of two coupled microwires; Inset: hysteresis loop of the system of two microwires; (b) SFDs corresponding to the same FORCs; (c) FORC diagram.

But the difference between the experimental FORC in Fig. 4 (a) and the simulation in Fig. 3 is evident. In the ideal case, the expected value for $H_{sw3}$ would be equal to $H_{sw2}$. This separation may be explained by the effect of the domains at the end of the wires [21,22]. When the return field is in the range $-76$ A/m < $H_r$ < $-46$ A/m the domain wall of the first microwire has not reached the end of it. There is an unreversed region at the end of this wire that, when the field is increased, will help the magnetization of the rest of the wire to switch up. This switching field will be $H_{sw3} = H_c + H_{int} - H_{int2}$, where $H_{int}$ is the magnetostatic field originated at the second microwire, and $H_{int2}$ is the interaction field produced by the change in the magnetic structure at the ends of microwires – from increased closure domains.

Fig. 4 (b) shows examples of the SFD curves of these representative three types of FORC. Besides the expected curves with two peaks at $H$ = 46 A/m and 76 A/m, the peak at $H$ = 63 A/m (not at $H$ = 76 A/m) produces the unpredicted features in the FORC diagrams.

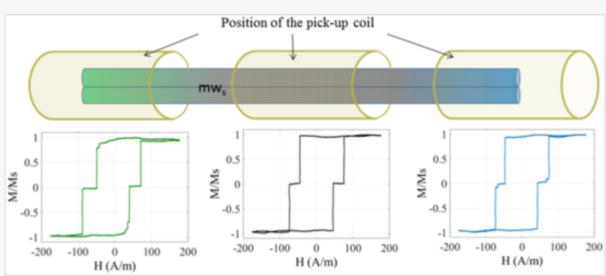
The two hysterons that would reproduce the hysteresis loop of our coupled wires would have coordinates $H_c$ = 61 A/m and $H_u$= ± 15 A/m on Preisach plane, that would translate into coordinates ($H$ = 76 A/m, $H_r$ = - 46 A/m) and ($H$ = 46 A/m, $H_r$ = - 76 A/m) on the FORC diagram. Experimentally, those two points appear at both sides of the diagonal line of the FORC diagram, but we see an additional pair of red-blue spots coming from the appearance and disappearance of the intermediate peak. This negative spots on the FORC diagram are a fingerprint of positive interactions, as pointed out by some previous works [19,23]. Pike, in their pioneering work of ref. [24], already précised that the appearance of negative regions on the FORC diagram made it difficult to name "distribution" to function "$\rho(H,H_r)$" in a strict way.

Not only the answer to the question if the bistable microwires can be associated with ideal hysterons is negative, but also the generalized use of hysterons to interpret the FORC diagram appears to be inadequate in at least those cases with positive magnetic interactions. Hence, researchers should also be cautious with the extended practice of calculating the magnetic interactions of the system as the bias field distribution (frequently referred to as the interaction field distribution).

In spite of this negative answer, FORC analysis reveals once again as tremendously useful to analyze the magnetic system of microwires and their interactions. Precisely the separation from the ideal FORC diagram evidences the non-bistable behaviour of the coupled wires, despite their bi-stepped hysteresis loop.

The latter is explained taking into account that the measurements are taken in the central region of the wires. A schematic view of the two wires and the hysteresis loops measured at both ends and in the middle region are shown in Fig. 5. According to the lateral loops, the domain wall of the first microwire that reverses magnetization is formed on the left side; this can explain the corresponding rounding of the left loop. In the second wire the domain wall is formed on the right side, as indicated by the discontinuous variation of the magnetization in the intermediate region of field, $-76$ A/m < H < $-46$ A/m. When the return field is also in this range, the second microwire is then not fully magnetized and the magnetostatic interaction with the first wire is reduced. Then, the switching of the first wire is produced at a smaller field.

**Fig. 5**




The hysteresis loops for the left (green), central (black) and right (blue) parts of the system of two coupled microwires. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

## 4 Conclusions

First order reversal curves analysis has been performed on single and coupled soft microwires with the twofold aim of checking their analogy to ideal magnetic hysterons and getting information on their mutual and internal magnetic interactions.

While the single microwire behaves as an ideal magnetic entity whose FORC diagram is identical to the expected Preisach plane, the combination of two parallel wires subjected to their mutual magnetostatic interaction is far from having the expected pattern. The particular features that distinguish the real sample pattern arise from the non-bistable behaviour of the interacting wires. The domain walls formed at the end of the microwires and the increase of the closure domains produce a reduction of the interaction effect. This creates on the FORC diagram a negative spot that is incompatible with its association to Preisach plane. Hence, the microwires cannot be physical realizations of magnetic hysterons.

Independent of this, FORC analysis proves to be an excellent tool to identify and separate the magnetic interactions within systems of bistable or quasi-bistable microwires, and FORC diagram a clear fingerprint of them.

## CRediT authorship contribution statement

**V. Kolesnikova:** Investigation, Data curation, Writing - original draft, Visualization, Writing - review & editing. **J.C. Martínez-García:** Methodology, Software. **V. Rodionova:** Conceptualization, Supervision, Writing - review & editing. **M. Rivas:** Conceptualization, Investigation, Data curation, Writing - review & editing, Software, Validation, Supervision.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Highlights

- A~~n rectangular~~bistable ~~hysteresis of the isolated single Fe-based~~ microwire was considered as an example of the magnetic hysteron~~ to study specifics of magnetic characteristics of real object, reflected~~ at FORC diagrams.
- The C~~lassical ~~P~~reisach model~~M of hysteresis was treated for the ~~system of two ~~magnetostaticaly interacted~~ Fe-based~~ microwires.
- ~~The system of two coupled bistable microwires cannot be considered as physical realizations of magnetic hysterons.~~ FORC diagram for real physical systems cannot be associated to Preisach plane.

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