

Research Article

Controlling the domain wall dynamics in Co-rich magnetic microwires with graded magnetic anisotropy

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ABSTRACT

We have shown after annealing Co-rich microwire in a temperature gradient, graded magnetic anisotropy is observed. In studied microwires annealed at variable temperatures, a gradual change in hysteresis loops along the length of the microwire from inclined to perfectly rectangular is observed. Accordingly, the remagnetization process along the length of such wires changes its character. In Co-rich microwire segments with squared hysteresis loops, single domain wall propagation is observed. At the same time the magnetization rotation is observed in the region with an inclined hysteresis loop. The domain wall propagation in Co-rich microwire with graded magnetic anisotropy is essentially non-uniform. A single domain wall propagates at a non-uniform speed in the region of the wire with graded magnetic anisotropy. At a certain position of the microwire with graded anisotropy inside the magnetization coil, the direction of the domain wall propagation changed to the opposite. The domain wall velocities differ significantly for cases where the magnetization switching starts from a region with graded magnetic anisotropy or from a region with rectangular hysteresis loops. The observed features of the domain wall dynamics in Co-rich microwires with graded magnetic anisotropy are discussed, taking into account the domain wall inertia and changes in the demagnetizing field during magnetization reversal.

1. Introduction

Efficient control of domain wall (DW) dynamics in elongated nanostructures has become a challenge in fundamental physics, given a number of technological applications related to magnetic memory and magnetic logic devices [1–5]. Thus, substantial efforts have been made to control a single DW propagation in magnetic wires by injection from a magnetically soft region connected to the end of the wire, by controlling the edge roughness, by transverse magnetic field or DWs pinning at artificially created defects [6–8].

One the routes for effective DW dynamics control is a design of materials with either graded magnetic anisotropy or multisegmented magnetic nanowires [9–12]. In these cases, the DW propagation can be effectively manipulated through different magnetic anisotropy characteristics in different parts of magnetic materials. On the other hand the

DW velocity is one of the relevant parameters for proposed technological applications involving DW propagation. Typically, the DW velocity, v , up to 100 m/s is reported in planar nanowires [4,8]. However, higher DW velocities (typically up to 1000 m/s) have been reported in cylindrical amorphous micrometric wires [14,15]. Such v -values can be further improved by either annealing or by minimization of the magnetoelastic anisotropy through the selection of the chemical composition with a low magnetostriction coefficient, λ_s , value [15].

Several attempts have been reported to control the DW propagation in amorphous microwires, such as controllable DW pinning by local antiparallel magnetic field or by controllable DW collision [16,17]. Aforementioned amorphous magnetic wires can be prepared by several fabrication methods, such as in-rotating water, melt extraction of Taylor-Ulitovsky methods [18–25]. The common feature of all these methods is that all of them involve rapid quenching from the melt,

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allowing to obtain glassy-like (amorphous) structure at room temperature. Amorphous magnetic materials exhibit quite unusual combination of extremely soft magnetic properties [19,22,26], excellent mechanical properties [21,23,26] and relatively simple and fast fabrication technology [19–26].

One of the common features of amorphous wires is that they can exhibit spontaneous magnetic bistability characterized by perfectly rectangular hysteresis loops originated by a remagnetization process through a single and large Barkhausen jump between two remanent states with opposite magnetization. In such wires the demagnetized state cannot be observed: once the applied magnetic field achieves a critical value (usually called as switching field), the magnetization switches between two remanent states) through a fast DW propagation [15,19,20,27]. The highest v -values (up to 4500 m/s) are reported in magnetic microwires prepared using Taylor-Ulitovsky method [28–30].

The latter (Taylor-Ulitovsky) fabrication method is suitable for fast (about 100 m per minute) and inexpensive fabrication of perfectly cylindrical magnetic amorphous wires with most extended diameters range: from submicrometric (0.1 μm) to 100 μm diameters (i.e., four orders of magnitude) [13,24,31]. Magnetic wires prepared by this method are provided with a flexible and insulating glass coating, which can remarkably enhance corrosion and even mechanical properties and thus extend the possibilities of applications [24,32,33].

Extremely fast DW propagation in magnetic microwires has been a subject of intensive research over the past two decades [28–30,34,35]. For applications involving DW propagation, not only the v -values are relevant, but also the degree to which the DW propagation can be manipulated. However, there are very few experimental studies on the controllable DW dynamics in amorphous microwires in which the nearly supersonic v -values have been already achieved [16,17]. Recently, we proposed a rather simple method for obtaining graded magnetic anisotropy in Fe-rich magnetic microwire using stress-annealing in temperature gradient [36–38]. This method is based on the substantial dependence of the magnetic anisotropy of Fe-rich microwires on the annealing temperature and stress during stress-annealing. Previously, aforementioned graded magnetic anisotropy was obtained using rather sophisticated techniques involving the change of the chemical composition during the fabrication process [11,12]. Generally, the development of magnetic materials with graded anisotropy has attracted remarkable attention due to the possibilities of precise control and continuous magnetic anisotropy changing in various materials and the obtaining of diverse magnetic structures [11,12,39–41]. Development of graded magnetic materials is an effective tool for precise control of the switching fields, development of depth-dependent ferromagnetic/antiferromagnetic interfaces, in-plane and out-of-plane components of magnetization, continuous modification of the exchange coupling constant, internal quasi-phase boundaries separating ordered from disordered magnetic regions within the same ferromagnetic graded sample etc [39–42]. Accordingly, development of magnetic materials with graded properties represent a promising new avenue in modern material science [39]. In particular, theoretically predicted and experimentally shown, that the DW propagation in such microwires with graded magnetic anisotropy can be effectively controlled [9,36,37]. Particularly, we showed that graded magnetic anisotropy obtained using stress-annealing of Fe-rich microwires in a temperature gradient can be effectively used for controlling the DW dynamics in such Fe-rich microwires. Evidently, such method allowing fast and simple preparation of Fe-rich magnetic microwires with graded magnetic anisotropy and hence effective control of DW propagation is much simpler than previously reported rather complex techniques involving a change in the chemical composition during the fabrication process [10–12,39–42].

On the other hand, we recently reported that annealing (without stress) allows to obtain perfectly rectangular hysteresis loops in Co-rich glass-coated microwires [15,28]. In such Co-rich microwires with annealing-induced magnetic bistability, the highest v -values and even current-induced DW propagation were reported [15,28]. As pointed out

in very recent publications, in Co-rich glass-coated microwires, a graded anisotropy can be induced in an even simpler way: by conventional furnace annealing (without stress) in a temperature gradient [38,43]. The origin of such graded anisotropy is due to the substantial dependence of the hysteresis loops shape of Co-rich glass-coated microwires on the annealing temperature [38,43].

In this paper we report on recent experimental results on the control of the DW propagation in Co-rich microwire with graded magnetic anisotropy.

2. Experimental

We investigated the effect of temperature gradient annealing on magnetic properties and DW dynamics in Co-rich $\text{Co}_{69.2}\text{Fe}_{3.6}\text{Ni}_1\text{B}_{12.5}\text{Si}_{11}\text{Mo}_{1.5}\text{C}_{1.2}$ (metallic nucleus diameter $d = 19.8 \mu\text{m}$, total diameter $D = 23.2 \mu\text{m}$) glass-coated microwire fabricated by Taylor-Ulitovsky technique described in details elsewhere [26,32,44]. Briefly, the fabrication process consists of melting the metallic alloy inside a glass tube (Duran) using an inductor heater, drawing a glass capillary from the softened glass, and finally drawing a glass-coated microwire and winding it on a rotating bobbin [26,32,44]. A coolant jet is used to increase the quenching rate and obtain such microwires in amorphous state. This method makes it possible in a few minutes to prepare fairly long (up to several km long) continuous metallic microwires coated by an insulating glass shell [26,32,44]. The image of the samples (obtained using Zeiss Gemini 500 Field Emission Scanning Electron Microscope) is provided in Fig. 1a.

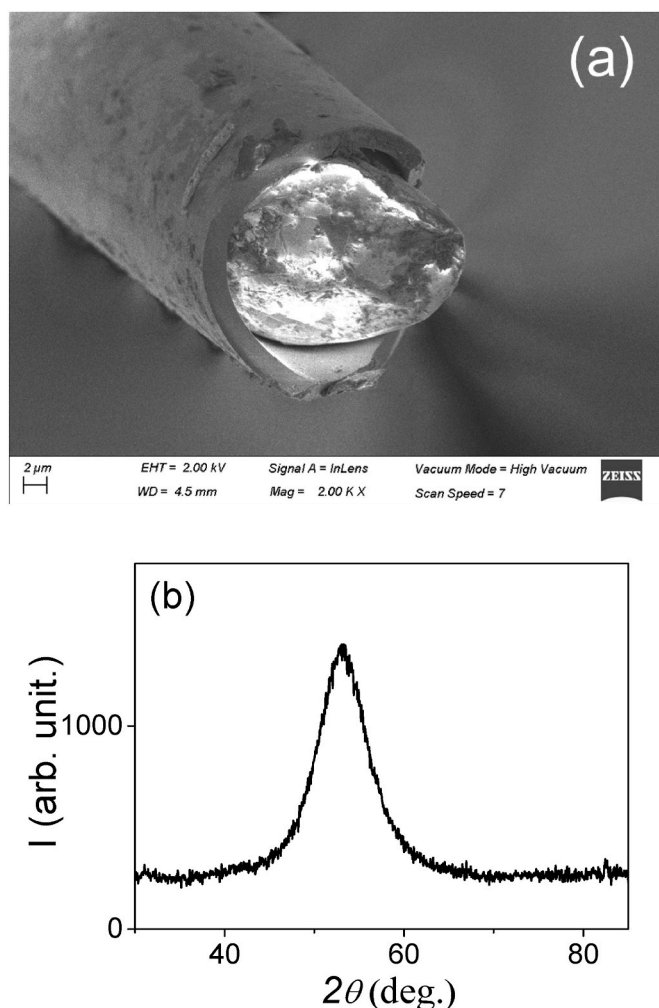


Fig. 1. SEM image (a) and XRD pattern (b) of studied sample.

The amorphous structure of studied microwire is confirmed by broad halo in X-ray diffraction (XRD) pattern obtained using a BRUKER (D8 Advance) X-ray diffractometer with $\text{CoK}\alpha$ ($\lambda = 1.54 \text{ \AA}$) radiation (see Fig. 1b).

We used the fluxmetric method to measure the hysteresis loops of the studied sample, using a setup developed and successfully employed for the characterization of soft magnetic thin wires [45]. Initially, the experimental setup was designed to measure a long (10 cm) microwire placed in a thin (about 8 mm in diameter) and long (120 mm) solenoid producing a uniform magnetic field H . Additionally, as recently described, we used a modified experimental setup in which local hysteresis loops in different parts of studied microwires were measured using a short (2 mm long) moving pick-up coil [37,38]. For comparison, the hysteresis loops of the studied samples were presented as magnetic field, H , dependencies of normalized magnetization M/M_0 (being M and M_0 the magnetic moments at a given and at maximum H -values, respectively).

Studied samples were annealed in a conventional furnace (Thermolyne 62700). Similarly to any real furnace, in used furnace exists a temperature profile, characterized by a zone with constant temperature and temperature gradient [46,47]. Using a standard (NiCr–Ni) thermocouple, moving it along the studied microwire, we experimentally determined the temperature distribution in the furnace (see Fig. 2). As shown in Fig. 2, there is a zone with a constant temperature, T , and a zone with T gradient close to the furnace wall.

For evaluation of the influence of annealing temperature, T_{ann} , on hysteresis loops of studied samples we annealed the samples in a zone with a constant temperature, T . While, to study the effect of annealing in T gradient, a part of the 160 mm long microwire was also annealed in the zone with T gradient (see Fig. 2). In this case, segments of the microwire placed closer to the furnace wall were annealed in the T -gradient. While part of the microwire located in the central zone of the furnace was annealed at a constant T .

To measure the DW velocity, v , we used the Sixtus-Tonks-like experimental scheme, successfully employed to study the DW dynamics of thin magnetic wires [15,17,28]. The experimental setup has been described in detail previously [15,17,28]. In this setup a uniform magnetic field is created by a long solenoid. Inside such a solenoid, three pick-up coils are placed, located along the studied microwire, at the same distance, l . One end of the studied microwire is placed outside the magnetizing coil to ensure the propagation of the single DW from the opposite sample end [15,17,28]. The travelling DW induces the

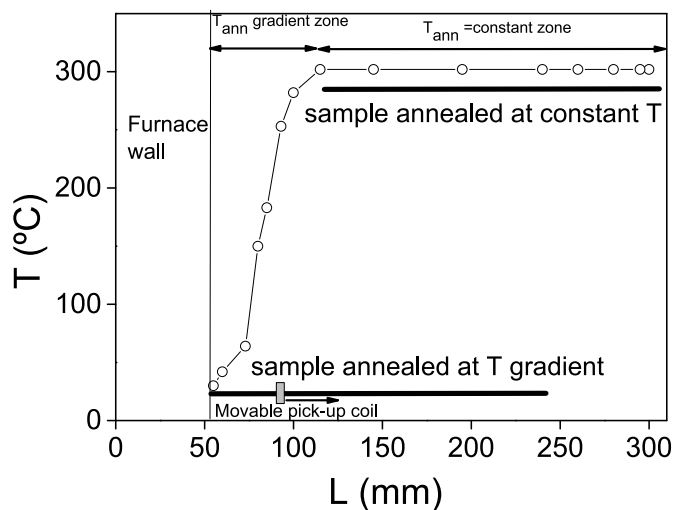


Fig. 2. Experimentally determined temperature profile measured at a furnace temperature set to 300 °C using (NiCr–Ni) thermocouple and schematic representation of a microwire with segments annealed in a T gradient and annealed at $T = \text{const}$.

electromotive force, EMF , peaks in the pick-up coils. The v -values can be estimated from the time difference, Δt , between the EMF peaks, induced by the propagating DW, as:

$$v = \frac{l}{\Delta t} \quad (1)$$

3. Results and discussion

The hysteresis loop of as-prepared and heat treated in constant temperature, T ($T = \text{const}$) zone samples, at $T_{ann} = 250 \text{ °C}$ and 300 °C are provided in Fig. 3. As can be seen from Fig. 3, the hysteresis loops depend significantly on T_{ann} . After annealing at high enough T_{ann} , the hysteresis loops become perfectly rectangular (see Fig. 3). A similar effect of annealing on the hysteresis loops of Co-rich glass-coated microwires with vanishing negative λ_s -values has been previously reported [48,49]. Accordingly, as shown in Fig. 4a–f, in the microwire annealed at T gradient, a gradual change in local hysteresis loops along the microwire was obtained. The local hysteresis loops change from almost linear (in the zone annealed at low T_{ann}) to perfectly rectangular (annealed at a sufficiently high T_{ann}). Such local hysteresis loops were measured using a short pick-up coil moved along the microwire. Each hysteresis loop was measured at different position, l , along the microwire annealed at T gradient. Fig. 4a–f shows the most representative hysteresis loops. Observed modification in local hysteresis loops (measured at different l) correlates with the change in T_{ann} along the sample (shown in Fig. 1) during annealing at T gradient. The schematic representation of the microwire with graded magnetic anisotropy is shown in Fig. 4g.

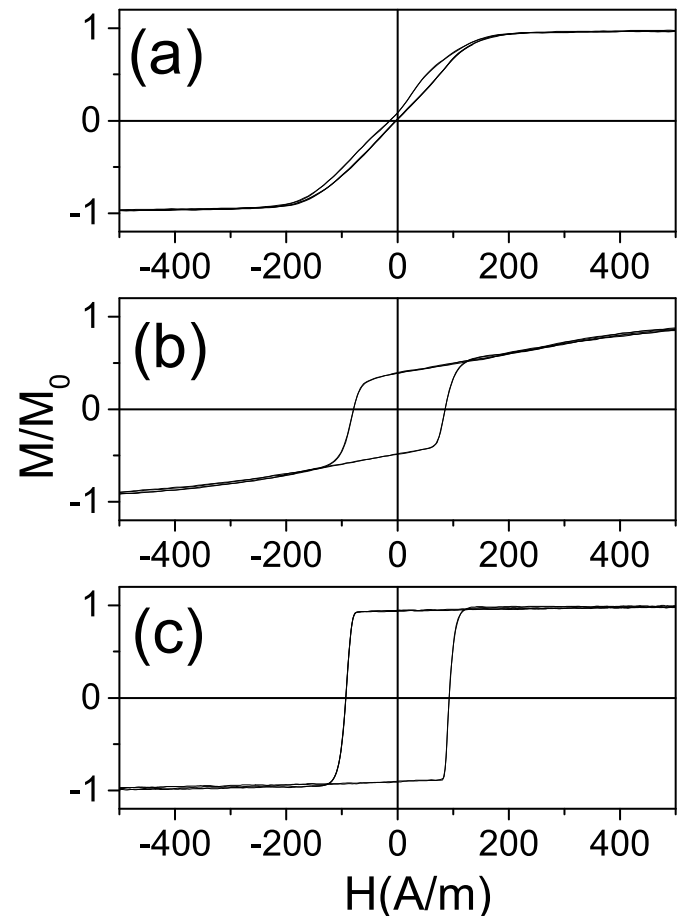


Fig. 3. Hysteresis loops of as-prepared (a) annealed at $T_{ann} = 250 \text{ °C}$ (b) and $T_{ann} = 300 \text{ °C}$ sample (c).

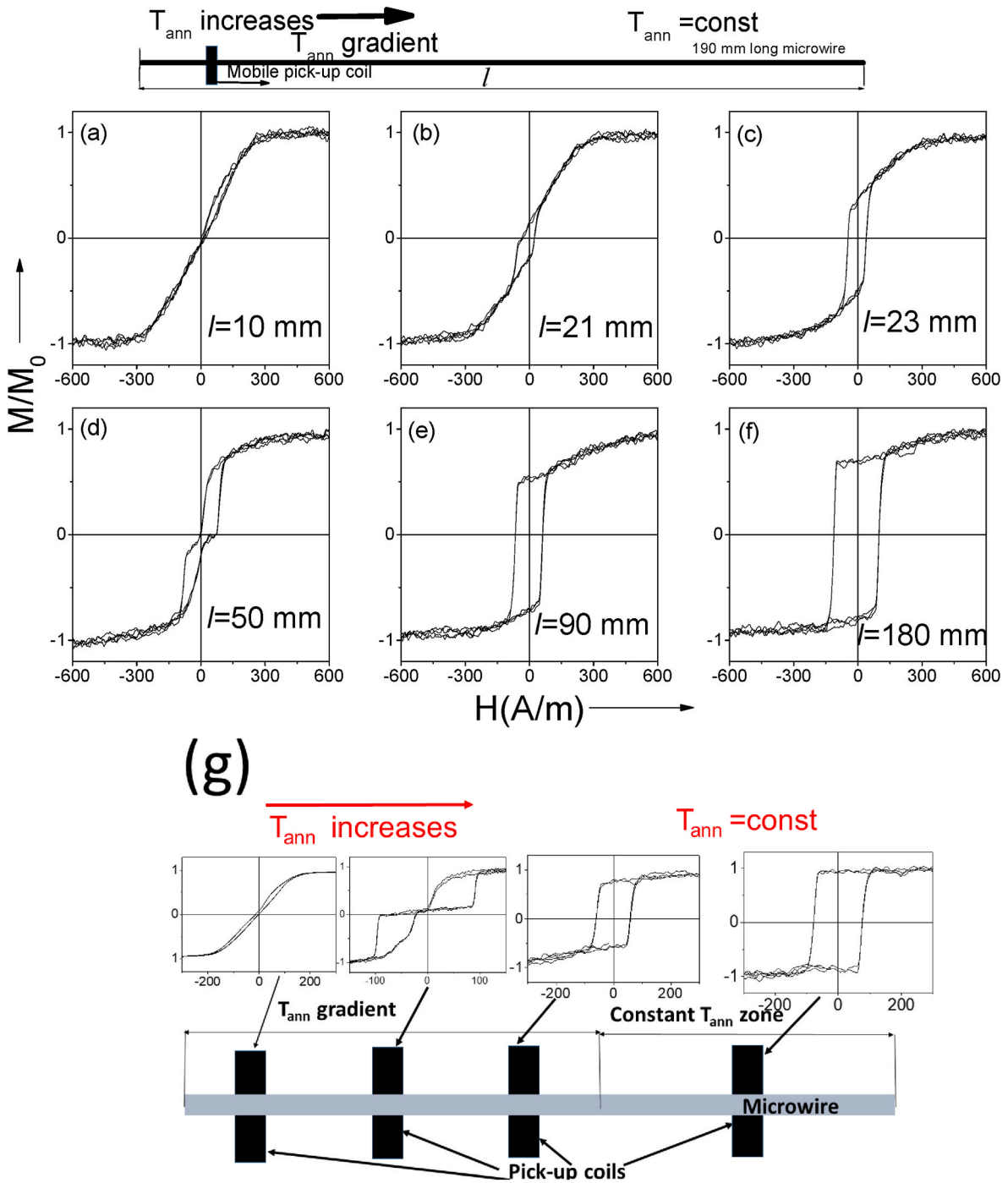


Fig. 4. Local hysteresis loops of studied microwires annealed in T -gradient measured by short movable pick-up coil at $l = 10$ mm (a), $l = 21$ mm (b), $l = 23$ mm (c) and $l = 50$ mm (d) $l = 90$ mm (e) $l = 180$ mm (f) and the scheme of the graded magnetic anisotropy appearing as a continuous magnetic anisotropy gradient over the sample length after annealing in T gradient (g).

As observed from Fig. 4a–f, substantially different local hysteresis loops (measured by movable short pick-up coil at different position, l , along the microwire) are obtained in the microwire, annealed in T -gradient. A gradual change in the hysteresis loops from nearly linear (typical for as-prepared Co-rich microwires) to perfectly rectangular along the sample length is observed. This transformation of local hysteresis loops correlates with a change in T_{ann} and must be attributed to the different character of the remagnetization process: from magnetization rotation (for as-prepared and annealed at low T_{ann} sample segments) to DW propagation (for those annealed at a sufficiently high T_{ann}). The most unusual hysteresis loops are observed at intermediate l -

values, i.e. at $l = 50$ mm (see Fig. 4d). The stepped hysteresis loop shape observed at $l = 50$ mm can be explained by the superposition of contributions from both magnetization rotation (typically reported for as-prepared Co-rich microwires with an inclined hysteresis loop) and remagnetization by DW propagation (as in the annealed Co-rich microwires with magnetic bistability induced by annealing). Finally, almost perfectly rectangular hysteresis loops are obtained for $l \geq 90$ mm (see Fig. 4e and f)

Accordingly, the microwire annealed in T_{ann} gradient exhibits spatial variation in local hysteresis loops, i.e. graded magnetic anisotropy.

As expected from perfectly rectangular hysteresis loops of studied

samples annealed at high enough T_{ann} , the remagnetization of these samples runs by single DW propagation. Observation of single DW propagation in Co-rich microwires with magnetic bistability induced by annealing was also reported previously [49,50]. Using experimental setup described above, we can measure DW velocity between pick-up coils 1 and 2 and 2 and 3, v_{1-2} and v_{2-3} respectively. In the segments of studied sample annealed at $T_{ann} = \text{const}$ observed $v_{1-2}(H)$ and $v_{2-3}(H)$ dependencies are linear and v_{1-2} and v_{2-3} values are almost the same (see Fig. 5a). Such $v(H)$ dependencies are typical for a viscous regime, where $v(H)$ dependence is described in terms of DW mobility, S as [1,51]:

$$v = S(H - H_0) \quad (2)$$

where H_0 is the critical propagation field.

Such linear $v(H)$ dependence is predicted for H -values below the Walker breakdown field, H_W [51].

However, although in the sample segment annealed in the T_{ann} gradient, the $v_{1-2}(H)$ and $v_{2-3}(H)$ dependencies are also linear, the observed v_{1-2} and v_{2-3} values differ substantially (see Fig. 5b).

Such difference in the observed v_{1-2} and v_{2-3} values must be attributed to observed graded anisotropy. From Fig. 5 it is evident that the DW travels with a non-uniform velocity, v , in segments of the microwires with graded anisotropy.

The relationship between v and H within the Walker model, v , is given as [51]:

$$v = \left(\frac{2\pi\gamma\Delta}{\alpha} \right) H \quad (3)$$

where γ is the gyromagnetic ratio, α is the magnetic damping parameter Δ - DW width. Therefore, non-uniform DW propagation characterized by change in v must be attributed to change in Δ and hence change in

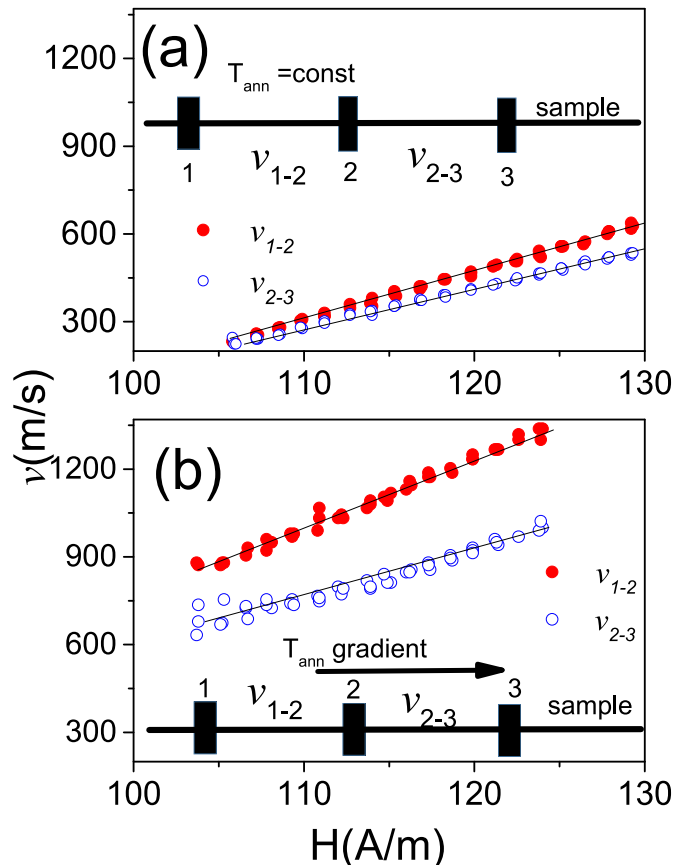


Fig. 5. $v(H)$ dependencies in microwire segments annealed at constant T_{ann} (a) and in T_{ann} gradient (b), 1,2,3 are the pick-up coils.

magnetic anisotropy along the sample length.

With exception of Fig. 4d, where the hysteresis loop has irregular shape, the modification of the local hysteresis loop with T_{ann} consists in increase of remanent magnetization, M_r/M_0 , and coercivity, H_c . Dependencies of M_r/M_0 and H_c on position along the sample length, l , evaluated from Fig. 4 are shown in Fig. 6.

The domain structure of magnetic wires (which allows to explain main features of magnetic wires, such as magnetic bistability or Giant magnetoimpedance, GMI effect) is commonly discussed in terms of the core-shell model assuming that there is an inner axially magnetized single domain surrounded by an outer domain shell with a transverse magnetization orientation (either radial or circular) [19,20,28,52]. Such domain structure was experimentally confirmed in glass-coated microwires of different chemical compositions [53,54]. The radius of the inner axially magnetized core, R_c , can be estimated in terms of the core-shell model of the domain structure of magnetic wires with a rectangular hysteresis loop from M_r/M_0 , as [19,28]:

$$R_c = R(M_r/M_0)^{1/2} \quad (4)$$

where R is the radius of microwire.

From experimentally obtained $M_r/M_0(l)$ dependence, shown in Fig. 6a, we evaluated $R_c(l)$ dependence in the sample segment with graded magnetic anisotropy (see Fig. 6b). As follows from Fig. 6b, in a microwire annealed in a T_{ann} gradient, a gradual change in the domain structure along the microwire occurs, consisting of a change in R_c . For the samples segments annealed at high enough T_{ann} , R_c (8.6 μm) becomes close to R (9.9 μm). Lower R_c - values must be related to thicker outer domain shell with transverse magnetic anisotropy. Recently was reported that such outer domain shell with transverse magnetic anisotropy affects the DW dynamics in a similar way as the transverse magnetic field, i.e. allows to achieve higher v -values [55]. Therefore, higher v -values observed in the sample segments with graded magnetic anisotropy must be attributed to the contribution of outer domain shell with transverse magnetic anisotropy.

In most of previous publications, to ensure single DW propagation, one end of the studied microwires was located outside the magnetizing coil [15,30] or several types of coils were used (i.e., starting and blocking coils apart of magnetizing coil) [56]. As evidenced from Figs. 4 and 6, softer magnetic properties (lower H_c) are obtained in the sample segment with graded anisotropy. Consequently, the single DW propagation in such microwire with graded magnetic anisotropy runs from a sample segment with lower H_c , as evidenced by the sequence of the peaks of electromagnetic force, EMF , appearing first in the pick-up coil 1 closest to the sample segment with graded anisotropy (see Fig. 7a).

This character of DW propagation (the direction of DW propagation) can be changed if the opposite end of the sample is inserted inside the magnetizing coil, while the sample segment with graded magnetic anisotropy is taken outside the magnetizing coil (see Fig. 7b). As evidenced from Fig. 7b, the sequence of the EMF peaks has changed and, hence, in this case the DW travels in the opposite direction.

One more interesting feature of observed $v(H)$ dependencies is that the v -values are substantially different for two studied aforementioned cases (see Fig. 7c and d). The v_{1-2} and v_{2-3} values for the case when the DW travels from the sample segment with graded anisotropy are almost double higher than in the case when the DW releases from the segment annealed at $T_{ann} = \text{const}$. The difference in the $v_{1-2}(H)$ and $v_{2-3}(H)$ dependencies shown in Figs. 5 and 7 is that the $v_{1-2}(H)$ and $v_{2-3}(H)$ dependencies, shown in Fig. 7c, are measured in a sample segment annealed at $T_{ann} = \text{const}$, whereas the $v_{1-2}(H)$ and $v_{2-3}(H)$ dependencies shown in Fig. 5b are measured in the sample segment annealed in the T_{ann} gradient. However, after the DW release and initial propagation in a sample segment annealed in the T_{ann} gradient, the DW moves faster even in the rest of the sample (annealed at $T_{ann} = \text{const}$). In several previous publications the so-called "unidirectional" effect, consisting in different v -values for DW with different magnetic history [29,56]. Although the

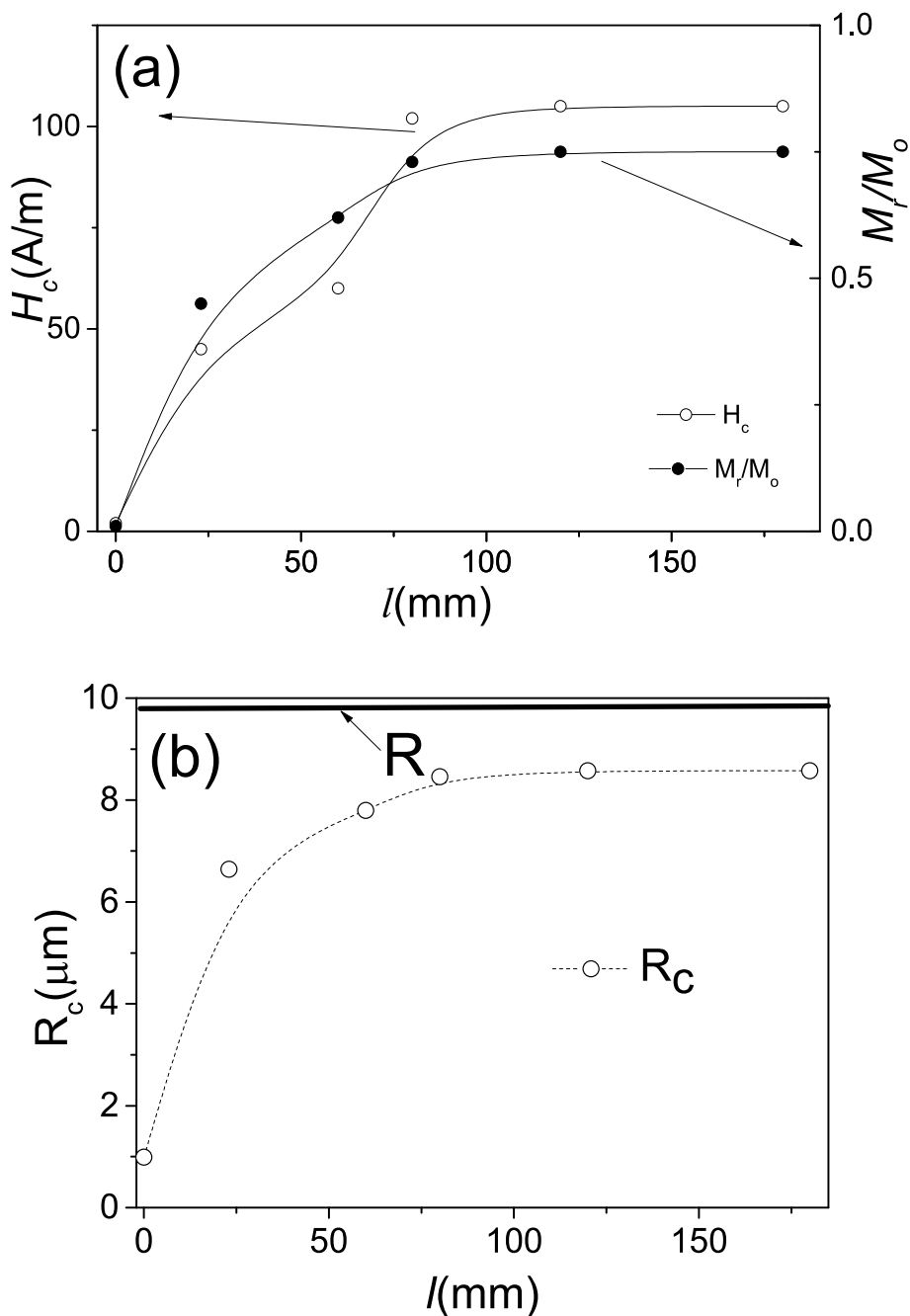


Fig. 6. $M_r/M_0(l)$ and $H_c(l)$ dependencies of studied sample with graded anisotropy (a) and $R_c(l)$ evaluated from $M_r/M_0(l)$ dependence (b).

origin of “unidirectional” effect is not yet clear, there are several factors, such as defects the concentration and origin [57] as well as the magnetoelastic contribution [35], that affect the DW dynamics in microwires.

It is worth mentioning that there are several models for the spatial structure of the propagating DW in amorphous microwires [15, 56, 58, 59]. For Fe-rich microwires with spontaneous magnetic bistability, it was found that such DW is essentially not abrupt and present rather complex shape with quite extended characteristic DW width, δ_w , several times exceeding microwire diameter, d [59,60]. Additionally, δ_w/d is affected by the magnetic anisotropy as well as by H -value. Extremely high ν -values are also explained by such extended size of the propagating DW since the axial velocity related to the axial velocity by a factor R_c/δ_w and could be up to 2 orders of magnitude lower than axial DW velocity, ν .

As previously was discussed [58,59], by analyzing the EMF peaks in the pick-up coils, one can evaluate the characteristics of the travelling DW. Thus, the characteristic DW width, δ_w of a uniformly propagating DW can be evaluated from the pulse duration, τ , as $\delta_w = \nu\tau$. Although for a rigorous evaluation the pick-up coil must be single turn, some information can be extracted from a comparison of the EMF peaks measured in the same setup. As can be observed from Fig. 7a and b, the EMF peaks in the pick-up coils are rather wide. Below we provide a comparison of the DW characteristics from the EMF peaks observed in the studied Co-rich microwire with annealing-induced by annealing magnetic bistability and the as-prepared Fe-rich microwire ($d \sim 15.2 \mu\text{m}$) with spontaneous magnetic bistability, previously studied by us [55]. The $\nu(H)$ dependence for as-prepared Fe₇₅B₉Si₁₂C₄ microwire is provided in Fig. 8a. The pulse duration, τ , for the studied Co-rich microwire is about 2×10^{-5} s (0.02 ms) at $\nu \sim 800$ m/s, whereas in Fe-rich microwire $\tau \sim 1.2$

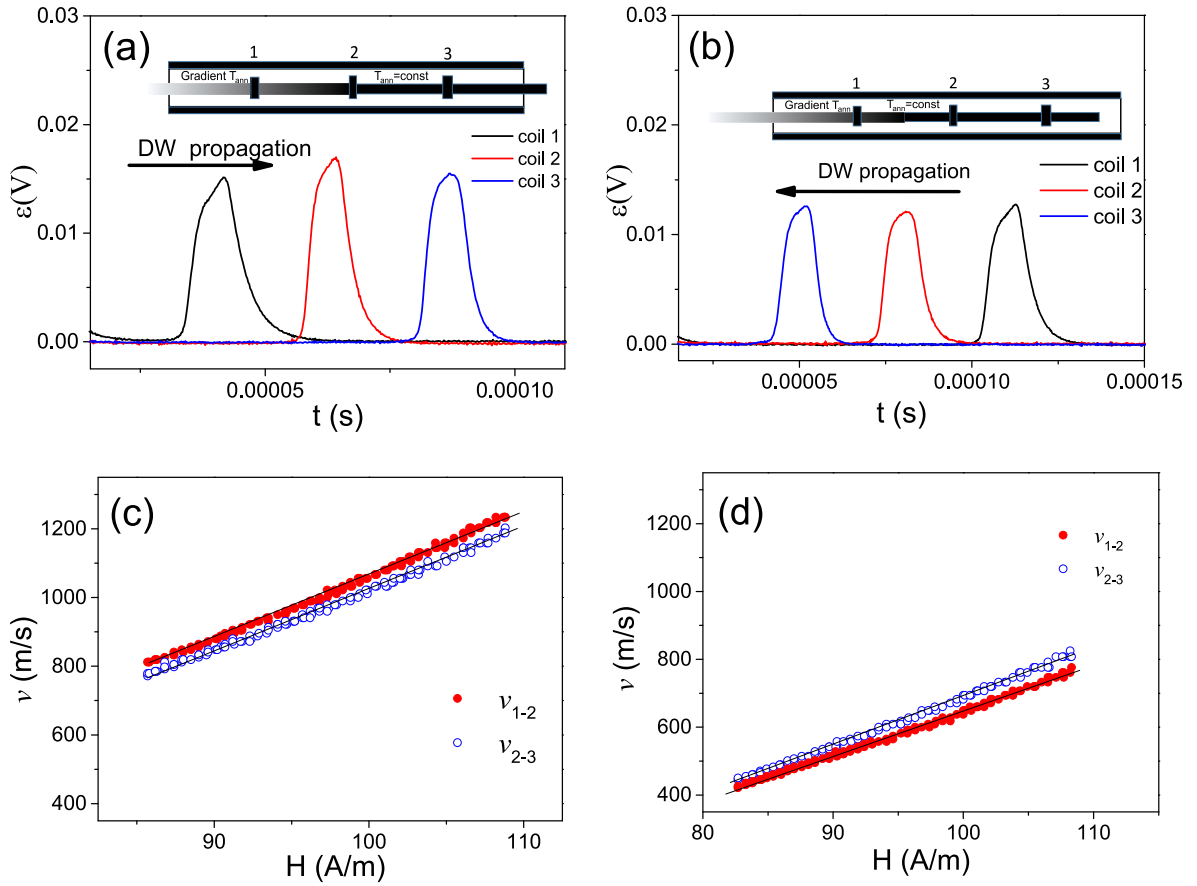


Fig. 7. Sequences of the EMF peaks for the sample inserted symmetrically in the experimental setup (a) and when the sample segment with graded anisotropy is taken outside the magnetized coil (b) and $v(H)$ dependencies measured for these cases (c,d).

$\times 10^{-5}$ s (0.012 ms) for $v \approx 320$ m/s (see Fig. 8b). A rough estimation for the studied Co-rich microwire gives $\delta_w \sim 1.6$ cm. A similar evaluation for Fe-rich microwires gives $\delta_w \sim 0.4$ cm.

Accordingly, in the studied Co-rich microwire, the propagating DW width is almost 4 times higher than for Fe-rich microwires. Such difference can be attributed to the relation of the DW width, δ_w , and magnetic anisotropy constant, K , given by:

$$\delta_w \sim (A/K)^{1/2} \quad (5)$$

where A is the exchange stiffness constant.

As mentioned above in the amorphous materials main origin of magnetic anisotropy the magnetoelastic anisotropy, K_{me} , is determined by the magnetostriction coefficient, λ_s , and the internal stress, σ_i , as [8, 11,12]:

$$K_{me} \approx 3/2 \lambda_s \sigma_i, \quad (6)$$

Considering that in Fe-rich microwires $\lambda_s \approx 35 - 40 \times 10^{-6}$, and for the studied Co-rich microwires $\lambda_s \approx 10^{-6}$ [45,49,50], such difference in δ_w -values in studied microwires seems reasonable.

In previous publications higher v -values have been reported in magnetic microwires with transverse character of magnetic anisotropy in the outer domain shell, given that transverse magnetic anisotropy affects the DW dynamics in similarly to an applied transverse magnetic field [37,55].

As mentioned above, the DW propagation in the segment with graded magnetic anisotropy is not uniform. Therefore, the DW mass, M_d , may affect the DW dynamics [61–64].

The M_d is given as [64,65]:

$$M_d = \frac{2}{\mu_o \gamma^2 \Delta} \quad (7)$$

where γ is the magnetomechanical ratio.

Indeed, previously the magnetic field driven DW dynamics is described in terms of linear harmonic oscillator, as [66–70]:

$$M_d \frac{d^2 x}{dt^2} + L \frac{dx}{dt} + Kx = 2\mu_o M_s H \quad (8)$$

being L -damping coefficient, K -elastic coefficient, x -domain wall displacement and $\mu_o M_s$ - saturation magnetization. When the DW propagation is uniform, the first term of (8) is usually neglected [66,69]. However, as shown above, in the segment with graded anisotropy the DW propagation is essentially non-uniform and observed v -values are substantially higher. Therefore, one can suggest that once high enough DW velocity is achieved in the segment with graded anisotropy, the DW velocity continue moving at higher velocity even in the rest of the sample due to the DW inertia. The relevant effect of the DW inertia on DW propagation is pointed out elsewhere [70].

On the other hand, the higher v - and S - values observed in Co-rich microwires should be attributed to lower K_{me} due to the order of magnitude lower λ_s -values [35].

One more general observation from Fig. 7c and d is that the v -values at the beginning of the DW propagation (obtained from the first pair of the pick-up coils) are slightly higher than the v -values obtained from the second pair of the pick-up coils, i.e. $v_{1-2} > v_{2-3}$ (Fig. 7c) and $v_{2-3} > v_{1-2}$ (Fig. 7d). The observed difference is systematic and the difference in v -values is about 40–50 m/s (see Fig. 7c and d). One of the reasons for such difference in v -values is that the DW dynamics can be affected by the change in demagnetizing field of the sample during the DW propagation

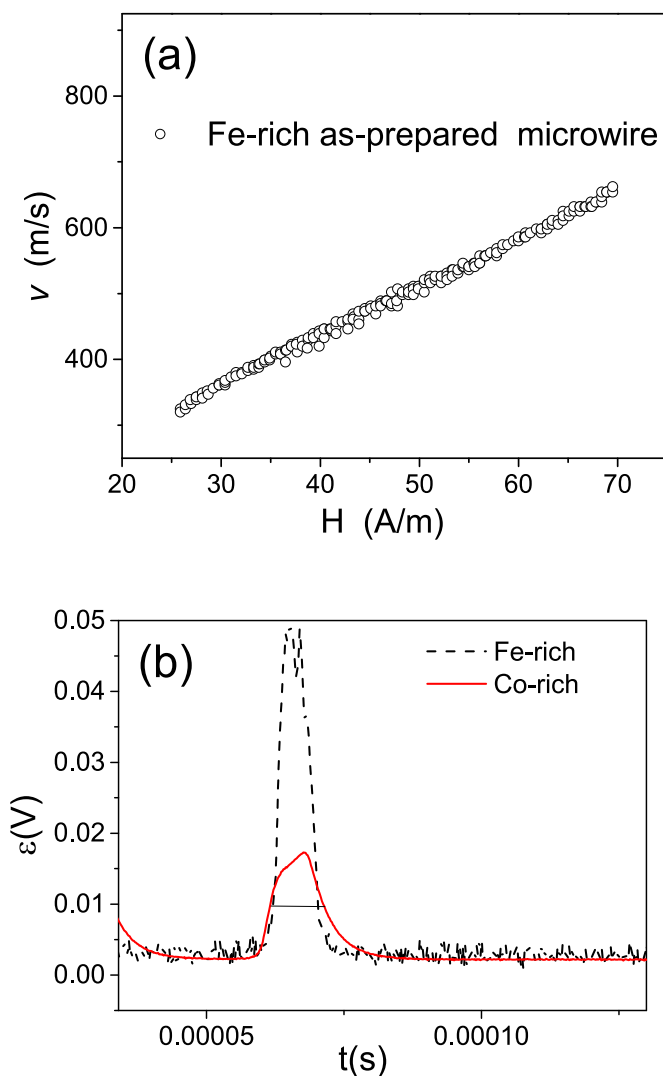


Fig. 8. $v(H)$ dependence of as-prepared $\text{Fe}_{75}\text{B}_9\text{Si}_{12}\text{C}_4$ microwire (a) and the EMF peaks for the studied Co-rich microwire with annealing-induced magnetic anisotropy and as-prepared $\text{Fe}_{75}\text{B}_9\text{Si}_{12}\text{C}_4$ microwire (b).

[71]. Indeed, the magnetic field driven DW dynamics is determined by the superposition of the magnetic field created by the solenoid and the demagnetizing field of the axially magnetized single domain. The latter continuously change during the magnetization switching due to change in the size of the axially magnetized domain with the opposite magnetization orientation. More detailed analysis of such contribution originated by the stray field on the DW velocity is provided in our recent studies [72].

Summarizing the observed dependencies, we demonstrated that annealing of Co-rich microwires in T -gradient can be useful for obtaining microwires with graded magnetic anisotropy and effective controlling of the DW propagation. Annealing in a temperature gradient is a fairly simple tool suitable for a large amount of microwires without the use of complex technological processes, like controlled deposition with changing the chemical composition or varying the sputtering pressure [11,12,73]. Unlike Fe-rich microwires where stress annealing in T -gradient is required to obtain graded magnetic anisotropy, in Co-rich microwires graded anisotropy can be obtained in an even simpler way using furnace annealing (without stress) in a temperature gradient.

4. Conclusion

Annealing in a temperature gradient allows to design graded

magnetic anisotropy in Co-rich magnetic microwires. In such microwires, a gradual variation of the hysteresis loops along the microwire length is observed. While inclined hysteresis loops are observed in as-prepared Co-rich microwires and annealed at low temperature, perfectly rectangular hysteresis loops are obtained for microwires annealed at high enough temperature. In such microwires, a gradual change in local hysteresis loops is observed along the length of the microwire. While as-prepared and annealed at low-temperatures Co-rich microwires exhibit linear hysteresis loops, such microwires annealed at sufficiently high temperatures exhibit perfectly rectangular hysteresis loops.

Irregular hysteresis loops are observed in Co-rich microwires annealed at intermediate annealing temperatures. The origin of such hysteresis loops is explained by the contributions of magnetization rotation and domain wall propagation. A single DW propagation is observed in Co-rich microwire segments with rectangular hysteresis loops. We observed that the DW propagation in segments of Co-rich microwire segments with graded anisotropy is essentially non-uniform and hence can be effectively controlled. Changing the position of the microwire with graded anisotropy inside the magnetization coil, the direction of the domain wall propagation changed to the opposite. The domain wall velocities are substantially different for the cases if the domain wall is released from the segment with graded magnetic anisotropy or from the region with rectangular hysteresis loops. The observed peculiarities of the domain wall dynamics in Co-rich microwires with graded magnetic anisotropy are discussed considering domain wall inertia and change in the demagnetizing field during the magnetization reversal. Unlike Fe-rich microwires, which require gradient stress annealing to obtain graded magnetic anisotropy, in Co-rich microwires, graded magnetic anisotropy can be obtained in an even simpler way using a temperature gradient furnace annealing (without stress).

CRedit authorship contribution statement

P. Corte-León: Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **V. Zhukova:** Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **J.M. Blanco:** Visualization, Validation, Methodology, Investigation, Data curation. **A. Zhukov:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of interest

The authors of the manuscript “Controlling the domain wall propagation in Co-rich magnetic microwires with graded magnetic anisotropy” by P. Corte-León, V. Zhukova, J. M. Blanco, and A. Zhukov declare no competing financial or/and non-financial interests.

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