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Modelling the Hysteresis Curves of Ferromagnetic Amorphous Wires

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We present a model to examine the influence of various pinning regions on the magnetic hysteresis of a ferromagnetic amorphous wire by revealing the correlation between its magnetic hysteresis and pinning region configuration. Magnetization is performed with the motion of 180-degrees domain walls. Domain configuration in every stage of magnetization is traced by analyzing the total energy of domain-domain, domain wall-domain, domain wall-pinning center, and external magnetic field interactions. The predicted hysteresis loops obtained are found to be in good agreement with the experimental ones in literature.

Keywords: Ferromagnetic, amorphous, wire

1. Introduction

Amorphous wires have been a topic of ongoing interest for more than a decade due to their outstanding magnetic properties and possible applications, such as sensors and transducers [1-4]. As a characteristic behavior, they have two stable remanence states between which the magnetic reversal occurs through a large Barkhausen jump [5] when the wire is long enough [6,7]. Fe-based amorphous wires consist of two main regions; cylindrical inner core, and a shell magnetized radially or circumferentially external to the core. In the literature, most works have considered the magnetic reversal in such wires as reverse domain nucleation which occurs in the cylindrical core [6-8].
The anisotropy distribution in such wires is a consequence of the method of preparation. The very rapid cooling rates that are necessary to retain the amorphous state produce thermally induced stresses and hence associated magnetoelastic interactions, which manifest themselves as a magnetic anisotropy. Additional uniaxial anisotropy can be induced by thermomagnetic or mechanical treatment. When a ferromagnetic material is deformed, a magnetic anisotropy is induced in a direction which depends on geometry of the deformation [9]. In literature, some works considered the magnetization in bistable amorphous wires as directionally alternating wall propagation [5-7,10]. We report a model to examine the influence of various pinning regions on the magnetic hysteresis of a ferromagnetic amorphous wire by revealing the correlation between its magnetic hysteresis and pinning region configuration.
The wire is assumed to be consisting of axially oriented cylinders (Fig. 1). The cylinders are axially magnetized with radius-independent magnetic charges on both ends. Each of them interacts with others, external field, and the local fields representing the pinning region. The effect of closure domains is represented by a pair of mutually directed magnetic fields at each end. In addition to the closure domains, two kinds of pinning regions are employed. One of them is uniaxial anisotropy which can arise from press-

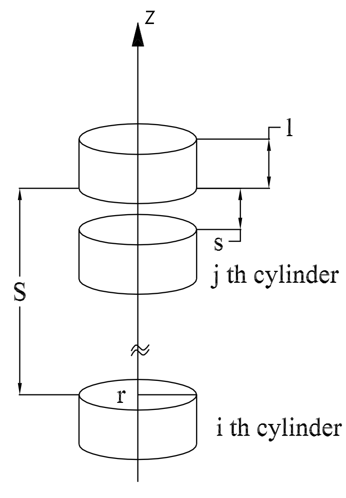

Figure 1. Schematic of the wire divided into small cylinders

ing the wire perpendicular to its axis, while the other is unidirectional anisotropy arising from local thermomagnetic treatment of the wire. While the former of these is modelled as a pair of magnetic fields directing toward the ends, the latter is implemented through a field biasing in one direction of the wire.
The pinning sites can resist against domain wall motion. While the magnetic moments in these regions may energetically favor the anisotropy field directions, after completing magnetic reversal, they contribute to the magnetization with small angle rotation. This well known mechanism is important in highly anisotropic magnetic materials and is not considered in this study.
Magnetization is performed with 180-degrees domain wall (separating two oppositely magnetized domains) motion. Domain wall undergoes a Barkhausen jump when the total energy looses its minimum. This jump causes a sudden change in magnetic flux through the wire resulting in electromotive force induced across a pick up coil. These voltage spikes produced in each magnetic reversal are known as Barkhausen noise [11]. In AC magnetization, Barkhausen noise is produced at the applied field frequency. In this study we consider DC magnetization and thus do not focus on Barkhausen noise.
Since in general there are more than one energy minima along the wire, a magnetic hysteresis is observed.

2. Calculation details

The total interaction energy among the cylinders is,

$$E_m = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} U_{ij} \tag{1}$$

where n is the number of cylinders, U_{ij} is mutual interaction energy between ith and jth cylinders. The magnetostatic potential at the point (R, z) in cylindrical coordinates due to a disc of magnetic charge density m_i and radius r is given by [12],

$$\varphi = \frac{m_i r}{2} \int_0^\infty J_1(xr) J_0(xR) e^{-xz} x^{-1} dx \tag{2}$$

with $J_n(x)$ is the first kind Bessel function of nth order. The interaction energy of the two coaxial discs is;

$$W(z) = \pi m_i m_j r^2 \int_0^\infty J_1^2(xr) e^{-xz} x^{-2} dx. \tag{3}$$

Where z is the distance between the two discs. Using $W(z)$, in Eq.3, U_{ij} can be formulated as

$$U_{ij} = 2W_{ij}(l + S) - W_{ij}(2l + S) - W_{ij}(S), \tag{4}$$

where l is the cylinder length, and S is the distance between the closest ends of the two adjacent cylinders. The distance between the cylinders numbered i and j (with $j > i$) is taken as

$$S = (j - i)s + (j - i - 1)l. \tag{5}$$

The total energy can be written as;

$$E(x) = E_m(x) - HM(x) + E_y(x). \tag{6}$$

Here H is the external field, $M(x)$ is magnetization of the wire, $E_y(x)$ is the interaction energy between wire and the pinning regions, and is given by

$$E_y(x) = -\sum m_i H_i \tag{7}$$

Here m_i and H_i denote magnetic moments of pinned parts of the wire and magnetic fields created by the pinning regions respectively, and x is the distance between the wall and an arbitrary end. $M(x)$ is the sum of magnetization of individual cylinders and taken as

$$M(x) = \sum_{i=1}^{n} m_i(x). \tag{8}$$

We include x as an argument because dipole moments of the cylinders and hence the total energy depend on x . Reduced energy is taken as;

$$e(x) = rE(x)/M_s^2, \tag{9}$$

where M_s is the saturation magnetization. Reduced magnetic field and reduced magnetization are taken as

$$\begin{aligned} h &= rH/M_s \\ \mu(x) &= M(x)/M_s \end{aligned} \tag{10}$$

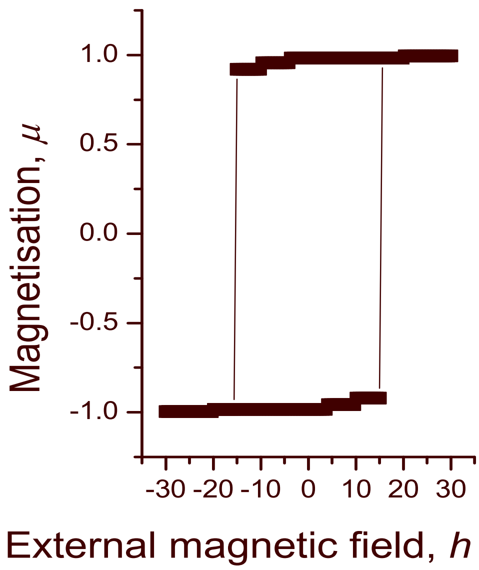

Figure 2. Magnetic hysteresis of the amorphous wire with pinning centers at ends because of boundary effects

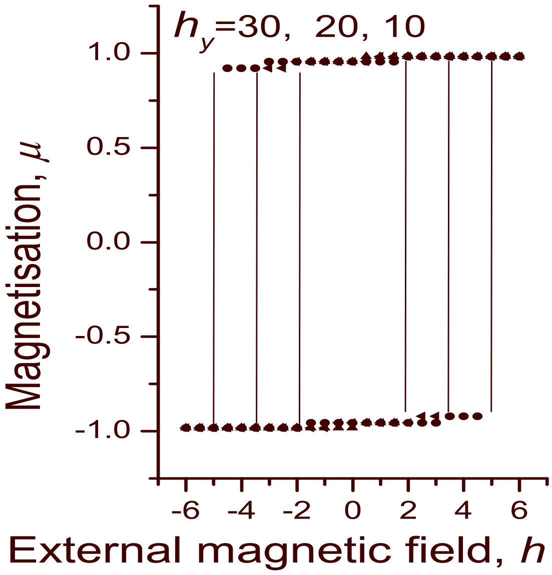

Figure 3. Broadening of the magnetic hysteresis by virtue of the strengthening the pinning centers at the ends.

respectively, so that,

$$e(x) = e_m(x) - h\mu(x) + e_y(x) \tag{11}$$

or explicitly,

$$e(x) = r\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} U_{ij}/M_s^2 - rHM(x)/M_s^2 - r\sum m_i H_i/M_s^2 \tag{12}$$

3. Results and Discussion

In Fig. 2, we present the magnetic hysteresis loop for the case of no pinning region except for the ones representing the closure domains at ends. In both directions, the fine structure is observed before the Barkhausen jumps. From energy point of view, the pinnings of the wall at the ends before reverse magnetization are due to the minima at the ends in the energy vs. x curve. At sufficiently strong external field, domain wall overcomes the energy barrier and undergoes a large Barkhausen jump. This is what happens when h exceeds some critical value namely coercivity (h_c). As h approaches h_c, the energy minimum continuously gets shallower and displaces with small steps resulting in the fine structure. At $h = h_c$, the energy barrier turns to an inflection, and the wall is released to perform an irreversible jump.

In Fig. 3, the broadening of the hysteresis curves for increasing h_y are seen. Energy minima at the ends deepen and hence coercivity (h_c) increases as a result of strengthening of pinning centers here. Depinning of the wall occurs gradually at the end where the motion begins because of the energy minimum. Then reverse magnetization process shows a sudden complete instead of stairwise change at the terminal end. This sudden occurrence is due to the fact that, the energy minimum at the terminal end disappears when the energy required to overcome the minimum at the starting end is provided by the external magnetic field. This statement is reinforced by the domain wall velocity measurements with two pick up coils [5,9]. For three values of distance (s) between the adjacent cylinders, coercivity versus pinning field (h_y) curves are seen in Fig. 4. These figures consist of three pairs of intersecting straight lines. The h_y values at which intersection occurs, decreases with increasing s.

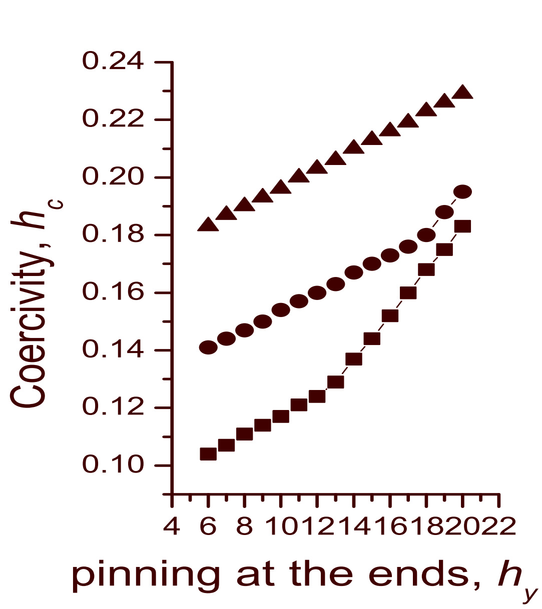

Figure 4. Coercivity versus pinning field graphics for three values of distance (s) between the adjacent cylinders.

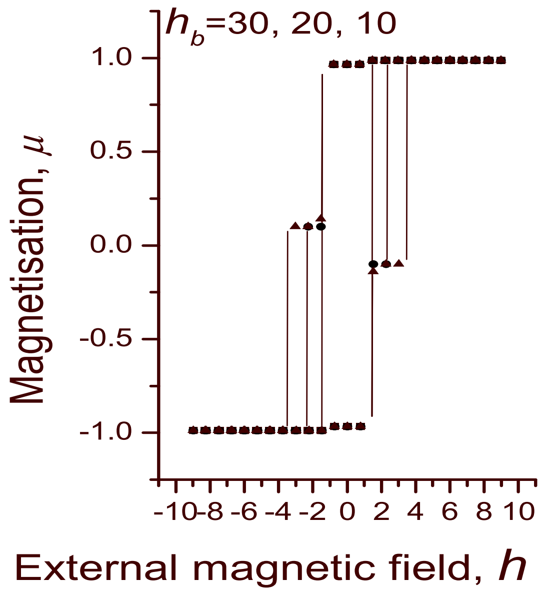

Figure 6. Magnetic hysteresis in the case of unidirectional anisotropy at the middle of the wire for three values of strength for a certain value of h_y, strength of pinning at the ends.

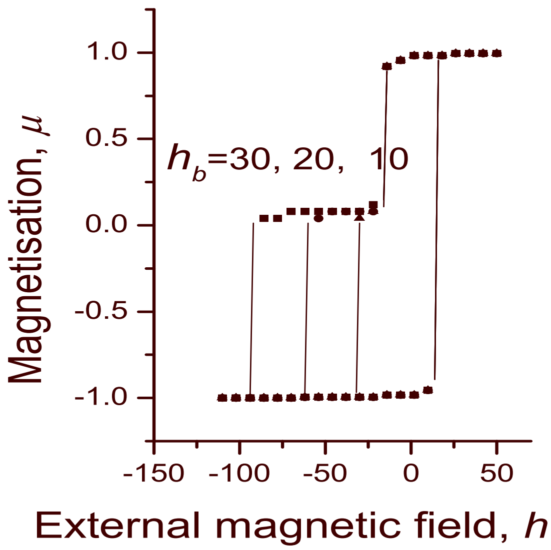

Figure 5. Magnetic hysteresis loops for increasing strength of unidirectional pinning center at midsection of the wire.

Magnetic hysteresis loops for increasing strength of unidirectional pinning region at midsection of the wire are shown in Fig. 5. Unidirectional pinning causes a unidirectional energy barrier that makes it difficult for domain wall to propagate freely in the opposite direction to this bias. The energy required to overcome the barrier causes the horizontal line seen in descending part of the loops.

The relation between coercivities seen in the descending portions of the curves implies a proportionality beyond a threshold between biasing anisotropy field h_b and coercivity. Lengths of horizontal lines increase with h_b.

In the case of uniaxial pinning region in the midsection of the wire, hysteresis loops for its three different values of strength, are seen in Fig. 6. Since unidirectional anisotropy is represented by a combination of biasing fields having opposite signs within two halves of the wire, upper and lower halves of hysteresis loops are shifted symmetrically with respect to μ axes. The domain wall is pinned both at the ends and at the center of the wire and this leads to two stage-large

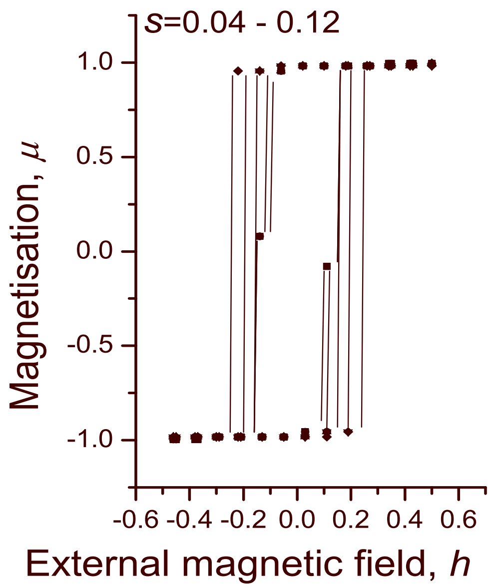

Figure 7. The vanishing of horizontal line in the hysteresis as the distance of adjacent cylinders (s) decreases and consequently total interaction energy among the cylinders increases.

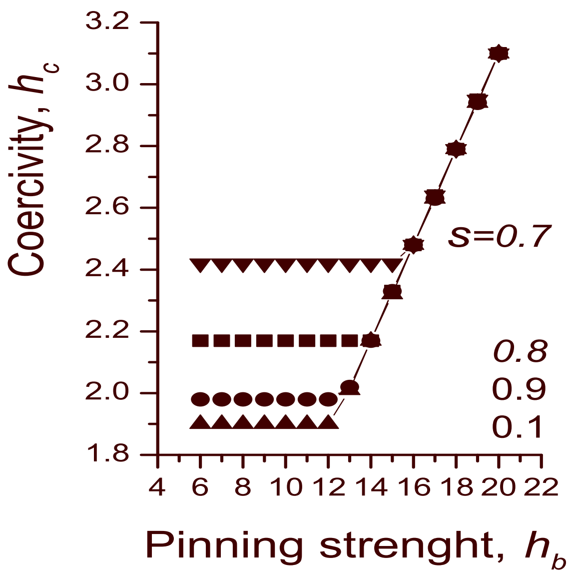

Figure 8. For $h_y = 10$ and various values of s, curves of coercivity versus strength of biasing fields h_b in the middle.

Barkhausen jumps in both directions. When the wall reaches the location of the unidirectional anisotropy, it is exposed to the opposite biasing field. Being opposite to the direction of the wall, biasing field impedes depinning and increases the depinning field. This effect can also be explained in the context of energy. The local anisotropy creates an energy barrier. The wall is pinned until extra energy from the external field suffices to overcome this barrier. In the case of uniaxial anisotropy, the same mechanism as the unidirectional anisotropy is employed in both directions of the wire. Again coercivity is found to be proportional to the magnitude of anisotropy field h_b beyond a threshold.

Hysteresis loops for various values of s, the distance between the closest ends of adjacent cylinders, are seen in Fig. 7. An increase in total interaction energy among cylinders leads to an impedance against reverse magnetization, and this results in an increase in coercivity. Since the magnitude of pinning in the middle of the wire is kept constant during the entire process, the depinning energy decreases with s. At a certain value of s, depinning energy vanishes.

For $h_y = 10$ and various values of s, curves of coercivity versus strength of biasing fields h_b in the middle are seen in Fig. 8. These curves can be used to explain the relation between coercivity and h_b field for the hysteresis loops seen in Fig. 5. When h_b is below a threshold that increases with h_y and is proportional to reduced energy, coercivity is independent of h_b and constant. This is because when h_b is less than the threshold and external field suffices to depin the wall at an end, central energy barrier vanishes and the wall is no longer pinned here. Beyond the threshold, coercivity is proportional to the central uniaxial anisotropy field h_b since the contribution of the uniaxial anisotropy to the total energy is also proportional to it. Consequently the depinning energy supplied by the external field is proportional to h_b.

Beyond the threshold, slope of the line depends on the number of cylinders n , and is independent of h_b. In Fig. 9, the evolution of one of these curves against increasing n is shown.

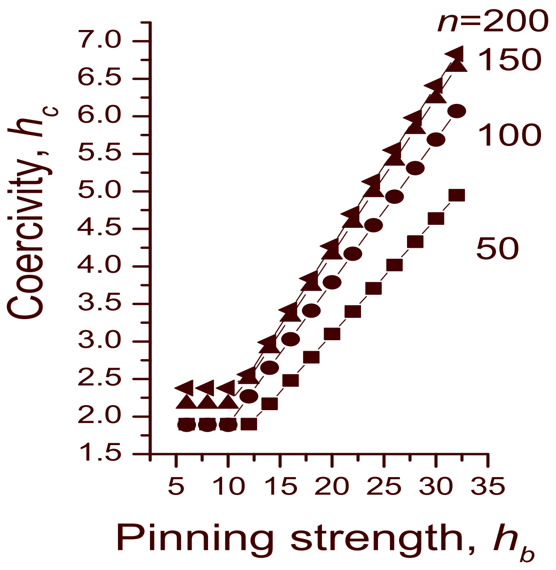

Figure 9. Evolution of coercivity versus h_b curve against increasing n.

4. Conclusion

In the present work, the dependence of magnetic hysteresis of a ferromagnetic amorphous wire on the configuration of pinning regions, is modelled. In the case that no pinning region except the ones representing the closure domains at ends is included, the hysteresis loop differs from a perfect rectangular shape by small steps before single large Barkhausen jumps in both directions. This curve is in good agreement with the experimentally observed ones in literature [1,5]. The fine structure of this curve confirms the existence of the pinning centers at the ends of the wires. Coercivity of the loop is linearly proportional to the magnitude of the pinning regions and decreases as the distance between the adjacent cylinders increases. When a local DC magnetic field, representing unidirectional pinning center is added to middle of the wire, the rectangular like hysteresis loop looses its symmetry. Depending on the direction of this field, for example in the descending part, one long horizontal stretch, accompanied by small steps appears while it is observed in either portions of the loop in the case of uniaxial anisotropy. The relation between coercivity and the magnitude in both cases and the dependence of this relation on the number of the cylinders is also presented.

We further showed that hysteresis curves of various shapes can be obtained by forming the pinning regions at different locations along the wire which can be experimentally formed by deformations perpendicular to the axis of a magnetostrictive amorphous ferromagnetic wire.

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