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The influence of annealing on domain wall propagation in bistable amorphous microwire with unidirectional effect

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ABSTRACT

The effect of gradual annealing on the domain wall mobility (velocity), nucleation, critical depinning and propagation fields in amorphous FeSiB microwires has been studied. A new experimental set-up, presented in this paper, allows measurement of average domain wall velocity for four different conditions and detection of the presence of unidirectional effect in wall propagation without manipulation of the microwire. The proposed interpretation is that a domain wall is considered as a relatively long object which can change its axial dimension due to inhomogeneity of damping forces acting on the wall during its propagation. It is demonstrated that unidirectional effect in domain wall propagation can be strongly reduced by annealing the wire at temperatures higher than 350 °C.

1. Introduction

Magnetic microwires have been the subject of interest for researchers for more than two decades. Glass-coated microwires with amorphous or nano-crystalline structure form a special group of these materials. Characteristic stress distribution causes that the typical domain structure of a glass-coated microwire with positive magnetostriction [1–5] consists of a large axial domain in its central part and radial domains in its outer shell. At a certain value of external magnetic field (critical field), the closure domain structure at the microwire ends can produce free domain walls which subsequently propagate along the microwire in a large Barkhausen jump [1,6–11]. This critical field is usually higher than the wall coercive fields and the microwire is magnetized in a single Barkhausen jump. This so-called bi-stable behaviour [1,3,6,8–10] results in a rectangular hysteresis loop, and it gives a unique opportunity to study the dynamics of a single domain wall [1–11]. Two main topics are usually the subject of study. The first is the process of free domain wall production. This occurs by depinning a domain wall from the closure domain structure at the wire end [12] or by nucleation of a reversed domain in regions far from the microwire ends [7,13–15]. Both processes are characterized by corresponding critical fields, the so-called switching (depinning) field or nucleation field. The second topic consists of measurements of domain wall velocity as a function of an external magnetic field ($v(H)$ dependences). Various modifications of the classical Sixtus – Tonks experiment [11] are used for these studies. Our modifications of this experiment consist in the following: for the measurements of the above-mentioned switching field no starting coil is needed, and additional pick-up coils are added so that possible nucleation of reverse domains in the central parts of the microwire can be detected.

Interpretation of $v(H)$ dependences is based on two standard damping mechanisms [1,6,16–19]: eddy current damping and spin relaxation damping. In some articles a mechanism based on structural relaxation is also considered. Full quantitative understanding of $v(H)$ dependences cannot be achieved without a realistic model of domain wall structure. Based on the axial dimension of the boundary (domain wall) between axial domains, two basic concepts can be found in articles dealing with this problem. Relatively good agreement between theoretical and experimental values of domain wall mobility can be obtained on the assumption that the axial wall dimension is comparable with the radius of the microwire. However, such a thin domain boundary is in contradiction with the typical width of voltage peaks induced in the pick-up coils during the Sixtus – Tonks [11] experiment. Based on these experiments the dimension of the domain boundary should be much larger (more than 50 times) than the radius of microwire [20]. The interpretation of these experiments requires consideration of a long (planar or conical) domain wall. In this case even low normal (to the wall plane) velocity can cause the axial velocity measured in the Sixtus-Tonks experiment to rise very high. Model domain wall mobility calculations, in which eddy currents or spin relaxation damping are taken into account, give in this case high values of domain wall mobility which do not

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agree with the experimental ones in a high field region. As can be seen, none of these concepts explains the observed behaviour completely. Moreover, there is another phenomenon which has not been satisfactorily explained so far. It is the negative field value [6,9,18,21] which is obtained by extrapolation of the linear parts of $v(H)$ dependences. In most works dealing with the dynamics of a single domain wall in so-called bistable magnetic microwires, the wall is considered as a solid object which does not change its shape in different applied fields, or possible changes in wall structure are discussed to interpret the observed behaviour. If the axial dimension of the wall is much larger than the diameter of the metal core of the microwire, then changes in the wall axial dimension or wall deformation during its propagation can naturally be expected. A dynamic model which takes into account these processes is proposed in this work.

The existence of the so-called unidirectional effect observed in glass-coated $Fe_{77.5}Si_{15}B_{7.5}$ microwire has been reported recently in Ref. [22]. For a given wire region (i.e. part of the wire between the pick-up coils in the Sixtus – Tonks experiment) four different domain wall (DW) velocities can be measured. Say for instance that the wall moves from wire end A to wire end B, then two types of wall (head-to-head or tail-to-tail) and corresponding velocities can be distinguished. If the letters A, B indicate the direction of DW motion, index 1 means the head-to-head and index 2 the tail-to-tail type of wall, then the so-called unidirectional effect means that the relation between the four velocities versus field dependences can be expressed as $v_{AB1}(H) \approx v_{BA2}(H) \neq v_{AB2}(H) \approx v_{BA1}(H)$ [22]. In other words wall velocity depends on the magnetization orientation to which the wire is magnetized by wall propagation. The physical origin of this phenomenon is unknown. The experiments presented in this paper were performed on a sample of microwire exhibiting strong unidirectional effect, and the influence of annealing on this effect is studied.

In experimental set-ups usually used for the study of single DW dynamics in bistable microwires, the wall moves from one particular wire end. If the dynamics of a wall propagating in the opposite direction are to be studied, the microwire has to be reversed. In other words, manipulation of the microwire sample is necessary. In this paper we present a new experimental set-up which allows measurements of all four velocities without manipulation of the sample. However, the measurements of $v(H)$ dependences in the field regions where reversed domains are nucleated in the central parts of the microwire is not possible using this experimental set-up.

2. Experimental

The experimental set-up is schematically depicted in Fig. 1a. The system of coils consists of six coils, three magnetizing (So, C1, C2) and three pick-up coils (PuC1, PuC2, PuC3). The distance between pick-up coils PuC1 and PuC2 with length of 1 mm and diameter of 1 mm is 35 mm. The length and diameter of narrow pick-up coil PuC3 are 25 mm and 1 mm, respectively. The geometry and number of turns of coils C1 and C2 are the same, and these coils are connected in such a way that they create magnetic fields H_{C1}, H_{C2} opposite to the field H_{So} created by the solenoid So. Three resistors (R, $R_1 = R_2$) and the magnetizing coils produce magnetic fields for which $|H_{C1}| = |H_{C2}| > |H_{So}|$ holds for a given output voltage of the power supply. The keys K1 and K2 allow the fields H_{C1}, H_{C2} to be switched on/off independently. The measuring procedure consists of the following steps. In order to define the starting magnetic state, the microwire is magnetized by the field generated by solenoid So with keys K1 and K2 switched off (situation depicted in Fig. 1b). Then the keys K1 and K2 are switched on and the power supply produces fields in the magnetizing coils which fulfil the conditions mentioned above. The field H_{So} (which is in the opposite direction to the initial magnetization) is high enough to release domain walls from the wire ends. The propagation of these walls is stopped by fields H_{C1}, H_{C2} (in opposite direction to H_{So}). At this stage we have a situation where two domain walls are situated in positions where the sum of fields H_{So}, H_{C1}, H_{C2} is nearly zero (situation depicted in Fig. 1c). This situation remains the same also when these fields are changed in such a way that the field H_{So} equals the measured value H. Of course this is true only in the case when the fields for nucleation of opposite domains are higher than the field H for all parts of the microwire between coils C1 and C2. In our experiment the time interval for this step is long (about 1 s) to allow this nucleation if the measuring field is high enough. In the final step a single domain wall can propagate along the wire after switching off field H_{C1} or H_{C2}. Using pick-up coils its average velocity can be measured with the standard Sixtus – Tonks method. This method allows all four velocities to be measured without manipulation of the sample. It also allows the exclusion of measurements when additional domains (and domain walls) are nucleated.

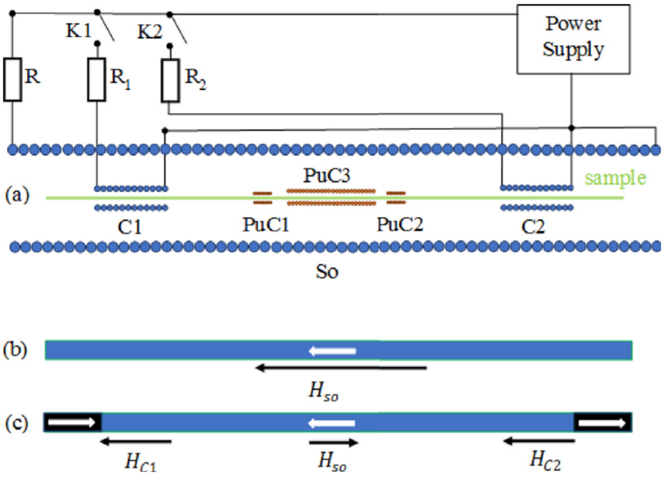

Fig. 1. Experimental set-up (a); starting magnetic state when the microwire is magnetized by the field generated by solenoid H_{So} with keys K1 and K2 switched off (b); the state after application of opposite H_{So} high enough to release domain walls from the wire ends and with keys K1 and K2 switched on (c).

Information about the magnetic state of the central part of the microwire can be obtained using pick-up coil PuC3. If the differences between fields $|H_{C1} - H_{So}|$, $|H_{C2} - H_{So}|$ are small enough so that a reversed domain cannot be nucleated inside the coils C1, C2, the system of coils in Fig. 1a allows measurement of hysteresis loops for four cases: magnetic reversal starts with depinning of the wall from the microwire ends (switches K1 and K2 are off); by depinning of the wall from the left end of the microwire (switch K1 is off and switch K2 is on); by depinning of the wall from the right end of the microwire (switch K1 is on and switch K2 is off); and by nucleation of a reversed domain in the central part of the wire (keys K1 and K2 are on). The same experimental procedure as described above for $v(H)$ dependences was also used for measurements of single points on corresponding hysteresis loops.

The measurements were carried out on a glass-coated $Fe_{77.5}Si_{15}B_{7.5}$ microwire prepared by means of the Taylor - Ulitovski method [1–3, 23–25]. The diameter of the metallic core was about 15 μm, the thickness of the glass coating was about 7.5 μm, and the length of the sample was 12.5 cm.

The annealing process consisted in the following steps. First the furnace temperature was stabilized and then the sample was placed in a thin ceramic tube was inserted into the furnace. After annealing for 30 min at a given temperature the sample was taken out of the furnace in order to accelerate the cooling process.

3. Model dependence of domain wall velocity on a constant external magnetic field

We consider a 180° domain wall. The force $f_{\perp}$ per unit wall area normal to the wall acting on an arbitrary point of this domain wall can be expressed by formula [26].