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Tailoring of domain wall dynamics in amorphous microwires by annealing

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We studied the effect of annealing on the magnetic properties and domain wall (DW) dynamics of magnetically bistable, Fe-based, glass-covered microwires with two different compositions, and different diameters. We observed the correlation of the domain wall dynamics with the distribution of the nucleation fields, measured in as-prepared samples, and after annealing for up to 150 min at temperatures of 250 and 300 °C. We found that both DW velocity and the range of the field limiting the single DW dynamics changed after annealing. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4795617]

Studies of electrical current and magnetic field driven domain wall (DW) propagation in thin magnetic wires (planar and cylindrical) have attracted considerable attention,[1–3] owing to proposed applications of controllable DW propagation for data storage (magnetic random memory, MRAM) and magnetic logics devices.[1,2] Extremely fast DW propagation has been reported for amorphous magnetically bistable microwires (usually exceeding 1000 m/s).[4,5]

The origin of the magnetic bistability of amorphous glass-coated microwires with positive magnetostriction constants is related to the fast magnetization switching of a large single axially magnetized domain.[5,6] The onset of such a peculiar domain structure, consisting of a single large axially magnetized domain surrounded by an outer radially magnetized shell, is determined by the stresses arising during simultaneous solidification of the composite wire, consisting of a metallic nucleus surrounded by the glass coating.[6–10] The strength of these stresses is determined by the relative volumes of solidifying metallic nucleus and glass coating.[7–10]

Additionally, the DW velocity, v, relies on the magnetoelastic anisotropy depending on the magnetostriction constant value, as well as on the internal or applied stress.[5,6] On the other hand, in our previous papers,[11,12] we showed that there is a correlation between the distribution of the local nucleation field along the length of the as-prepared bistable microwire, and the single-domain wall propagation limit. The minimum value of local nucleation field, H_{Nmin}, determines the threshold between single and multiple domain wall propagation regimes. Thus, we observed the spontaneous DW nucleation on local defects, which limits the single DW propagation regime in magnetically bistable Fe-based microwires.[11,12] Below H_{Nmin}, there is a linear dependence of DW velocity, v, on the applied magnetic field, H, for all microwires with positive sign of the magnetostriction constant.

Consequently, the microwires' inhomogeneities sufficiently affect the remagnetization process,[5,10–13] as was observed through the measurements of the distribution of the local nucleation fields, H_N, along the sample length, L. The origin of the defects is unclear and might be related to stress inhomogeneities, shape irregularities, oxides etc. It is assumed that at least some of these defects might have a magnetoelastic origin and, therefore, might be affected by heat treatment.

Therefore, the aim of this paper is to try to enhance the DW velocity by manipulating the magnetoelastic anisotropy and real structure of amorphous microwires through annealing at different temperatures and for different times.

We studied magnetic properties and DW dynamics of magnetically bistable Fe-based glass-covered microwires with two different compositions and different metallic nucleus, d, and total microwire, D, diameters as a function of time of annealing, t_{AN}. Primarily, we selected the microwires with the fewest defects using measurements of the distributions of the local nucleation fields, H_N, along the length of the different microwires, as previously described in Ref. 14. As mentioned above, the strength of internal stresses is mainly determined by the relative volumes of solidifying metallic nucleus and glass coating having different thermal expansion coefficients.[7–9] Therefore, we produced the samples with different ratios, $\rho = d/D$. The length, L, of the microwires was 13 cm. The limit of the length was determined by parameters of the set-up for measurements of the DW propagation.

We have investigated two samples of $Fe_{66.7}Cr_{11.4}B_{12}Si_9Ni_{0.9}$ (d = 17.6 μm, D = 38.6 μm, ρ = 0.46) and $Fe_{74}B_{13}Si_{11}C_2$ (d = 12.0 μm, D = 15.8 μm, ρ = 0.76) microwires (in total four samples). Two samples (one piece each of the $Fe_{66.7}Cr_{11.4}B_{12}Si_9Ni_{0.9}$ and $Fe_{74}B_{13}Si_{11}C_2$ wire) were annealed at T_{AN} = 250 °C for 30, 60, 90, 120, and 150 min. The other two samples were annealed at 300 °C for the same time. We studied the DW dynamics of the microwires using a Sixtus–Tonks-like technique, using three pick-up coils instead of two or one (see, for example, Refs. 5–7).

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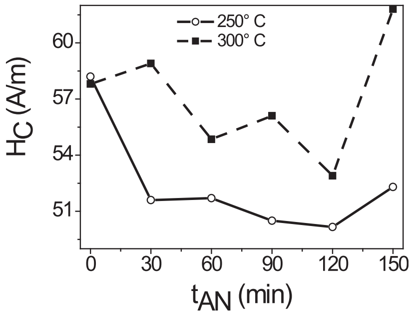

FIG. 1. Dependences of the coercive force of the samples, annealed at different temperatures, on annealing time for $Fe_{74}B_{13}Si_{11}C_2$ microwire.

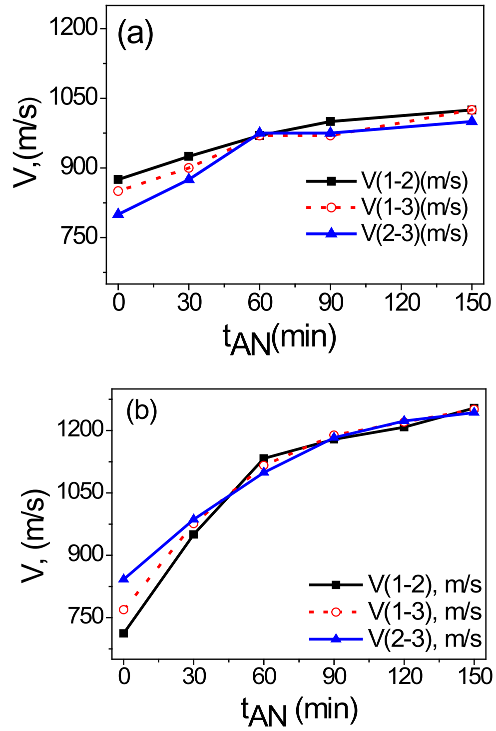

FIG. 3. Dependences of DW velocity on annealing time (a) for $Fe_{66,7}Cr_{11,4}B_{12}Si_9Ni_{0,9}$ sample annealed at $T_{AN} = 250\,°C$ (plotted for fixed magnetic field value $H = 300$ A/m) and (b) for $Fe_{74}B_{13}Si_{11}C_2$ microwire annealed at $T_{AN} = 300\,°C$ (plotted for $H = 130$ A/m).

Consequently we were able to measure DW velocities between the 1st and the 2nd pick-up coils, $V_{1\text{-}2}$, between the 1st and the 3d pick-up coils, $V_{1\text{-}3}$, and between the 2nd and the 3d pick-up coils, $V_{2\text{-}3}$. Hysteresis loops for all samples were measured by the induction method. The amplitude of the magnetic field was 220 A/m. The distribution of the nucleation fields, $H_N(L)$, was measured for as-prepared and for 150 min annealed samples using a technique described previously.[14]

To investigate the effect of the annealing time and temperature on magnetic properties and DW dynamics of glass-coated microwires, we used the following algorithm for measuring: As a first step, we performed the complex investigation of the magnetic properties of the as-prepared samples. We measured the hysteresis loop, DW dynamics (dependence of DW velocity, v, on magnetic field, H) and distribution of the nucleation fields for each sample.

After that, we annealed both samples at $T_{AN} = 250\,°C$ and 300 °C for different t_{AN} starting from 30 min, and we performed the measurements of the hysteresis loop and $v(H)$ dependences after each annealing, increasing the annealing time, t_{AN}, up to 150 min for both T_{AN}. In order to avoid the effect of any mechanical stress on the measurement results, we used a special sample holder shaped as a thin ceramic tube. The samples inside this holder were carefully placed inside the conventional furnace, and after each annealing, it was placed back in the set-up in order to measure $v(H)$ dependence at the same sample position.

Finally, after annealing for a 150 min and measuring of $v(H)$ dependences, we extracted the sample from the holder in order to repeat the measurements of the distribution of the nucleation fields along the microwire axis.

All measured samples present typical rectangular hysteresis loops. This behavior of the Fe-based glass-covered microwires has been described elsewhere (see, for example, Refs. 6 and 10). Dependences of the coercivity, H_C, on annealing time for the $Fe_{74}B_{13}Si_{11}C_2$ microwire measured at two different temperatures, are shown in Fig. 1.

The considerable difference in $H_C(t_{AN})$ for $T_{AN} = 250$ and 300 °C observed in the $Fe_{74}B_{13}Si_{11}C_2$ microwire might be explained by considering the main contribution of stress relaxation at lower T_{AN} and t_{AN}, and the increasing influence of first crystallization processes at higher T_{AN} and elevated t_{AN}.

The dependences for DW velocity between coils 2 and 3, $V(2\text{-}3)$, for the $Fe_{66.7}Cr_{11.4}B_{12}Si_9Ni_{0.9}$ microwires, and between coils 1 and 3, $V(1\text{-}3)$, for the $Fe_{74}B_{13}Si_{11}C_2$ microwires are presented in the Fig. 2. We observed typical almost linear $v(H)$ dependences in both as-prepared samples. After heat treatments at both temperatures, we observed extending of the magnetic field range where linear $v(H)$ dependence takes place (which corresponds to single DW propagation regime) and increasing of the DW velocity. At longest annealing time (above 120 min), both parameters (DW velocity and range of magnetic field for linear $v(H)$ dependence) are almost insensible on t_{AN}, exhibiting tendency to saturation.

In order to illustrate better the change in DW dynamics induced by annealing, we plotted the DW velocity value

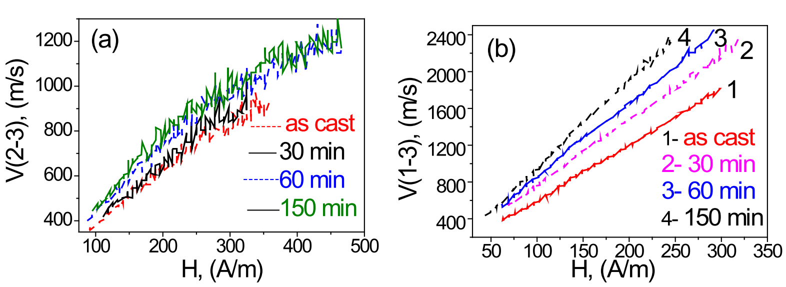

FIG. 2. Dependences of DW velocity on magnetic field for as-prepared samples, and (a) for $Fe_{66.7}Cr_{11.4}B_{12}Si_9Ni_{0.9}$ microwire annealed at $T_{AN} = 250\,°C$ for a 30, 60, 150 min and (b) for $Fe_{74}B_{13}Si_{11}C_2$ microwire annealed at $T_{AN} = 300\,°C$ for a 30, 60, 90, 150 min.

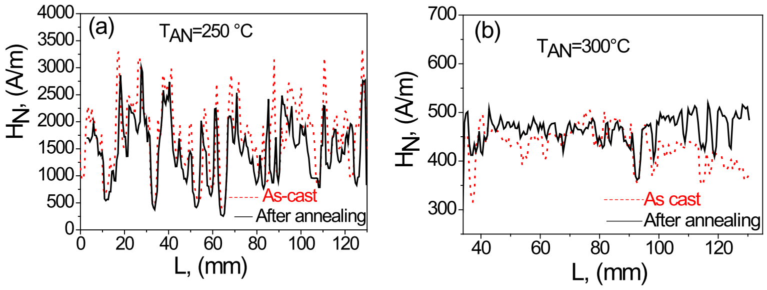

FIG. 4. Distribution of the local nucleation fields along the sample length, L, for as-prepared and annealed (a) $Fe_{66.7}Cr_{11.4}B_{12}Si_9Ni_{0.9}$ and (b) $Fe_{74}B_{13}Si_{11}C_2$ microwires.

measured at the same magnetic field after different heat treatments as a function of annealing time, choosing the magnetic field values at which linear $v(H)$ dependence has been observed after all heat treatments. For the $Fe_{66.7}Cr_{11.4}B_{12}Si_9Ni_{0.9}$ sample, we selected $H = 300$ A/m and for the $Fe_{74}B_{13}Si_{11}C_2$ microwire, $H = 130$ A/m. Dependences of DW velocity on annealing time obtained for both studied samples are presented in Figs. 3(a) and 3(b). We can observe a clear tendency of increasing of DW velocity with increasing of t_{AN} at fixed H values. The increase of the velocity observed in the $Fe_{66.7}Cr_{11.4}B_{12}Si_9Ni_{0.9}$ sample annealed at $T_{AN} = 250\,°C$ (Fig. 3(a)) is less pronounced in comparison with the $Fe_{74}B_{13}Si_{11}C_2$ microwire annealed at $T_{AN} = 300\,°C$ (Fig. 3(b)). Moreover, for the as-prepared samples, the difference for the velocities $V_{1\text{-}2}$, $V_{2\text{-}3}$, and $V_{1\text{-}3}$ is larger than for annealed samples with different t_{AN}.

Local nucleation field distributions in as-prepared and annealed ($T_{AN} = 250\,°C$, for $t_{AN} = 150$ min) $Fe_{66.7}Cr_{11.4}B_{12}Si_9Ni_{0.9}$ microwires, as well as in as-prepared and annealed at $T_{AN} = 300\,°C$ $Fe_{74}B_{13}Si_{11}C_2$ microwires, are shown in Figs. 4(a) and 4(b). As can be appreciated from Figs. 4(a) and 4(b), a decrease of oscillation amplitudes in $H_N(L)$ dependences takes place after annealing.

Observed decreases of the amplitude of local nucleation fields, increasing DW velocity, and the extending of the magnetic field range of single-DW propagation regime could be attributed to stress relaxation after annealing. Moreover, extending the magnetic field range for a single-DW propagation regime is in agreement with a considerable increase of the local nucleation fields (from 20% to 40%), previously reported for $Fe_{74}B_{13}Si_{11}C_2$ amorphous glass-coated microwire after annealing.[15]

It is worth mentioning that, previously,[16] we reported on the correlation between the amplitude of the $H_N(L)$ oscillations on local nucleation field distributions, and the type of DW propagation. We observed accelerated DW propagation in microwires with higher amplitude $H_N(L)$ oscillations, and uniform DW propagation for smoother $H_N(L)$ distribution.[16] As observed in Fig. 3, decreasing differences between $V_{1\text{-}2}$, $V_{2\text{-}3}$, and $V_{1\text{-}3}$ values after annealing correlate well with recently reported correlations of the type of DW propagation with the defect density.

Finally, in the case of the $Fe_{74}B_{13}Si_{11}C_2$ microwire, we observed higher DW velocities and a different range of magnetic fields (starting from about 50 A/m up to about 300 A/m) for single DW propagation, compared to the $Fe_{66.7}Cr_{11.4}B_{12}Si_9Ni_{0.9}$ microwire (magnetic field range from about 100 A/m up to about 350 A/m in as-prepared sample). This considerable difference must be attributed to the stronger internal stresses of the $Fe_{66.7}Cr_{11.4}B_{12}Si_9Ni_{0.9}$ microwire, with lower ρ-ratio values.

Consequently we can assume that at least a proportion of the samples' inhomogeneities, manifested through the oscillations of the local nucleation fields and limiting single DW regime, have an origin related to inhomogeneities in the internal stress distribution. Additionally, from the results presented above, we may assume two possible mechanisms of influence on the defects on DW dynamics: DW nucleation and the pinning of propagating DWs. Annealing of microwires, giving rise to internal stress relaxation and/or release of some defect, can enhance the DW velocity at a given magnetic field, as well as allow us to extend the range of magnetic fields in which a single DW propagation takes place.

We demonstrated that the annealing of microwires allows the manipulation of the magnetoelastic anisotropy of glass-coated microwires, and therefore enhances the DW velocity by extending the field range for single DW propagation, as well as enhancing DW velocity at a given magnetic field due to internal stress relaxation. We observed a correlation between the annealing influence on the local nucleation field distribution, and a change of magnetic field dependence of DW velocity, in amorphous Fe-based microwires with two different compositions and geometric parameters. Consequently, the nature of local defects limiting the single DW propagation regime and damping the DW might be related with the internal stress distribution.

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