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Detailed Study of the Hysteresis Loops for Annealed Amorphous Alloy Wires Having Vanishing Magnetostriction

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***Abstract*—The evolution of Barkhausen events during the magnetization process in current and furnace annealed Co-based amorphous wire having vanishing magnetostriction, λ_s, is reported. Their origin is explained using the core-shell model commonly accepted for this class of wire. It is argued that the application of stresses during the annealing process, in wire having slightly negative and slightly positive λ_s, changes the internal magnetic domain structure. Anisotropy induced by anelastic creep can be used to avoid the formation of these Barkhausen events. The behavior of the coercivity and susceptibility is also reported.**

***Index Terms*—Amorphous wire, Barkhausen effect, soft magnetic material, vanishing magnetostriction.**

I. Introduction

Amorphous magnetic alloy wires have been widely studied on account of their very soft magnetic nature and their magnetoimpedance behavior [1], [2]. A core-shell magnetic domain configuration has been proposed [3] and extended to the cases of wires with high positive, negative and vanishing saturation magnetostriction (λ_s) values, and for wires both in their as-cast state and after thermomechanical treatment [4]. Because of the magnetic softness and the cylindrical geometry of the wires, it is very difficult to observe their internal magnetic structure, and the usual hysteresis loop parameters are used to provide an interpretation. We have used an induction magnetometry technique [5], with the field applied along the wire axis during measurements, to investigate wires both in the region close to the coercive field and on emergence from saturation. New elements of understanding of the mechanism of magnetization derive from the observation of Barkhausen events, whose formation and annihilation will be ascribed to the particular magnetic state within the wire, generated by stress release and creep-anisotropy processes. These Barkhausen events are detected as large discontinuities in the loops, generated by sudden domain wall movements during the magnetization process.

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II. Experimental Procedure

$(Co_{0.94}Fe_{0.06})_{72.5}Si_{12.5}B_{15}$ (Co94) and $(Co_{0.93}Fe_{0.07})_{72.5}Si_{12.5}B_{15}$ (Co93) glassy alloy wires, of diameter 120 μm, prepared by the rotating water bath casting method [6], were subjected to current and furnace annealing treatments. Wires 200 mm in length were used for the annealing treatments, from which 40-mm-long samples were cut for magnetometry study. Current annealing was performed by passing current through the wire at a current density of 30 A/mm^2, and allowing the wire to heat up by the Joule effect. Rapid cooling was achieved by removing the current. Current annealing was performed for 40 and 50 s for Co93 and Co94 samples, respectively, these being the respective times required for complete stress relief. Furnace annealed samples were isothermally annealed at 360 °C in a tube furnace for 1 min, then water quenched. The tensile stress, applied longitudinally during stress annealing treatments, was 300 MPa. All the annealing treatments were performed in air and no significant oxide formation was detected by SEM studies.

The two alloys were characterized, in the as-cast state, by λ_s values, measured by the small angle magnetization rotation (SAMR) method [7], which were of similar magnitude but different sign: $\lambda_s = -3.7 \times 10^{-8}$ and $\lambda_s = +5.1 \times 10^{-8}$ for Co94 and Co93 alloys, respectively. In their as-cast state, the Co94 and Co93 wires exhibited values of J_s, measured with a VSM, of 0.58 ± 0.02 T and 0.60 ± 0.01 T while the coercivities, H_c, were 2.7 ± 1.1 A/m and 1.4 ± 0.6 A/m for positive λ_s and negative λ_s, respectively.

III. Results and Discussion

The magnetic domain configuration of both types of wire in their as-cast state is determined by the frozen-in stresses arising from the casting process, coupled with their magnetostrictive properties [8], and by a magnetostatic contribution. For large values of λ_s, the proposed magnetic model in Fe-based and Co-based amorphous alloy wires consists of an inner single-domain core with the easy axis parallel to the wire axis and an outer shell, with either radial or circular magnetization depending on whether the λ_s value is positive or negative [2]. The wires in this study are not expected to have a single domain core due to their vanishing λ_s. The inner core of such wires was reported [9] to consist of a multidomain state that extends along the wire axis. The magnetization process does not show the characteristic bistable behavior found in Fe-rich and Co-rich wires with

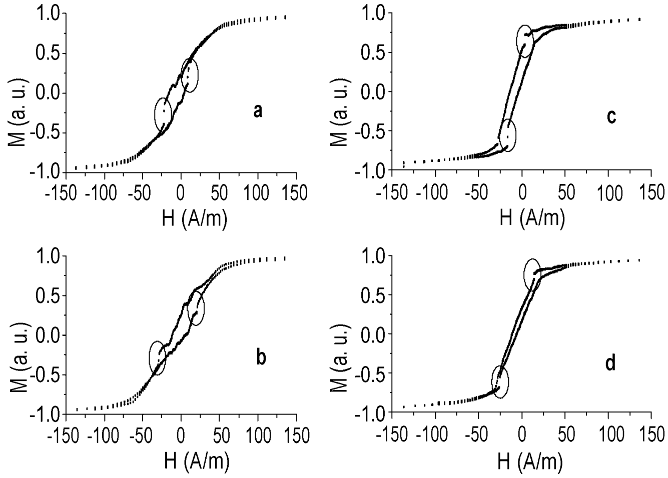

Fig. 1. Hysteresis loops from current (a), (b) and furnace (c), (d) annealed samples of Co 93 (a), (c) and Co 94 (b), (d) series. Barkhausen events are circled.

higher λ_s [1], [8], but occurs by a combination of wall movement and moment rotation.

In this study, when the wires were subjected to heat treatment, different behavior was observed for the cases of current annealing and furnace annealing.

As seen in Fig. 1(a) and (b), current annealing induces a hard axis parallel to the wire axis.

One of the consequences of the current annealing process is the establishment of a large Barkhausen event close to, but not at, the coercivity. By comparison, conventional furnace annealing [Fig. 1(c) and (d)] results in a squarer loop, which implies a different magnetic configuration with high values of susceptibility and a relatively unchanged coercivity [Fig. 2(a) and (b)]. The differences in magnetic properties between samples annealed by current or furnace methods have been explained previously [10] as arising from the difference in heat flow geometries and the induction of new stresses in the case of current annealed samples, where wires are subjected to a high cooling rate once the power source is switched off. The two processes therefore modify the domain structure in different ways.

In the case of current annealing the proposed magnetization process is similar to that for the case of Fe-rich wires [2], [3]. The volume fraction of the multidomain magnetic core increases, but the portion of the domains favorably aligned with the wire axis is reduced. Starting from positive magnetic saturation the sample is able, as the field is reduced, to demagnetize in a continuous manner without large Barkhausen events. Continuing to negative saturation, the magnetization process is characterized, in the case of Co94 and Co93 samples respectively, by around 15% and 25% of the reversal occurring via a Barkhausen event beyond H_c [Fig. 1(a) and (b)]. This previously unreported feature is interpreted as demonstrating a barrier to domain wall nucleation, or a sudden shell reorientation from magnetostatic coupling to the core.

In the case of furnace annealed samples, a different situation is found. The increase in susceptibility [Fig. 2(b)] indicates that the easy axis of the wire lies parallel to the longitudinal axis of the wire. The sign of λ_s plays an important role in the evolution of the magnetic properties. In the particular case of negative λ_s, the core and shell domain structure may become more clearly

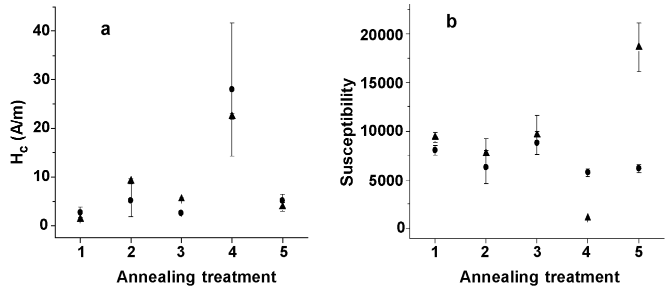

Fig. 2. Coercivity (a) and susceptibility (b) values for Co 93 (▲) and Co 94 (●) samples for the following treatments: as-cast (1), current annealed (2), furnace annealed (3), stress-current annealed (4), stress-furnace annealed (5).

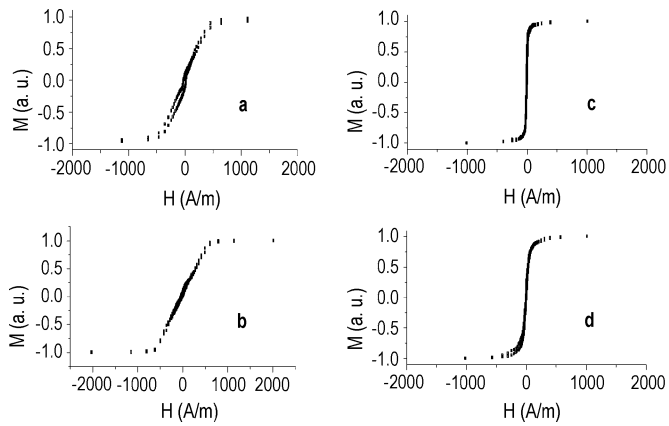

Fig. 3. Hysteresis loops from stress-current (a), (b) and stress-furnace (c), (d) annealed samples of Co 93 (a), (c) and Co 94 (b), (d) series.

defined, similar to the case of wire with higher values of λ_s, with a clear Barkhausen event occurring as shown in Fig. 1(c). Positive λ_s wires, less sensitive to the treatment than the negative λ_s samples, show a smoother magnetization process, with low coercive field values and high susceptibility [Fig. 1(d)]. The situation shown in Fig. 1(c) for negative λ_s wires indicates how the hysteresis loop experiences a larger discontinuity when the sample comes out of saturation. It should be noted that, while in the case of current annealed samples, the Barkhausen jump was recorded beyond but close to the coercive field, in this case, the phenomenon is observed during the demagnetization, close to the knee of the loop. The suggested interpretation, for this Barkhausen event is attributed to the reestablishment of the core-shell magnetic configuration of the remanent state, from the single domain forced in by the saturation state.

The Barkhausen events reported for current and furnace annealed samples can be avoided by applying an external stress during the annealing stage (Fig. 3). In this case, topological and chemical changes occur in the nearest neighbor atomic pair configurations in the direction of the applied stress [4], [11]. For stress-current annealed wires with positive λ_s it was reported [4] that the creep-induced-anisotropy increases with increasing applied stress. Typically, for wires annealed at a current density of 40.7 A/mm^2, the application of a stress $\geq$500 MPa would reduce the portion of the core domains and create a better defined shell structure, with the magnetization occurring mainly by shell domain wall movements [4]. An intermediate situation between the high stress magnetic configurations is obtained with the application of stresses lower than 500 MPa [4]. It has been proposed that the magnetic configuration so induced, still having a larger proportion of shell domains than as-cast samples, retains a sufficient fraction of the inner core domains to induce an axial orientation of the shell. The magnetization is therefore characterized by a domain rotation mechanism. As shown in Fig. 2(a) and (b), the trend of the susceptibility and coercivity is similar to that of simple current annealed samples, with higher values of H_c. The enhancement of the short-range atomic ordering increases the stability of the domain walls. Similar behavior was observed in negative λ_s samples, for which a somewhat weaker anisotropy is obtained.

Also, in the case of stress annealed wires, furnace annealing gives very different properties from current annealing, as shown in Fig. 3(c) and (d). With a relatively unchanged coercivity and a small reduction in the susceptibility, the hysteresis loops appear to be not very different from the counterpart for the as-cast state. A magnetization free of the Barkhausen jumps is generated by the furnace annealing treatment. The reason for the large disparity between the current and furnace treatments can again be ascribed to differences in the dynamics of the two processes. At the end of the furnace annealing, the stress is removed when the sample is extracted from the furnace, during which phase the cooling rate is relatively low prior to quenching in water. The magnitude of the anisotropy created by the induced stress is therefore reduced, once the stress is removed.

The anisotropy induced by a stress annealing is in all cases larger than that originating from heat treatment alone, irrespective of the annealing method.

IV. Conclusion

Amorphous alloy wires with vanishing magnetostriction exhibit a series of changes in their magnetic structure as they are subjected to different annealing treatments. A purely thermal treatment gives rise to a series of Barkhausen jumps which correspond to different magnetic states and which can be manipulated by a creep-induced-anisotropy mechanism. The magnetic configuration, which is established on releasing the stresses that are quenched in by the initial casting process, is replaced by a new core-shell distribution imposed by the stress applied during the heat treatment. As a result, the magnetization reversal occurs smoothly and free of Barkhausen jumps.

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