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Effects of Intrinsic Forces in Toroidal Cores Wound of Soft-Magnetic Ribbons

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Magnetic anisotropy as shown by hysteresis loops of tape-wound toroidal cores has been inspected as to the specific response of the anisotropy to core-internal forces during and after annealing. The loops of toroids are compared to that of strip samples annealed together in various ambience. The core-internal forces were manipulated by means of different core construction, too. The results show that it is the heterogeneity, which produces the most effective forces. Different annealing-induced ribbon shrinkage makes the cores effectively heterogeneous and governs their magnetic response, whereas inherent ribbon heterogeneity affects the core properties, too, and is essential for homogeneous cores.

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1. Introduction

The most obvious reason to study the intrinsic forces in tape-wound toroidal cores is to aid a proper core construction and manufacturing. Nevertheless, certain less studied properties of rapidly quenched (RQ) ribbons emerge as specifically important in this task and so new knowledge about the materials could be gained. The principal property of RQ ribbons, which can result in intrinsic force in the cores is the anisotropic shrinkage of the as-cast ribbon during thermal treatment [1]. Bobbins [2] or inhomogeneous heating (thermal stress) are the better known reasons for the core-internal force. Apart from these "ribbon-external" causes, the ribbons show macroscopic heterogeneity (MH). We chose this term to encompass particular properties known as "surface oxide layer" or "surface crystallization" etc., where surfaces differ from the ribbon interior. This ribbon-internal property can create macroscopic force and can behave differently in cores than within a free strip. The major task of this work is to look for possible systemic core — strip differences in MH behavior and to see whether the forces due to the ribbon shrinkage also add to the magnetic anisotropy of annealed tape-wound toroidal cores.

2. Experimental

Planar-flow casting on air was used to prepare the ribbons of 22 to 26 μm thickness. In the following text, labels for the composition are used as follows: "Hitperm" — $Fe_{61}Co_{20}Nb_7B_{12}$ (6 mm wide), low-Si Finemet "lo-SiFM" — $Fe_{78}Nb_3Cu_1B_{13.5}Si_{4.5}$ (10 mm wide), high-Si Finemet "hi-SiFM" — $Fe_{73.5}Nb_3Cu_1B_9Si_{13.5}$ (10 mm wide). The hysteresis loops were recorded by a digitizing-oscilloscope-based setup at 21 Hz sinusoidal excitation. The harmonics contents of the response signal was inversely proportional to the sample cross-section (the richest for single strips) and this fact has been taken into account at the evaluation. The strips are 8 to 10 cm long so as to keep the demagnetization factor D (calculated using elliptic integrals) of 6 and 10 mm wide samples in a narrow range 5.9 to 6.7×10^{-5}, respectively. The toroidal cores show 30 mm inner diameter and ≈ 34 and ≈ 31 mm outer diameter for 50- and 10-turns cores, respectively. All the cores were wound under 3 MPa tension of ribbon with the air side up.

3. Results and discussion

The three materials were chosen according to their substantially different annealing-induced dilatation behavior as seen in Fig. 1. We only consider changes of the ribbon length since there is no obvious reason to observe ribbon width changes for axially unaffected toroids.

Whereas hi-SiFM shrinks significantly due to partial crystallization, the lo-SiFM hardly shrinks despite of its lower first crystallization onset temperature [3]. The Hitperm starts to flow viscously at $\approx 400\,^{\circ}$C. It flows less above $\approx 500\,^{\circ}$C, but at a non-falling temperature up to $600\,^{\circ}$C, it does not shrink even against a tension as low as 1 MPa (Fig. 2).

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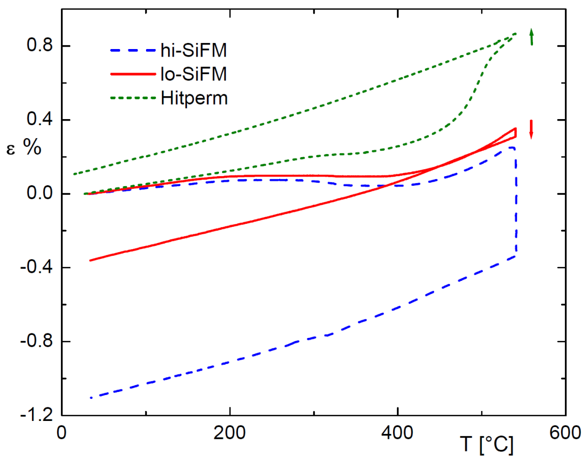

Fig. 1. Longitudinal dilatation measured at 7 K/min temperature rate under ≈ 2.5 MPa tension. The arrows on the right indicate the small dimension change during the 40 min isotherm.

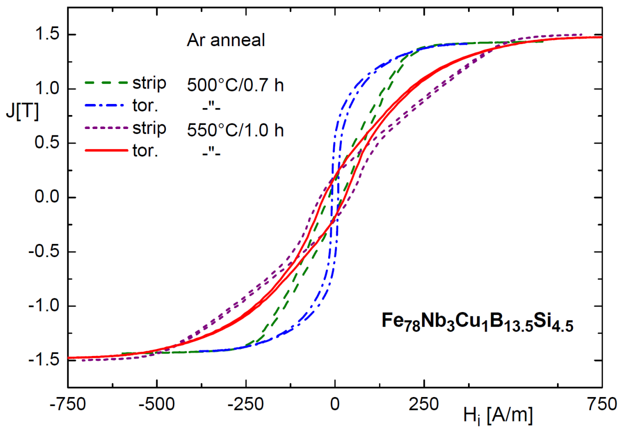

Fig. 2. Hysteresis loops after different Ar annealing. H_i denotes the internal field, D — the demagnetization factor. $H_\mathrm{i} = H_\mathrm{ext} - DJ/\mu_0$ for the strips, $H_\mathrm{i} \sim H_\mathrm{ext}$ for the 50-turn toroids.

The loops of lo-SiFM show all some extent of hard-ribbon-axis (HRA) anisotropy, which causes the tilt. The material is highly positively magnetostrictive ($\lambda_\mathrm{s} \approx 10^{-5}$, 540 °C annealed), thus magnetoelastic anisotropy according to the well-known relation $K_\mathrm{u} = (3/2)\lambda_\mathrm{s}\sigma$ provides the most straightforward explanation. The stress σ is an in-plane one and comes from ribbon surfaces squeezing the ribbon interior. Its source could be the surface crystallization, for which is the material known [4]. The three slant loops show a "belly" at low fields, which is a consequence of in-plane stress that forces the easy direction off the ribbon plane and induces stripe domains that cause the excess hysteresis [5]. Since the stress in the above sense is shown less by toroids than strips, there is little reason to look for additional core-specific stress. In contrary, the MH transformation (e.g. surface crystallization), which runs during annealing could be somewhat limited within the toroids and so the benchmark of MH-caused in-plane stress — a slant loop with belly — comes less well expressed (Fig. 3).

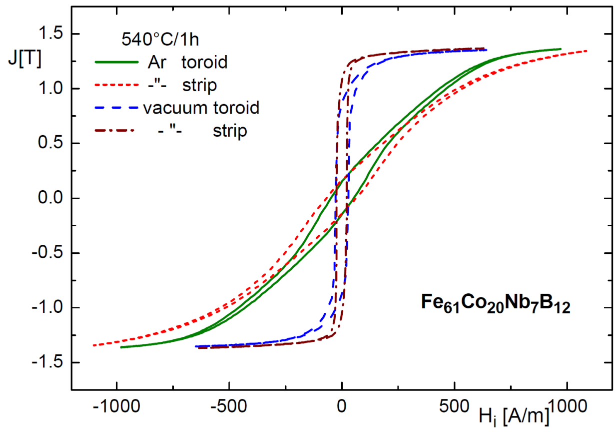

Fig. 3. Hysteresis loops of Hitperm after annealing in different ambience. The exciting field H for strips and 50-turn toroids follows the same principle as for Fig. 2.

Hitperms can flow and do not shrink powerfully — significant relaxation or building of only a weak stress within toroids can thus be expected. Indeed, only minor differences between toroids and strips are observed. Whereas lo-SiFM showed only negligible toroid-strip difference after 540 °C vacuum annealing (therefore not shown), the Hitperm toroid shows a more round-knee loop than the reference strip. Nevertheless, Hitperm is extremely sensitive to MH [6] and the ribbon batches show some longitudinal fluctuation of MH. Indeed, few equivalently annealed strip samples showed modestly tilted loops with higher coercivity, too. The 50-turn core consumes ≈ 5 m of ribbon and the ribbon properties are so averaged. Therefore it is not substantiated to ascribe the observed loop difference to a core-specific additional stress. Ar-annealed samples show the same toroid-strip relation as the lo-SiFM.

The reference experiment where we removed 10 outer turns from all Ar-annealed toroids resulted in a minor change of HRA anisotropy (as determined from the loop tilt). The change was an increase in Hitperm (≈ +5%) and a decrease (≈ −3%) in lo-SiFM. There thus might be some minor stress residuals within the cores. Nevertheless, an anisotropy coming from such stresses has never been found significant.

To introduce a well-defined heterogeneity, we wound a series of interlaced cores as if using a bimetal but without actually fixing the two "metals" together. Apart from standard 50-turn cores, reference 10-turn cores were wound, too, to enable easier inter-turn slipping. This was expected since materials with large annealing shrinkage difference have been chosen — lo-SiFM and hi-SiFM.

Figure 4 indeed displays huge differences. The induction was computed using the average of annealed density

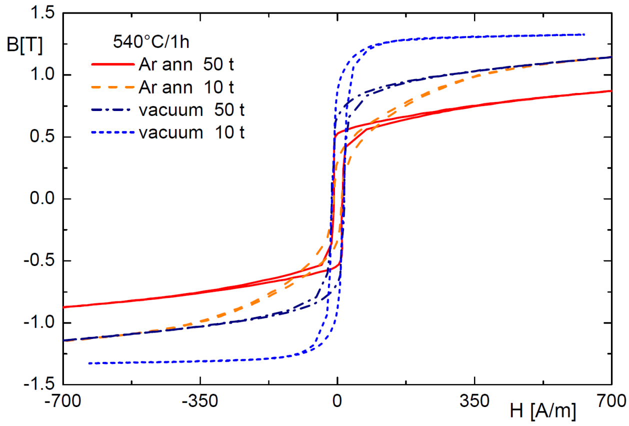

Fig. 4. Hysteresis loop of interlaced toroids annealed in different ambience. The number followed by "t" indicates the number of core turns.

(7.45 g/cm^3) of the two constituent materials. Ar annealing resulted in very poorly saturating loops. It is the lo-SiFM, which causes the effect — the more shrinking hi-SiFM exerts longitudinal (probably normal, too) compression and huge HRA builds up in the lo-SiFM part. The magnetoelastic interaction is again the main source. Creep-induced-like anisotropy (CILA) cannot be excluded as its sign is the same, however, no clear tilt is observed in the middle of the loop. It should be there if CILA has been created and preserved since the hi-SiFM acquires HRA anisotropy when annealed under tensile stress. Tens of MPa were for sure acting on the ribbons as can be judged from the above formula and the resulting anisotropy shown by lo-SiFM. The lack of clear CILA signs is somewhat surprising and deserves further analysis. Nevertheless, the steep part of the loop reaches roughly up to half of the attainable saturation and signals that at least the half of the core saturates promptly at a low field — most probably it is just the hi-SiFM part. Vacuum-annealed 50-turn core simply shows that some turns could slip over one another and relax a part of the stress so that not the whole used ribbon length stands under significant stress. Ar-annealed 10-turn core evidently could not fully relax the stress from different shrinkage — it appears that MH transformation in Ar creates slip-proof surfaces, which partly hinder the stress relaxation. The contribution of MH-caused lo-SiFM ribbon-internal stress is clearly visible by the gradual approach to saturation. Vacuum annealed 10-turn core successfully relaxed the stress and shows a "summed" loop with no clear signs of stress influence.

4. Conclusion

Ribbon properties essentially determine the magnetic properties of a homogeneous tape-wound core, at least up to the size used in our experiments. The annealing ambience affects the toroids similarly as it affects single strips, in particular — the MH-caused in-plane stress creates its typical magnetic anisotropy in toroids, too. Significant impact of core-specific stress can be expected on heterogeneous cores — e.g. composed of ribbons with different thermal expansion.

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References

[1] P. Butvin, B. Butvinová, G. Vlasák, P. Duhaj, M. Chromčíková, M. Liška, E. Illeková, P. Švec, *J. Phys. Conf. Series* **144**, 012101 (2009).

[2] P. Butvin, M. Hlásnik, P. Duhaj, B. Butvinová, K. Záveta, L. Kraus, K. Jurek, *J. Magn. Magn. Mater.* **112**, 359 (1992).

[3] E. Illeková, *Termochim. Acta* **387**, 47 (2002).

[4] P. Butvin, B. Butvinová, Z. Frait, J. Sitek, P. Švec, *J. Magn. Magn. Mater.* **215-216**, 293 (2000).

[5] A. Hubert, R. Schäfer, *Magnetic Domains: The Analysis of Magnetic Microstructures*, Springer-Verlag, Berlin 1998, p. 478.

[6] P. Butvin, B. Butvinová, J. Sitek, J. Degmová, G. Vlasák, P. Švec, D. Janičkovič, *J. Magn. Magn. Mater.* **320**, 1133 (2008).