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High-Frequency Inductor Materials

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The Finemet-type nanocrystalline alloy represents an advanced soft-magnetic metal–metal-type nanocomposite with an eddy-current-determined high-frequency limit. A survey of different heat treatments under tensile stress is presented to tailor the hysteresis loop by induced transversal anisotropy. The flattened loop having reduced effective permeability enhances the eddy-current limit in the MHz region; For example, continuous stress annealing in a tubular furnace of 1 m length at 650°C, pulling the ribbon with a velocity of 4 m/min under a tensile stress of 200 MPa, results in a wound core having a permeability of 120 and a frequency limit of 10 MHz. Careful annealing preserves the static coercivity below 10 A/m. The power loss at 0.1 T and 100 kHz is only 82 mW/cm^3, which is an order of magnitude lower then the values obtained for Sendust™ cores in similar conditions.

Key words: Nanocrystalline alloy, Finemet, tensile stress annealing, transversal induced anisotropy

INTRODUCTION

According to today's trends, electricity will be the dominant vector for energy transport and distribution. Contributions to such evolution are: on the demand side, a growing number of technologies which need electric power, and on the supply side, new energy sources such as wind and solar that are mainly aimed at producing electric power. For these reasons, new, optimized soft-magnetic materials are necessary for technologies such as advanced electric storage systems, smart controls, and power electronics for alternating current (AC)–direct current (DC) conversion. Reducing the mass and volume of inductors and transformers in power converters and inverters is a major demand nowadays in aerospace and automobile applications.

Downscaling of power electronic devices has led to the requirement for higher driving frequencies and higher working temperatures for inductive elements. Signal electronic devices also require high-frequency inductors to make maximum use of available bandwidth for transmitting and receiving signals. High working temperature is a prerequisite for both soft- and hard-magnetic materials to be used in drive-by-wire and brake-by-wire systems in modern electric automotive and aircraft industries.

The eddy-current limits for metallic cores should be shifted above 1 MHz to keep operating frequencies about 100 kHz to 500 kHz. This eddy-current frequency limit: $f \sim \frac{\rho}{t^2\mu}$ (where ρ is the specific electric resistance, t is the thickness, and μ is the effective permeability) is increased by transversal induced anisotropy, which diminishes the permeability while keeping the coercivity as low as possible. Especially in the context of aerospace applications, a magnetic material that can maintain a lower core loss over the applicable temperature range can provide a basis for nosing out the competition from ferrites (with a limited temperature range) and from crystalline permalloy of 17 μm thickness (with limited plastic yield strength).

It has been recognized[1] that, for low loss and wide temperature range applications, stress-annealed Finemet represents an advanced material permitting new solutions for high-frequency aerospace and vehicle magnetic applications. Compact toroids without a gap can be prepared with variable low permeability and high quality factor.[2] This work presents the magnetization properties and core loss as a function of continuous stress annealing parameters.

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EXPERIMENTAL PROCEDURES

Amorphous ribbons with Finemet composition ($Fe_{73.5}Si_{15.5}B_7Nb_3Cu_1$) of 4 mm, 6 mm, and 10 mm width were produced by planar flow casting. For comparison, some ribbons were obtained from Hitachi Metals Ltd. and from Vacuumschmelze GmbH as well. The equipment used for fabricating nanostructured Fe-based sheets with stress (creep)-induced anisotropy was similar to that applied by others,[2,3] based on an open tubular furnace through which the ribbon is passed under a stress between 10 MPa and 500 MPa with pulling velocity between 1 m/min and 50 m/min. Due to the high pulling velocity, the heating rate exceeds several hundred kelvin per second and the time spent at the maximal temperature is reduced to only a few seconds, equivalent to quench or flash annealing.

The saturation magnetostriction constant λ^s of the ribbon was determined by the small-angle magnetization rotation (SAMR) method from the change of the anisotropy constant due to the application of tensile stress. DC and AC magnetic properties of the prepared cores were determined using a computer-aided quasistatic loop tracer and an Agilent *RLC* analyzer, respectively. Most of the power loss data were taken between 1 kHz and 100 kHz (sinusoidal) at room temperature, at selected peak B_{peak} fields, mainly for B_p = 0.1 T.

RESULTS AND DISCUSSION

In accordance with our earlier results,[4] the induced anisotropy, K_i, was found to vary linearly with the applied stress, σ, and the steepness, $m = \Delta K_i/\Delta\sigma$, was found to be around 8×10^{-6} to 10×10^{-6} (8 ppm to 10 ppm), depending on the details of the technology. This experimental steepness is in accordance with the back-stress model of Herzer[5] ($K_i = -3/2\lambda^s_{cr} \cdot x_{cr} \cdot \sigma$). The saturation magnetostriction of the sample is a weighted sum of the amorphous ($\lambda_{am} \approx +22$ ppm) and crystalline $Fe_{80}Si_{20}$ ($\lambda_{cr} \approx -9$ ppm) components and decreases with the crystalline fraction x_{cr} as $\lambda = 22 - 0.32 \cdot x_{cr}$. Zero magnetostriction is obtained for a crystalline fraction $x_{cr} \approx 70\%$. The coercive field determined from the quasistatic measurements (Fig. 1a, b) was minimal as a function of the furnace temperature where the magnetostriction was also minimal (Fig. 2).

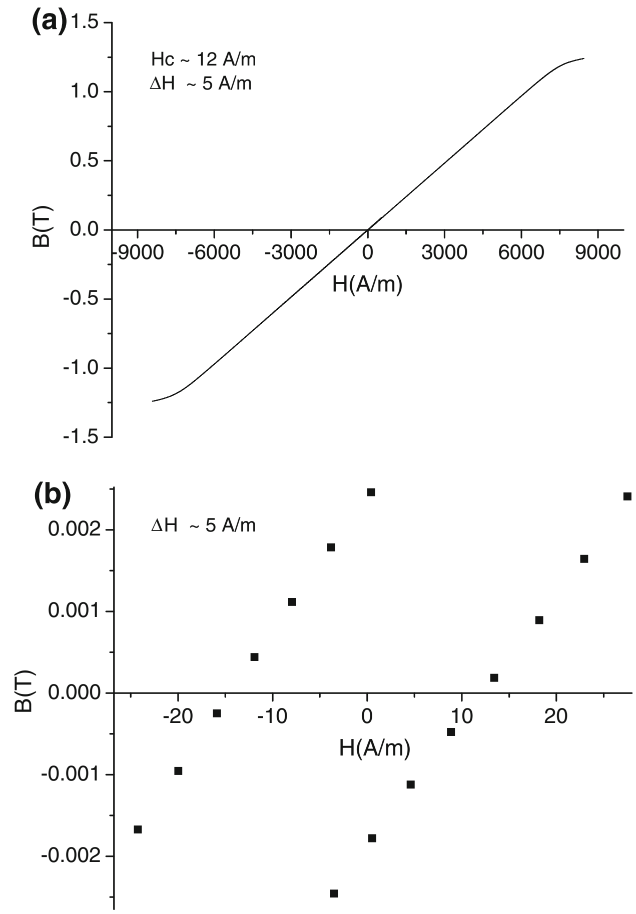

Fig. 1. (a) Linear hysteresis loop ($\mu_{eff} \approx 128$) obtained by continuous stress annealing. (b) Quasistatic measurement (f = 0.005 Hz) with resolution of about 5 A/m.

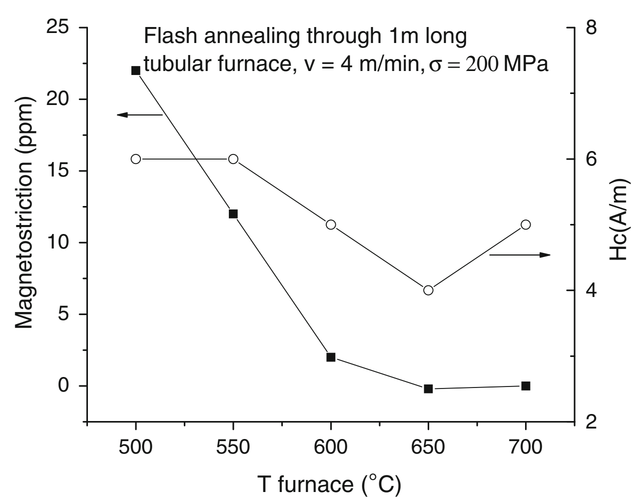

Fig. 2. Dependence of the magnetostriction and coercivity on the temperature of the tubular furnace.

As the magnetization in the core changes by magnetization rotation, the power loss is very near to the value determined by classical eddy-current calculations: $P_{cl} = (\pi \cdot t \cdot B_p \cdot f)^2/6\rho$, where t and ρ are the ribbon thickness and the resistivity, respectively. Considering $t = 20\ \mu$m and $\rho = 120\ \mu\Omega$ cm, one obtains $P_{cl} = 55$ mW/cm^3 for B_p = 0.1 T and f = 100 kHz. This is a lower bound for the eddy-current loss.

Estimation of the hysteresis loss is rather difficult because the apparent H_c (H_c^{ap}) at the given B_p is not known beforehand. In the linear approximation, $P_h = 4H_c^{ap} \cdot B_p \cdot f$. Considering $H_c^{ap} \approx 1$ A/m, one obtains $P_h = 40$ mW/cm^3 for B_p = 0.1 T and f = 100 kHz. This is an upper bound for the hysteresis loss for the ultrasoft-magnetic materials considered here, for which H_c^{sat} is less then 10 A/m.

Table I. Comparison of losses for different cores

	μ_{eff}	P (mW/cm^3) at 0.1 T and 100 kHz	Frequency dependence at B_p = 0.1 T
Powder core			
Sendust	100	900	$1.07 \times 10^{-4} f^{1.378}$
Molypermalloy	100	700	$2.76 \times 10^{-5} f^{1.475}$
Fe-based bulk metallic glass powder	120	600	$1.8 \times 10^{-6} f^{1.76}$
Fe-based traditional metallic glass powder	120	580	$1.89 \times 10^{-5} f^{1.497}$
Toroid cores			
Round-type Finemet	90000	72	$1.53 \times 10^{-9} f^{2.134}$
Magnetic field-annealed 500F type	20000	63	$5.64 \times 10^{-8} f^{1.81}$
Continuous stress-annealed Finemet	120	82	$1.4 \times 10^{-8} f^{1.953}$
Continuous stress-annealed Finemet	980	85	$2.14 \times 10^{-9} f^{2.12}$

Usually, above 100 kHz the hysteresis loss can be neglected beside the eddy-current one. However, if one introduces large stresses during the preparation of the tape core using small core diameter, H_c is increased and so the hysteresis loss can no longer be neglected.[6]

Table I presents a comparison between the frequency dependencies of the core loss of different types of samples obtained at B_p = 0.1 T peak induction. Empirically it was found that the hysteresis loss, in general, is proportional to $(B_p^{1.5-2} \cdot f)$ and the eddy-current loss increases as $(B_p^{1.5-2.5} \cdot f^{1.5-2})$. Table I shows that the total loss goes as $f^{1.5-2}$, indicating that the hysteresis loss can be neglected beside the eddy-current loss at high frequencies.

The flatness varies linearly with the applied stress, as is expected from the expression for permeability as a rotational process: $1/\mu = 2K_i/J_s^2$, but applying continuous (flash) annealing (at 640°C to 660°C), the flatness increases more strongly than for the static annealed (at 530°C to 550°C) samples (Fig. 3).

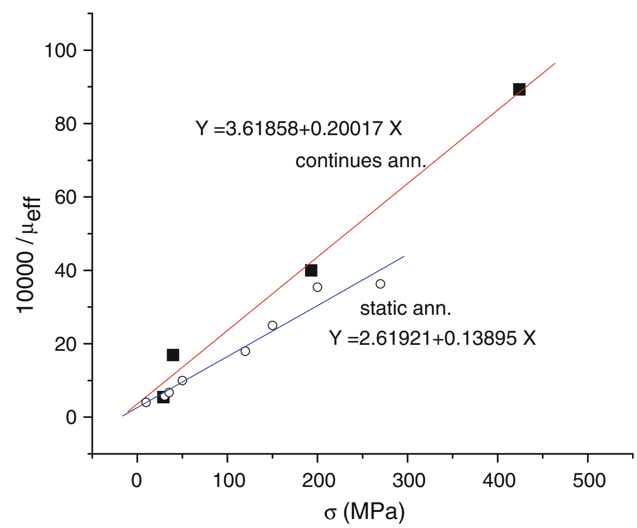

Fig. 3. Evolution of the inverse effective permeability (flatness) as a function of applied stress for statically annealed (550°C, 0.5 h) and continuously annealed (650°C, 15 s) samples.

In addition, it was found that the flatness does not depend on the velocity of the ribbon, whereas the coercivity does. In Fig. 4, optimization of the coercive force as a function of pulling velocity is presented for a 6-mm-wide ribbon passing under a stress of 28 MPa through a 3-m-long furnace kept at 660°C.

There is an optimal velocity around 10 m/min to 15 m/min. This is why, to increase productivity, the velocity of the ribbon should be increased together with the length of the tubular furnace, maintaining about 5 s to 10 s annealing time, which was found necessary to develop the stress-induced anisotropy at 650°C to 670°C.

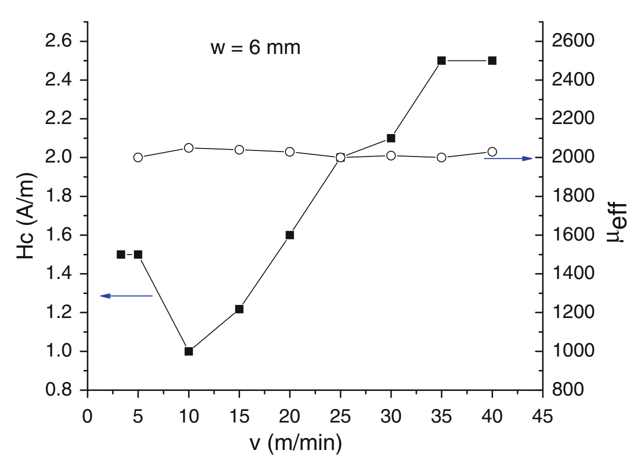

Fig. 4. Coercivity and effective permeability as a function of pulling velocity for a 6-mm-wide ribbon annealed at T_{ann} = 660°C.

The creep was studied as a function of both the pulling stress and pulling velocity. It was found that, while the overall elongation increases linearly with the applied stress (Fig. 5), the increase of length and decrease of cross-section ($\Delta S/S_0$) depend on the pulling velocity as well (Fig. 6).

In addition, it was found that the devitrification process front advances along the ribbon, occurring heterogeneously across the width of the ribbon to form a V-like profile.

The depth of this V-like profile increases with the pulling velocity, which is detrimental for the coercivity. The wider the ribbon, the more difficult it is

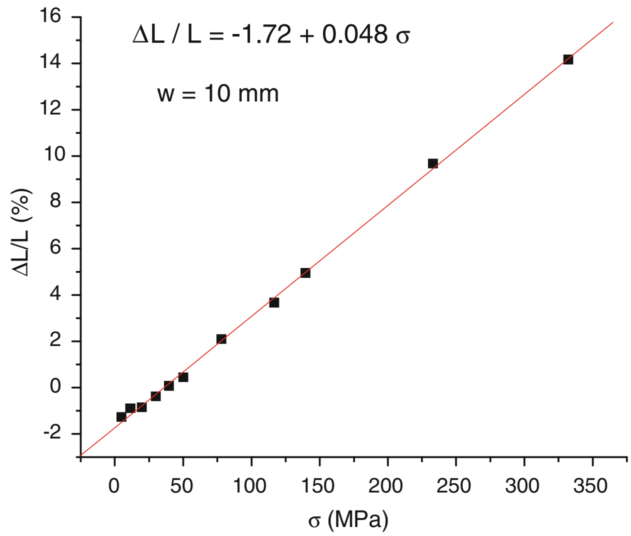

Fig. 5. Elongation as a function of tensile stress of a 10-mm-wide ribbon in a 3-m-long furnace at 660°C applying *v* = 20 m/min.

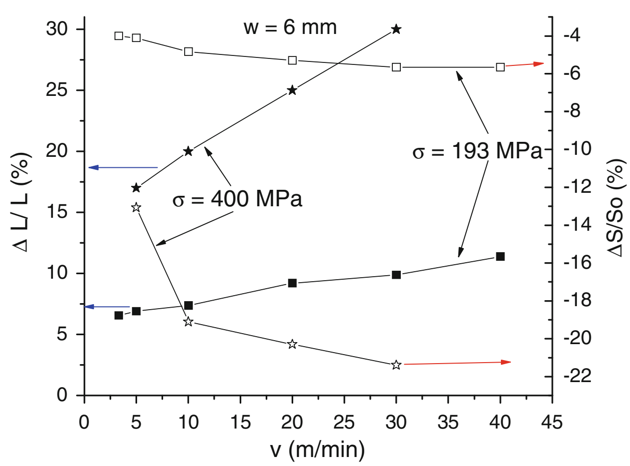

Fig. 6. Increase of length and contraction of cross-section as a function of pulling velocity in a 3-m-long tubular furnace kept at 640°C.

to avoid this V profile and ensure high productivity by a large pulling velocity.

Considering all these problems, continuous or flash annealing proved to be superior to the cut cores, although the impregnated Finemet-type core can be easily cut and the cut core presents no severe deterioration of magnetic properties. The in-plane eddy-current loss generated by leakage flux normal to the ribbon surface could be reduced considerably, by attachment of a thin ferrite plate to cut surfaces.[7] Still, the power loss figures of 900 mW/cm^3 at 0.2 T and 225 mW/cm^3 at 0.1 T (100 kHz) are higher then those obtainable by continues stress annealing.

CONCLUSIONS

The technologically important parameters of continuous (flash) annealing are the annealing temperature, pulling velocity, and tensile stress. To obtain high productivity, high pulling velocity should be applied (above 20 m/min), at the highest temperature allowed by the time–temperature-dependent devitrification process (660°C to 670°C). Cores with effective permeabilities between 100 and 20,000 can be produced in large quantities less expensively then those obtainable by magnetic field annealing having $\mu_{eff} > 20{,}000$. The localized devitrification of the passing ribbon should proceed uniformly across the width of the ribbon to ensure the lowest coercivity. For a wider ribbon (above 10 mm) it is more difficult to ensure uniform crystallization.

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