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Comparison of Uniaxial and Rotational Magnetostriction of Non-oriented and Grain-oriented Electrical Steel

Abstract. *Surface domain patterns in electrical steel, which appear under rotational magnetisation, were noted to be comparable to those which are observed under high compressive stress. This paper presents comparison of peak to peak magnetostriction of Epstein strips under high compression magnetised along rolling and transverse directions, and disc samples under rotational and uniaxial magnetisation with no external stress applied. Good correlation was found between magnetostriction measurement results obtained in the rolling direction of non-oriented Epstein strips under high compression and disc samples under rotational magnetisation. Also it was observed that the rotational magnetostriction of grain-oriented electrical steel is greater than its uniaxial value under compressive stress.*

Streszczenie*. Artykuł prezentuje porównanie magnetostrykcji pasków Epsteina magnesowanych wzdłuż i prostopadle do kierunku walcowania (podanych naprężeniu) oraz próbek w formie dysku poddanych magnesowaniu osiowemu i rotacyjnemu (bez naprężenia). W przypadku blach niezorientowanych znaleziono korelację między magnetostrykcją w kierunku walcowania oraz stratami przy magnesowaniu rotacyjnym. W przypadku blach zorientowanych magnetostrykcja rotacyjna była większa niż jednoosiowa przy naprężeniu próbki. (****Porównanie jednoosiowej i rotacyjnej magnetostrykcji blach elektrotechnicznych zorientowanych i niezorientowanych****)*

Keywords: magnetostriction measurement, rotational and uniaxial magnetisation, compressive stress.
Słowa kluczowe: pomiar magnetostrykcji, magnesowanie rotacyjne.

I. Introduction

Uniaxial and rotational magnetostriction in magnetic cores of electrical machines such as transformers and motors are a potential source of core vibration and acoustic noise. The magnetic domain structures of electrical steels under dynamically rotating magnetisation alternate between well known bar patterns and a more complex distribution at certain times in the magnetising cycle [1]. This characteristic complex structure resembles that of stress pattern I and pattern II, which appear on the surface of grain-oriented electrical steel under high compressive stress applied parallel to its rolling direction [2]. Magnetostriction studies have been carried out on Epstein strips and discs of non-oriented and grain-oriented electrical steels under uniaxial and rotational magnetisation.

II. Experimental Approach

Samples were taken from grain-oriented (GO) electrical steel: conventional (CGO) and high permeability (HGO), and non-oriented (NO) electrical steel. Thicknesses from 0.30 to 0.50 mm were cut as 80 mm diameter discs and 305 mm long Epstein strips parallel to the rolling direction (RD) and the transverse direction (TD). All disc and Epstein samples were cut by electrical discharge machining (EDM) and then stress relief annealed. Peak to peak (pk-pk) magnetostriction under 50 Hz AC magnetisation was determined using two measurement techniques: piezoelectric accelerometers for Epstein samples [3] and surface mounted foil resistance strain gauges for disc samples [4].

Epstein strips were inserted singly into an AC magnetostriction measurement system. One end of the strip was clamped, and the other end was attached to an accelerometer, load cell and a pneumatic cylinder as shown in Fig.1.

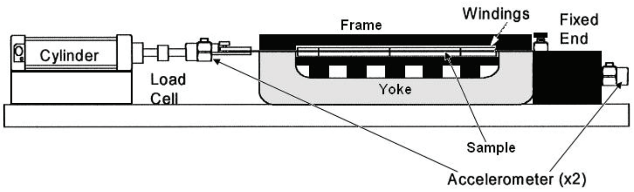

Fig.1. AC magnetostriction measurement system with two accelerometers.

Peak to peak magnetostriction was obtained from double integration of the output signal of the accelerometer with the measurement uncertainty of 0.5 % under no external stress condition and 5 % under 10 MPa of applied compressive stress. GO samples cut along the RD were singly magnetised along the strip length from 1.00 T to 1.70 T at 0.10 T intervals and 50 Hz with uncertainty 0.2 %. However, the maximum sinusoidal induction achievable in GO samples cut along the TD and NO strips was 1.50 T and 1.60 T respectively.

Each disc was magnetised in a two-dimensional (2D) magnetisation system. Fig.2a shows the two phase excitation winding used to produce alternating magnetisation along the RD and TD, and under rotational magnetisation in the induction ranged from 1.00 T to 1.70 T at 50 Hz with uncertainty 2 %. Components of flux density along the RD and TD were calculated from voltages induced in the orthogonal search coils wound at the centre of the sample.

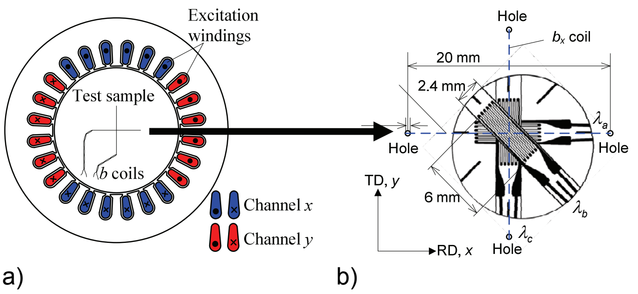

Fig.2. Schematic diagrams of two dimensional magnetostriction system: a) configuration of excitation windings and search coils, b) rosette resistance strain gauges placed at the centre of each disc sample.

Magnetostriction components along the RD and TD were measured using rosette resistance strain gauges placed in the centre of the disc sample (Fig.2b). The measurement uncertainty of the average peak to peak magnetostriction was evaluated to be ± 12%. Each gauge had an active area 6 mm long and 2 mm wide and a gauge factor of 2.1 ± 1 %. The nominal gauge resistance was 120 Ω. The resistance of the gauge changes proportionally to the change in strain on the surface of the sample. This resistance change is measured using Wheatstone bridge in a half bridge configuration with a set of dummy gauges attached on a dummy unmagnetised disc of Si-Fe steel for temperature compensation. Strain gauges placed with their measurement axes parallel to the rolling and the transverse directions were used to measure magnetostriction of the disc sample.

A static domain viewer based on the bitter technique was used to observe patterns on the uncoated steel surface of Epstein strips under compression of up to -10 MPa to help understand the magnetostriction mechanism under rotational magnetisation. Fig.3a shows static patterns observed on the surface of a typical CGO sample under compressive stress in demagnetised state.

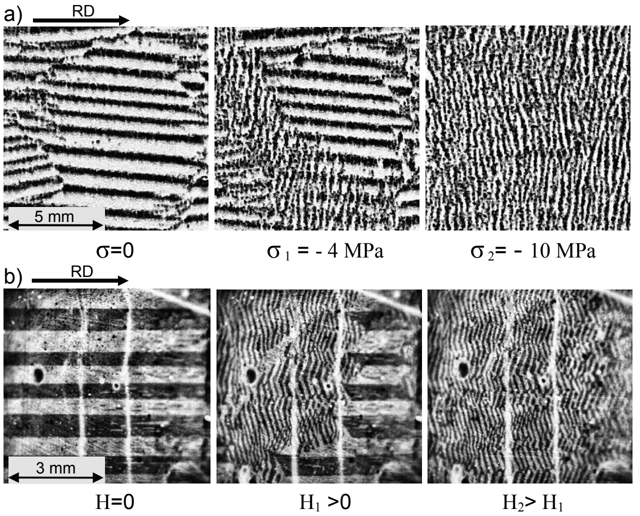

Fig.3. Static domain structures on the surface of a strip of CGO steel under: (a) compressive stress along the RD, (b) DC magnetisation along the TD.

Fig.3b shows similar transverse closure domains present on the polished surface due to DC magnetisation along the TD of the strip with no external applied stress. This was observed using a Kerr magneto optic microscope [5]. Static domain structures as presented in Figs. 3a and 3b were observed on the surface of two CGO samples.

III. Results

The magnetostriction of disc samples was measured along the RD and the TD under rotational ("Rotational Disc") and uniaxial ("Uniaxial Disc") magnetisation with no external applied stress. Epstein strips were magnetised along the RD and the TD, where magnetostriction was measured under various magnitudes of applied stress (+10 MPa to -10 MPa) [3]. Two values of pk-pk magnetostriction were chosen for analysis from the measurements under stress: maximum magnetostriction under high compression ("Uniaxial Epstein High Compression") and magnetostriction under no external applied stress ("Uniaxial Epstein No Stress"). All Epstein and disc samples were initially demagnetised by stress relief annealing and also by a slow reduction of an alternating field after each magnetisation cycle. The collation of magnetostriction measurements under reference conditions are presented in Table 1.

A disc sample of the 0.50 mm thick NO steel, magnetised under rotational magnetisation was found to have a comparable characteristic of magnetostriction to the Epstein strip under high compression (Fig.4a). A similar tendency was found for disc and Epstein strips with no external stress under uniaxial magnetisation in the RD. (Fig.4a) Epstein strips cut along the TD and magnetised with and without external applied stress, had a lower magnetostriction than disc samples under uniaxial and rotational magnetisation (Fig.4b).

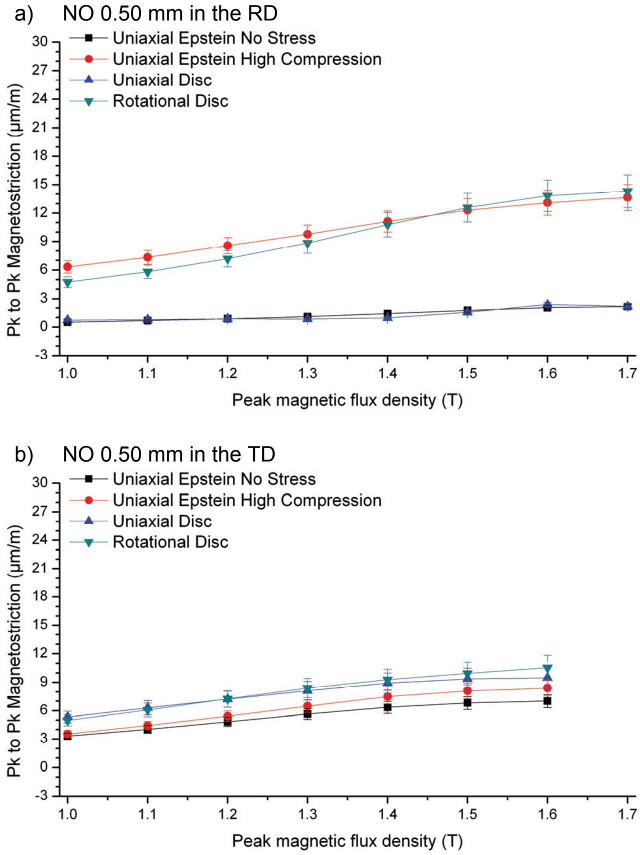

Fig.4. Variation of rotational and uniaxial pk-pk magnetostriction with flux density of 0.50 mm NO electrical steel measured along: (a) the RD, (b) the TD.

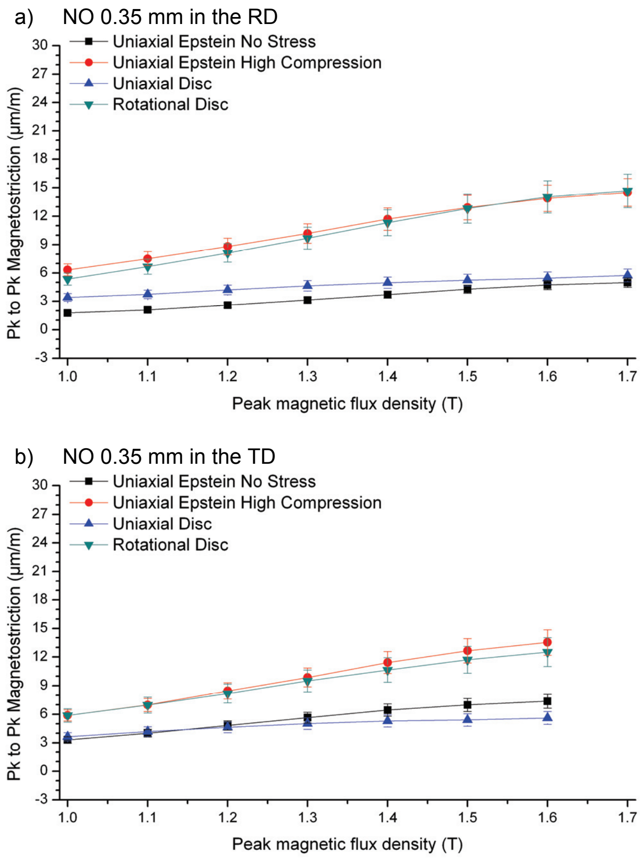

Fig.5. Variation of rotational and uniaxial pk-pk magnetostriction with flux density of 0.35 mm NO steel measured along: (a) the RD, (b) the TD.

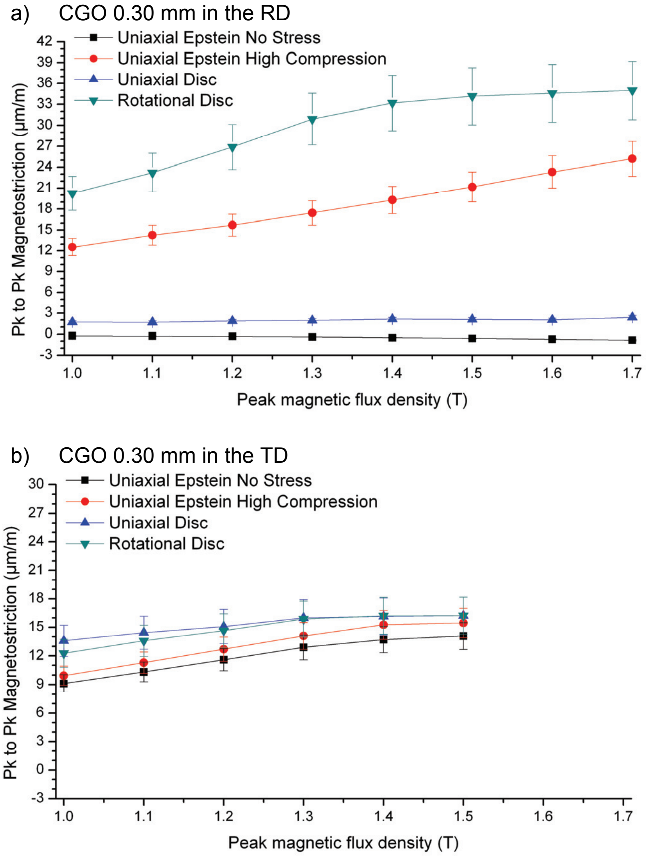

Fig.6. Variation of rotational and uniaxial pk-pk magnetostriction with flux density of 0.30 mm CGO electrical steel measured along: (a) RD, (b) TD.

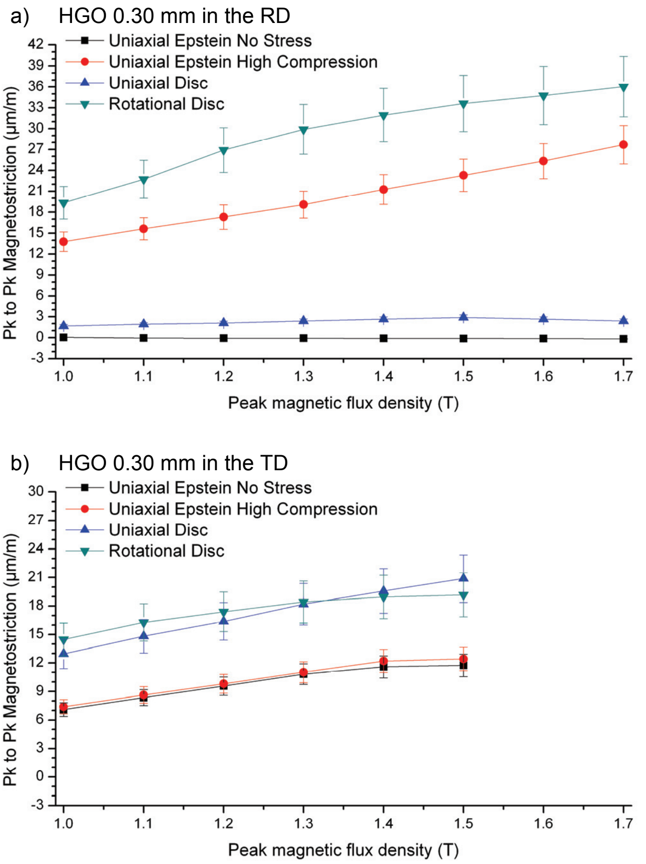

Fig.7. Variation of rotational and uniaxial pk-pk magnetostriction with flux density of 0.30 mm HGO electrical steel measured along: (a) RD, (b) TD.

Table 1. Collation of magnetostriction with reference conditions

Sample name	Applied stress	Excitation in	Magnetostriction measured in
Uniaxial Epstain No Stress	No Stress	RD	RD
		TD	TD
Uniaxial Epstain High Compression	Compression in RD	RD	RD
	Compression in TD	TD	TD
Uniaxial Disc	No Stress	RD	RD
		TD	TD
Rotational Disc	No Stress	Alternating Direction	RD and TD

A similar relationship was obtained for 0.35 mm thick NO steel disc magnetised in a rotational field and Epstein strip under higher compression (Fig.5a). However 0.35 mm thick NO steel Epstein strip under uniaxial magnetisation, exhibited lower magnetostriction along the RD than the disc sample magnetised in the same direction up to 1.4 T and comparable above that flux density level.

Magnetostriction measured along the TD was comparable to that of Epstein strip under stress and disc sample under rotational magnetisation at lower induction and higher for disc sample above 1.2 T (Fig.5b). A similar variation of magnetostriction can be observed due to uniaxial magnetisation for disc and Epstein samples with no applied stress (Fig.5b).

The magnetostriction of the 0.30 mm thick CGO and HGO disc samples under rotational magnetisation was higher than that of Epstein strips under high compression measured along both directions (Fig.6 and Fig.7). Also magnetostriction under uniaxial magnetisation with no external applied stress was slightly higher for disc samples than for Epstein strips along the RD and significantly higher along the TD.

IV. Discussion

Domain rotation is expected under rotational magnetisation at high magnetic flux density. Domains in an Epstein strip cut along its RD ([001]) are forced to be oriented along [110] direction close to the TD under high compression in the unmagnetised state. If the stressed strip is magnetised along its length, some domains rotate to the longitudinal direction. Thus, magnetostriction under rotational magnetisation and that under a high compressive stress are expected to be the same. This is explicit for the magnetostriction measured in the RD and the TD of the 0.35 mm thick NO steel in Fig.5, and the RD of 0.50 mm thick NO steel in Fig.4a. The large difference of magnetostriction between Epstein strips and disc samples along the TD of the 0.50 mm thick NO steel is believed to be due to the form effect [7]. The form effect gives rise to spontaneous magnetostriction of an ellipsoid of rotation shown in Fig. 8a magnetised along its length in order to reduce the magnetostatic energy so that the total energy of the system will be minimised [7].

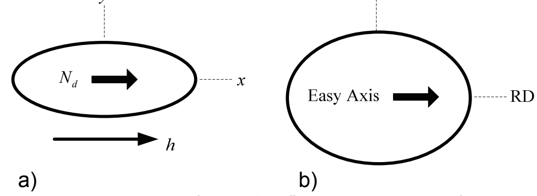

Fig.8. Demagnetisation factor "Nd" in an ellipsoid of rotation under external applied field "h" (a), equivalent shape of the 0.50 mm disc sample due to the magnetic anisotropy (b).

Disc samples of GO and 0.50 mm NO can be equivalent to an ellipse in Fig.8b due to the magnetic anisotropy. Therefore, the magnetostatic energy is the highest if magnetised along the TD. Additional magnetostriction occurs with more magnetostatic energy due to the form effect. The Becker-Döring [8] equation (1) is used to calculate the saturation magnetostriction of a single crystal (grain) of ideal GO steel.

(1)

$$\lambda_S = \frac{3}{2}\lambda_{100}\left(\alpha_1^2\beta_1^2 + \alpha_2^2\beta_2^2 + \alpha_3^2\beta_3^2 - \frac{1}{3}\right) + 3\lambda_{111}\left(\alpha_1\alpha_2\beta_1\beta_2 + \alpha_2\alpha_3\beta_2\beta_3 + \alpha_3\alpha_1\beta_3\beta_1\right)$$

where $\alpha_1\alpha_2\alpha_3$ are the direction cosines of the magnetisation direction and $\beta_1\beta_2\beta_3$ are the direction cosines of the strain direction with respect to the cube edge. λ_{100} and λ_{111} are the saturation magnetostriction constants in the [100] and [111] directions.

If a perfectly oriented (110)[001] grain in a sheet of CGO is magnetised to saturation, switching of magnetic moments from the [001] to [110] directions would cause the magnetostriction along the RD to change from λ_{100} to $-\lambda_{100}/2$, and from $-\lambda_{100}/2$ to $(\lambda_{100}+3\lambda_{111})/4$ along the [110] direction as shown in Fig.9 [6].

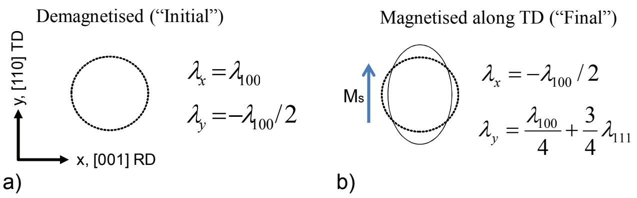

Fig.9. Schematic diagram of magnetostriction components in a single crystal of GO steel at the demagnetised state (a) and magnetised to saturation along the TD (b).

The observed magnetostriction is the difference between initial (Fig.9a) and final (Fig.9b) magnetostriction. Thus, in a perfectly oriented material, the pk-pk magnetostriction along the RD and the TD, when an initially demagnetised material is magnetised to saturation in the TD, are $-3\lambda_{100}/2$ = -35.55 μm/m and $3(\lambda_{100}+\lambda_{111})/4$ = 14.7 μm/m respectively (assuming values of λ_{100} = 23.7 μm/m and λ_{111} = -4.1 μm/m for 3% Si-Fe [7]).

This agrees closely with the measured magnetostriction along the RD of CGO and HGO under rotational magnetisation at saturation level. Again, additional strain due to the anisotropy-induced form effect is believed to cause the magnetostriction along the TD of CGO and HGO under rotational magnetisation to be higher than $3(\lambda_{100}+\lambda_{111})/4$ as with the 0.50 mm thick NO steel [9]. The samples cut along the TD as well as the RD under high compression could not be magnetised to saturation because of its complicated domain structure [9] so the ideal theoretical values would not be reached.

If Epstein strips of CGO and HGO cut along the TD are magnetised to saturation, the pk-pk magnetostriction along the sample length would be close to $3(\lambda_{100}+\lambda_{111})/4$. Similarly, the pk-pk magnetostriction of Epstein strips of CGO and HGO cut along the RD under a high compression magnetised at saturation along the strip length would be close to $-3\lambda_{100}/2$. These trends can be observed in Figs. 6 and 7 even though the samples were not saturated and there were the presence of the form effect, and flux closure domains.

IV. Conclusions

Magnetostriction of an isotropic electrical steel under rotational magnetisation and that under a high compressive stress is expected to be identical. Rotational magnetostriction measured along the RD of an anisotropic disc sample was found to have higher pk-pk value (close to $-3\lambda_{100}/2$) than that of an Epstein strip under high compression and uniaxial magnetisation in the RD. Magnetostriction of a disc sample measured along the RD and magnetised using a 2D system can be predicted by measurements on an Epstein strip along the RD under applied high compressive stress and vice versa.

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