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Should Epstein strip arrangement be changed?

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Abstract

The paper describes effect of texture on the anisotropy of magnetic properties and shows that an Epstein strip arrangement including strips cut in a direction 45° to the rolling direction gives property values that are closer to the average values than the traditional RD + TD arrangement.

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Induction motors are still the largest application of electrical steels. As there is a growing pressure to increase their energy efficiency, motor designers take advantage of all available means to increase it including the best possible materials property data.

One of the main features of the behaviour of steels in motors is their anisotropy [1]. The magnetic field rotates in all directions parallel to the surface of the sheets. Although they are called non-oriented electrical steels, their magnetic properties change when measured in different directions relative to the rolling direction of the sheet. As different types of electrical steels are being used, different anisotropies are at play [2].

The determination of the main magnetic characteristics, such as iron losses, magnetic permeability, flux density and magnetic field intensity, is most frequently done using a standardized procedure, the Epstein frame. Samples from a material to be characterized are cut along the rolling direction (RD) and at 90° to that direction (transverse direction, TD), and they are inserted in the orthogonal Epstein coils in such a way that the RD strips are inserted in two parallel coils, and the TD strips are inserted in the two other coils, orthogonal to the first ones.

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A standard Epstein value is not a good average of the magnetic properties in all directions, as it includes only two of them.

This paper builds additional evidence to the claims that including the lamination cut at 45° to RD leads to a better representation of the average properties of a material.

To average the magnetic properties in all directions one must include the orthorhombic symmetry of the crystallographic texture of the sheets. This symmetry implies that the magnetic properties measured at 22.5° produce the same values of samples cut at 157.5°, at 202.5° and at 337.5°. So, every direction parallel to the surface of the sheet is repeated four times along the 360°, except the RD and the TDs, that are repeated only twice, as indicated in Fig. 1. As an example, if we could measure the magnetic properties in five directions, the weighed average would be proportional to the average of 16 directions:

$$\overline{X} = (2X_{RD} + 4X_{22.5} + 4X_{45} + 4X_{67.5} + 2X_{TD})/16. \quad (1)$$

Depending on the crystallographic texture of the steel being examined, the implicit hypothesis of IEC and ASTM methods, that the average value can be obtained from the RD and TD, may be inadequate.

The behaviour of three different steels were examined in this paper. Their texture is sampled by the $\varphi_2 = 45°$ section of Bunge's ODF [3], as indicated in Fig. 2, and their

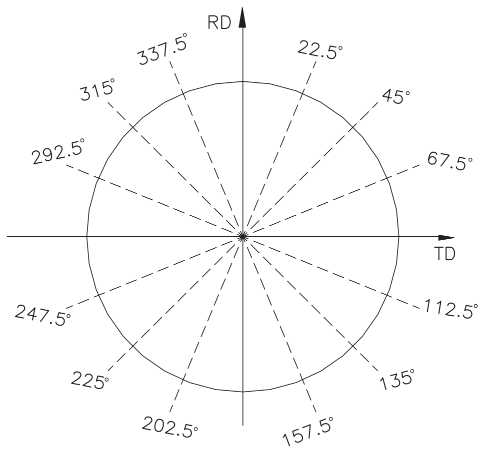

Fig. 1. Directions with similar magnetic properties in the plane parallel to the surface of the sheet.

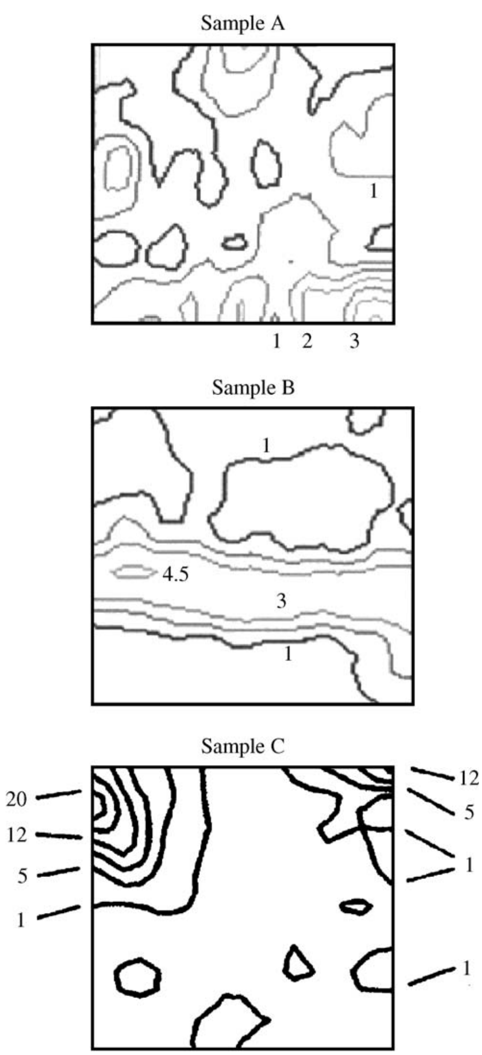

Fig. 2. Texture by the $\varphi_2 = 45^\circ$ section of Bunge's ODF. Numbers refer to iso-intensity lines.

composition is shown in Table 1. Samples A and B had strips cut at five different angles to the rolling direction (0, 22.5°, 45º, 67.5º and 90°). Sample C was cut in three

Table 1
Chemical composition of three steels

	Si (%)	Al (%)	Mn (%)	P (%)	C (%)	S (%)	N (ppm)	O (ppm)
A	0.28	0.25	0.42	0.08	0.005	0.01	55	35
B	0.26	0.28	0.37	0.09	0.003	0.01	23	23
C	0.13	0.12	0.45	0.04	0.007	0.01	40	35

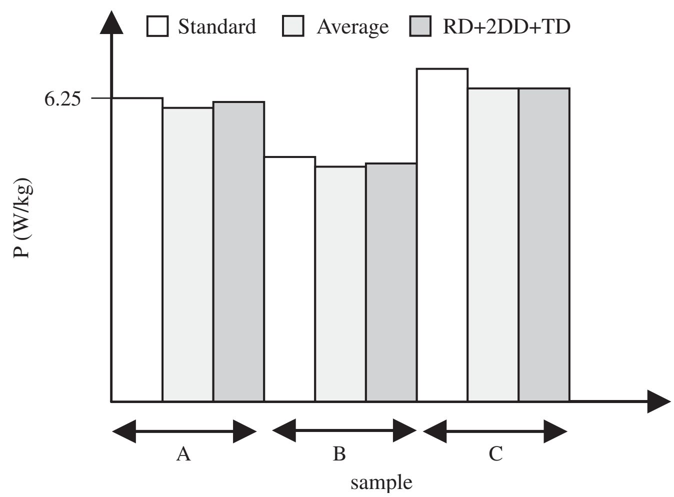

Fig. 3. Magnetic losses (at 1.5 T, 60 Hz) as a function of the cutting direction sample.

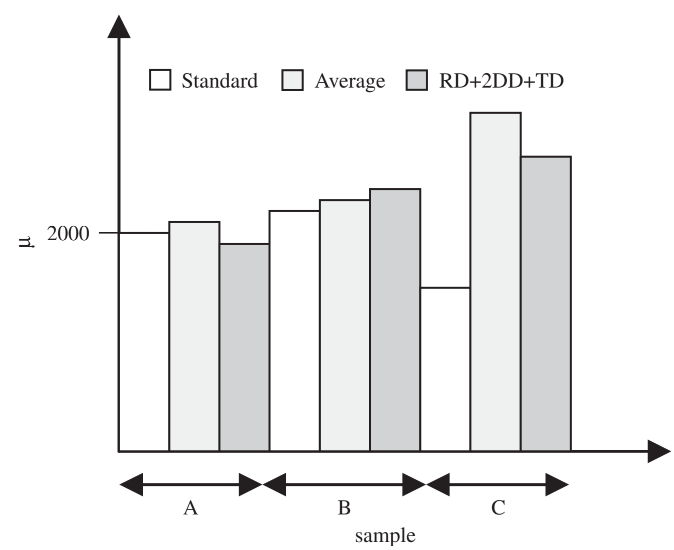

Fig. 4. Magnetic permeability (at 1.5 T, 60 Hz) as a function of the cutting direction sample.

directions (RD, 45° and TD). All strips were 0.5 mm thick. Magnetic losses and the magnetization curve were measured at 60 Hz.

Magnetic losses at 1.5 T as a function of direction is shown in Fig. 3, and magnetic permeability at 1.5 T, as a function of direction, is shown in Fig. 4. The uncommon texture of Sample C results in an uncommon angular behaviour, with its best properties at 45°.

Table 2
Magnetic losses (at 1.5 T, 60 Hz)

Sample	Standard (W/kg)	Average (W/kg)	RD + 2DD + TD (W/kg)
A	6.25	6.0	6.15
B	5.00	4.84	4.90
C	6.80	6.50	6.50

Table 3
Magnetic permeability (at 1.5 T, 60 Hz)

Sample	Standard	Average	RD + 2DD + TD
A	2000	2106	1850
B	2200	2275	2300
C	1450	3150	2700

It is readily understood that the standard Epstein frame arrangement is inadequate for sample C, but even in samples A and B, with more common textures, the average value of the magnetic properties is not the value obtained in the standard arrangement. It has been proposed before [1], that an arrangement with RD strips inserted in one Epstein coil, TD inserted in the parallel coil, and 50% of strips, cut in the diagonal direction (DD) in the two orthogonal coils (the RD + 2DD + TD arrangement) could give a better average. Tables 2 and 3 compare the three possibilities, the standard Epstein, the average value of Epstein measurements made in different directions, as indicated in Eq. (1), and the alternative RD + 2DD + TD proposal.

It can be seen that the RD + 2DD + TD arrangement gives results that are closer to the average value than the standard arrangement, even in steels that have usual textures, such as samples A and B. Such arrangement will certainly increase quality costs. Nevertheless, electrical industry may accept it as the benefits of a better design based on a better average probably overcome the small added costs.

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