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The angular dependence of magnetic properties of electrical steels

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Introduction

The magnetic property anisotropy of the so called nonoriented electrical steels is well known. The Epstein frame test procedure recognizes it, but it assumes that the average value of the magnetic properties is the average of the value at the rolling direction (RD) and the value at 90° from that direction (TD) [1, 2]. Honda and co-workers [3] have shown that, for some of the most common electrical steels, the magnetic properties were at worst when measured with Epstein strips cut at 55° from RD. They also suggested that an Epstein frame composed of 25% of the strips cut at RD, 25% cut at TD and 50% cut at 45° would give results closer to the ones obtained with ring specimens, which should be the true average value of the magnetic properties for applications where the magnetic field rotates in all in-plane directions.

The angular behavior of the magnetic properties of non-oriented steels is usually attributed to the crystallographic texture, to the occurrence of significant amount of a (110)[001] component [4]. In fact, a common way to improve the magnetic properties of nonoriented electrical steels has been to adjust steel processing to decrease the "gamma fiber" texture component and to increase the "Goss component" .

This paper intends to show that texture is not the only source of anisotropy of magnetic properties. This will be done by using a new approach (the subdivision of hysteresis loss in two parts [5]) to describe the angular behavior of three types of electrical steels: a typical fully-processed steel from Acesita, a typical semi-processed steel from CSN and a special semi-processed steel here called sample E. The other source of anisotropy can be the mean inter-inclusion distance [6].

The separation of total magnetic losses in its hysteresis, classical and excess (or anomalous) losses components offered important clues to the development of electrical steels processing. It has been shown that the magnetic losses anisotropy is mostly confined to the hysteresis component [7,8]. A detailed observation of the angular dependence of magnetic properties suggests that the induction B_{50} has a good correlation with crystallographic texture, showing the worst properties at 45-60°, while magnetic loss shows a similar but weaker dependence [3]. Previous results on 2%Si fully processed steel [7] showed that although the hysteresis loss goes through a maximum around 50°, coercive force increased monotonically with the angle, suggesting that other variables besides texture are also affecting it. Furthermore, applying a graphical subdivision technique to the hysteresis curve [5], it was clear that the "high-induction component" followed the texture behaviour, while the "low-induction component" increased monotonically with the angle from the rolling direction. Independently addressing similar angular behaviour in industrial practice, Cunha [6] proposed considering another source of anisotropy, the distance between inclusions. Having shown that this distance increases monotonically with the angle, his model assumes that the angular dependence of the total magnetic losses is a function of two factors, one directly associated to Magnetocrystalline Anisotropy Energy (E_A), and the other related to the variation of distance between inclusions.

Experimental

Samples of three commercial steels were investigated. Although no extensive chemical analysis was performed, electrical resistivity measurement should be able to take care of most the effect of that variable. Table I presents data about the samples.

Acesita sample was cut at every 10^o from RD, whereas CSN sample was cut every 22.5^o and sample E only every 45^o. Acesita samples were cut and stress relieved at 700^{o}C. CSN and Sample E were cut and annealed in decarburizing atmosphere at 760^{o}C for 2h, where recrystallization occurred and final grain size attained.

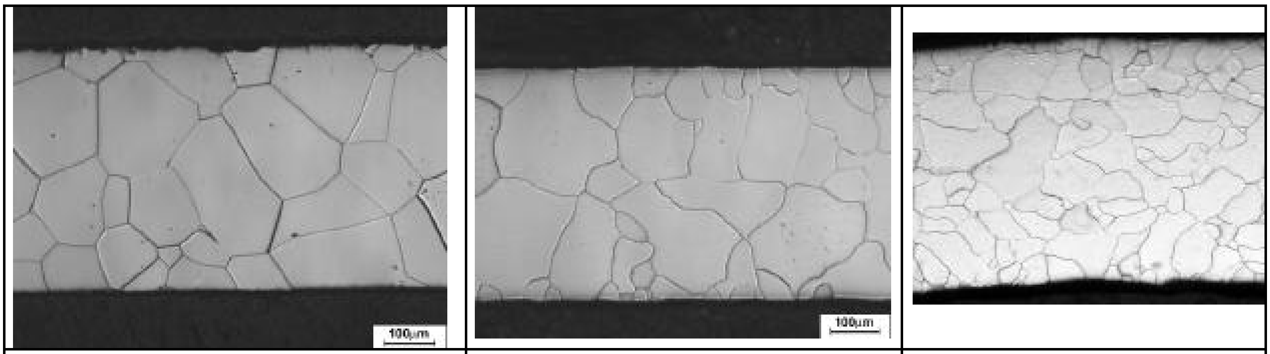
Electrical resistivity (?) was measured on an Epstein strip, using the 4-points method. Density was measured by the hydrostatic method. Mean thickness was calculated from weight, length, width and density. Approximate Si+Al content was estimated using the formula (%Si+%Al) = (? -- 12,5 – 16*%P) / 11. Saturation Polarization was calculated using the formula J_{sat} = 2,16 - 0,048*(%Si+%Al). Grain size was measured by the intersect method. Magnetic measurements were performed with a 25cm Epstein frame, at maximum induction of 1.5T, at 60Hz or 0.005Hz for hysteresis curve measurement. Total Losses were measured at 60Hz, Hysteresis Loss was calculated based on the quasi-static hysteresis area, Eddy Current Loss was calculated with the "classical" equation and Excess Loss (or Anomalous Loss) is the difference between Total Losses and the sum of Hysteresis Loss and Classical Loss.

Results

Table I shows some physical characteristics of the three samples, measured or calculated as explained above. Figure 1 shows the microstructure of the three samples.

Table I Physical characteristics of the three samples and approximate Si+Al content

	thickness	Electrical resistivity	density	Approximate Si+Al content	Jsat	Grain size
	(mm)	µOcm	kg/m^3	%	T	µm
Acesita E110	0.47	55.3	7600	3,85	1,972	130
CSN 55700	0.48	21.4	7815	0,68	2,127	100
Sample E	0.496	16.9	7850	0,35	2,143	60



Acesita	CSN	Sample E

Figure 1. Microstructure of the three samples shows wavy grain boundaries in the annealed semi-process steels and straight grain boundaries in the fully processed steel.

Figure 2 shows the angular behavior of Total Losses at 1.5T, 60Hz, for the three samples. There are big differences between the mean values of the samples, due to chemical composition and microstructure: the lower the Si+Al content, higher is the Classical Loss component; decreasing grain size (below 150 µm) increases loss;

The angular behavior of the three samples is also much different: The sample from Acesita shows the typical behavior of the electrical steels, with the lowest value at RD, the peak value at around 55^o and an intermediate value at TD. The sample from CSN shows little anisotropy, but sample C shows a much different behavior, with the lowest losses at 45^o.

One way to attribute a value to the anisotropy of a sample, one may use the equation:

Anisotropy index = (maximum value - minimum value) / average value.

Based on that equation, one finds 19% anisotropy for the Total Losses of the Acesita sample, 4% for the CSN sample and 16% for the Sample E.

Figure 3 compares the values of induction at 5000A/m (B_{50}). Its results show an inverse behavior when compared to the losses, and this is qualitatively compatible with the Total loss results of Figure 2. It shows a very high value for sample E at 45^o. If one assumes that B_{50} is strongly related to texture, this high value of B_{50} at 45^o suggests the presence of a strong <100> pole in that direction.

Texture measurements show that Acesita sample has a strong Goss component, in the CSN sample the (111)//ND predominates and in the Sample E a very strong component close to (115)<110> was found. Those texture characteristics are compatible with the angular behavior of B_{50}

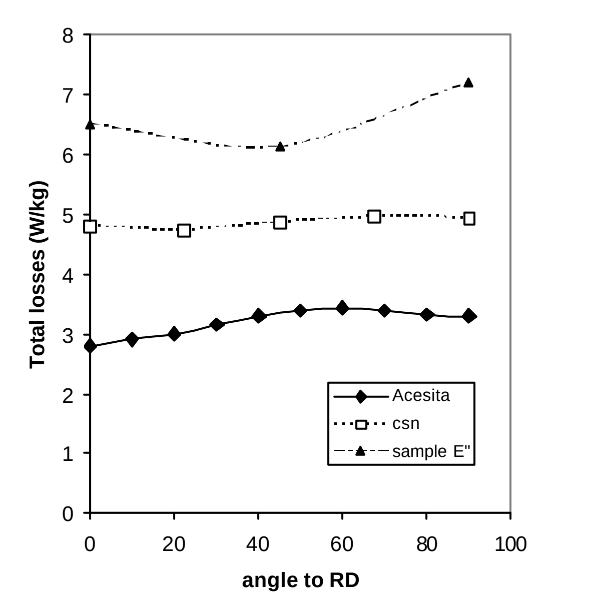


Figure 2. Total losses at 1.5T, 60Hz

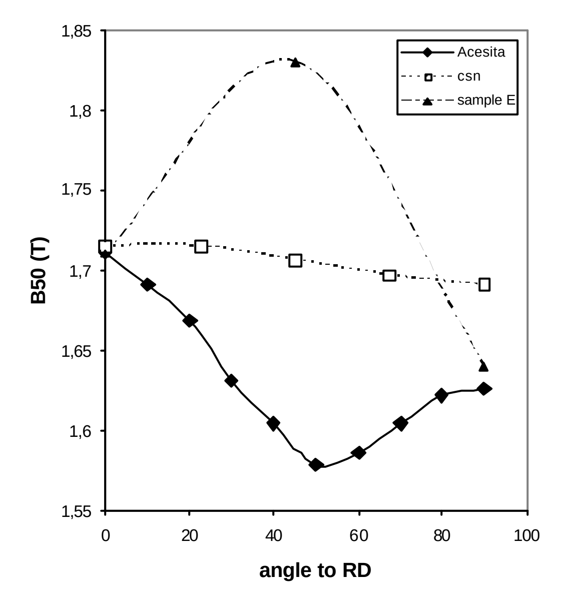


Figure 3. Induction at 50A/cm

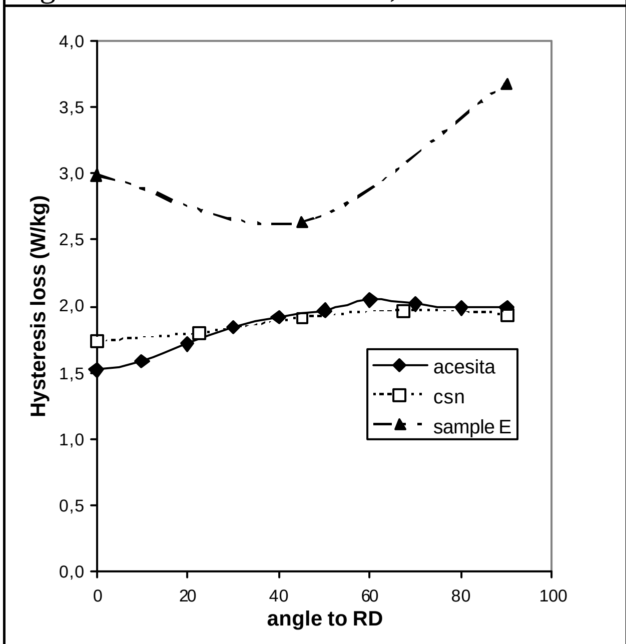


Figure 4. Hysteresis loss at 1.5T, 60Hz

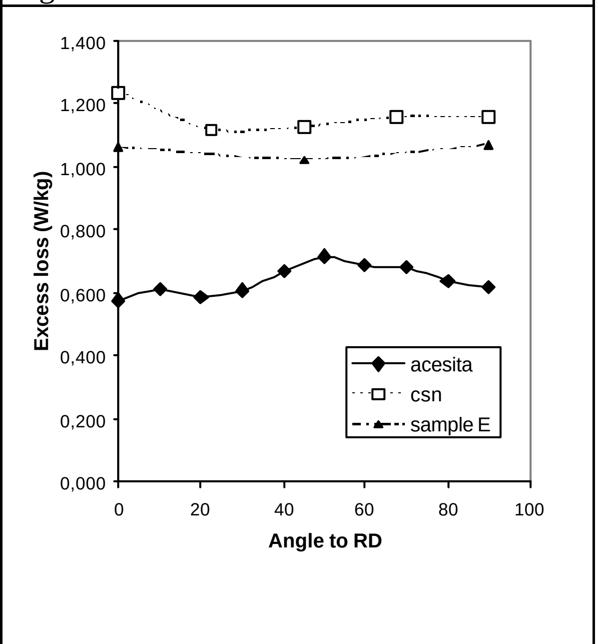


Figure 5. Excess Losses at 1.5T, 60Hz

Hysteresis loss values were similar in the Acesita and CSN products, as shown in Figure 4. Most of the Total Losses anisotropy shown in Figure 3 has to be attributed to the hysteresis loss component, because the absolute value of excess loss anisotropy is very small, as shown in Figure 5. The absolute difference between the maximum and minimum value of Total Losses was 0.64, 0,22 and 1,09W/kg for the Acesita, CSN and E sample, respectively. The absolute difference of hysteresis loss was 0.53, 0.23 and 1.04W/kg, respectively.

It should also be noted that the hysteresis loss values for the Acesita and CSN samples are very small (hysteresis energy loss of 28mJ/kg and 31mJ/kg at 1.5T, respectively). As a comparison, the values in ref. 12 for 3%Si steel with grain size of

150 µm range from 26 to 38mJ/kg. On the other hand, Sample E has a much higher value of hysteresis loss, probably due to its much smaller grain size.

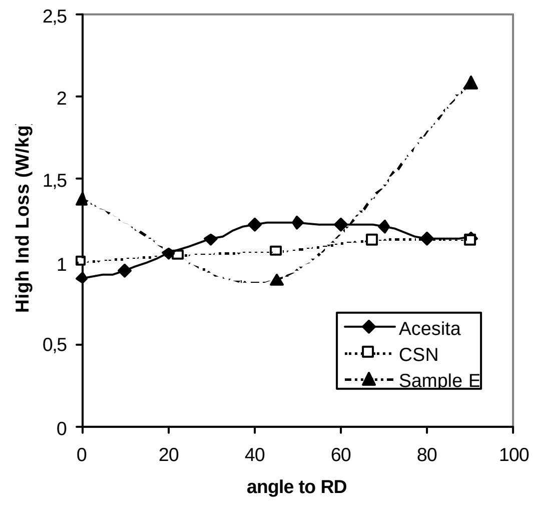


Figure 6. "High Induction" Hysteresis component

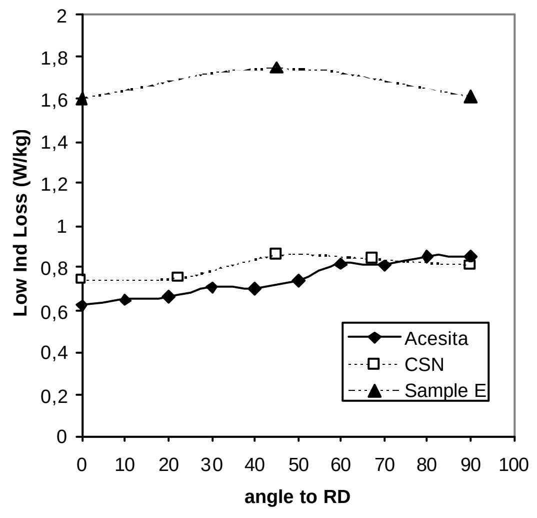


Figure 7. "Low Induction" Hysteresis Component

Applying the graphical method of subdividing the hysteresis loss in the "High-induction" and "Low-induction" components, Figures 6 and 7 show that both components present anisotropy, but of different kind. The anisotropy of the "High Induction" component shows the overall behavior of the hysteresis loss anisotropy for each sample, while the "Low-induction" component is quite different: the Acesita sample presented a monotonic increase with the angle, the CSN sample presented very small anisotropy and Sample E showed a peak at 45^o .

It is no simple task to correlate texture measurements to magnetic properties, mainly because it is difficult to synthesize texture in one parameter. In the case of angular behavior of magnetic properties, Vanderschueren and others [9] have used an A parameter, while Cunha has suggested the use of the average Magnetocrystalline Anisotropy Energy value for each direction of applied H [6]. Due to insufficient data values, we will not use those methods, and will use an indirect texture evaluation instead. It is accepted that B_{50} is the property most sensitive to texture, but still affected by the effect of alloy addition decreasing saturation polarization. To compare values of samples with different chemical compositions, B_{50}/J_{sat} is a better choice. Figure 8 shows that the "High Induction" component monotonically decreases as B_{50}/J_{sat} increases, while the "Low Induction" component shows little correlation (Fig. 9). This indicates that the "High Induction" component of Hysteresis Loss is sensitive to texture, while the "Low Induction" component is not, for the three samples investigated.

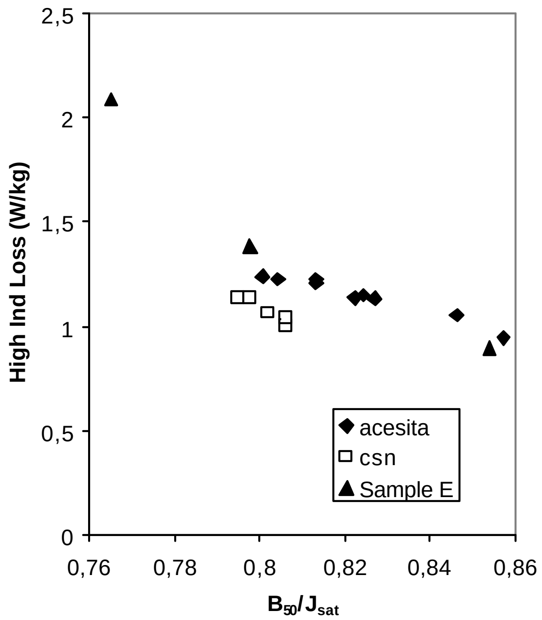


Figure 8 "High Induction" component of Hysteresis as a function of B_{50}/J_{sat}.

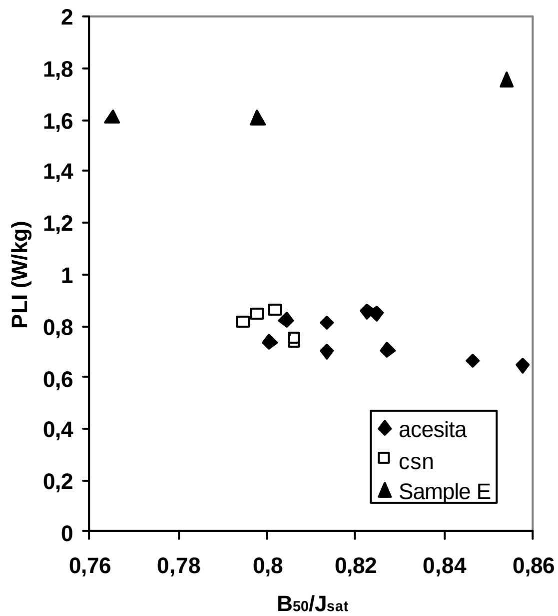


Figure 9. "Low Induction" component of Hysteresis as a function of B_{50}/J_{sat}.

There is no doubt that the predominant energy dissipation mechanism in the "low-induction" region is domain wall movement. It is somehow surprising that it shows little correlation to texture. In fact, coercive force also lacks correlation to texture, as can be seen in Figure 10. In all three cases, coercive force increase with the angle to RD. Cunha found evidence that the mean inclusion distance decreases with the angle to RD [6]. Based on Kersten modeling [10], coercive force must increase with the decrease of inclusion distance.

There is not much information about energy dissipation mechanisms in the "high induction" region. It should not be domain rotation, because it is reversible and non dissipative, for cubic crystals. Chikazumi mentions the existence of large Barkhausen jumps above the knee of the curve of the lower branch. He attributes those jumps to domain wall displacement and/or irreversible domain rotation, but states that "irreversible rotation is expected in fine particles or in an extremely heterogeneous materials which contains a lot of inclusions and precipitates", which is not the case of the samples here investigated. [11]. It must be associated with the annihilation of domains when B increases above the knee of the hysteresis curve, in the first quadrant, and with the nucleation of domains when B decreases. It seems reasonable that the volume of the closure domains associated with grain boundaries and inclusions should be related to texture.

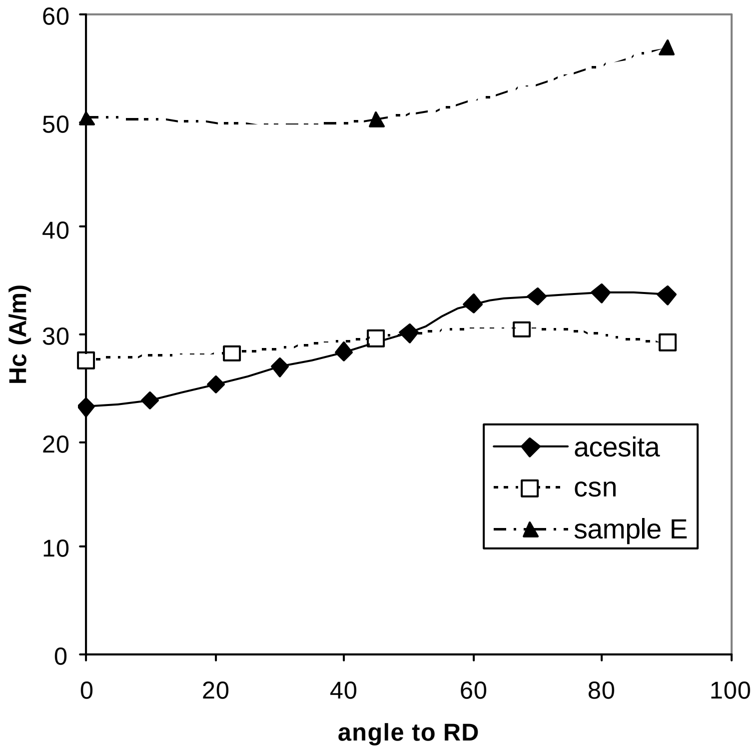


Figure 10. Coercive force from 1.5T, measured at 0.005Hz.

Conclusions

1. The angular behavior of Total Losses changes significantly depending on the processing of the electrical steels. The values obtained with present measurement specifications most probably do not represent the average values of the commercial materials.
2. The anisotropy of Total Losses is almost exclusively related to the angular behavior of the hysteresis loss component. The classical parasitic loss is, by definition, isotropic, and the anisotropy of excess loss is smaller than 0,1W/kg in the three investigated steels.
3. The subdivision of hysteresis loss was useful to show that the "High Induction" component correlates well with the texture related parameter B_{50}/J_{sat}.
4. Texture is not the only source of anisotropy. The coercive force, which is a major parameter of the "Low Induction" component, does not correlate with the above texture parameter. Instead, it increases monotonically with the angle to RD. This behavior is probably related to the anisotropy in the mean inter-inclusion distance.

Literature

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