

Losses due to the transverse component of flux density in grain oriented electrical steels

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Grain-oriented electrical steel is widely used as the magnetic core material in energy efficient power transformers. The AC performance of a material in strip form magnetized along its rolling direction is measured in a standardized Epstein frame. The principle of the measurement method depends on magnetization being completely aligned along the longitudinal direction of the strips. However mis-oriented grains are subject to small components of flux change at angles to the rolling direction causing additional loss which the standard measurement method does not detect. This paper describes how orthogonal sensors were used to detect and quantify such components of loss in conventional grain-oriented steel magnetized along its rolling direction. Additional localized losses associated with these components are found to vary greatly from grain to grain but may contribute an additional 10 % to the conventionally measured loss. Implications of this effect are considered in the paper.

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1. Introduction

Electrical steel is used for magnetic cores of most motors and transformers. It is widely recognised today that between 5 % and 10 % of all electrical energy generated is wasted as magnetic losses in such cores. In particular, although modern power distribution transformers may be more 98 % efficient there is a renewed drive to reduce their core losses. The steel manufacturers have made significant progress in this area and the basic loss of best grade material has fallen from around 1.7 W/kg in 1960 to as low as 0.7 W/kg today.

Grain-oriented electrical steel sheet is the most effective core material for transformer cores. It is usually produced as rolled sheet around 0.23 mm to 0.35 mm thick and highly anisotropic due to a strong alignment of [001] (100) grains with the rolling direction. The majority of the material volume comprises 180° bar domains oriented in the [100] directions of the individual grains, which themselves can be up to 10 mm or more in diameter. Magnetization in the presence of an AC field applied parallel to the rolling direction is mainly by 180° domain wall motion parallel to the [100] directions of individual grains. Other processes occur, but for clarity these need not be discussed here.

Accurate measurement of the losses in grain-oriented electrical steel is important for initial grading of the product, assessing the accuracy of predictive material modelling techniques and predicting the performance of energy efficient transformer cores. The standard method is based on testing strips of steel assembled in an Epstein square in the form of an open circuit single phase transformer core [1]. Although the method is very reproducible and well established, there are increasing questions of its absolute accuracy [2]. In this paper we

draw attention to a further source of error, which can occur in the testing of grain-oriented electrical steel in particular.

Determination of losses depends on detecting the instantaneous tangential component of the surface field, h , and spatial variation of rate of change of flux density db/dt through the thickness of the material [3]. In rotational and two-dimensional magnetization studies, or determination of localized surface field profiles, orthogonal components h_x , h_y and db_x/dt , db_y/dt are detected. However, for conventional single strip or Epstein frame measurement, under unidirectional magnetising field conditions, only h_x and db_x/dt (longitudinal in the Epstein strip) are used for the loss calculation. Due to the mis-oriented nature of grains in grain-oriented steel the flux changes caused by the 180° wall motion produce changes in the y components of h and b in individual grains. Hence when the loss is calculated only from the x direction components of h and b indicated value might be lower than the actual value of loss occurring in the material. This grain to grain mis-orientation of local field and flux density is well known [3], [4], [5], but the loss due to the misaligned field components has only been recognised to a limited extent [6], [7].

2. Experimentation

A single decoated sheet of 3.25% silicon iron, high permeability, grain oriented, 116 mm × 75 mm, was chosen for the measurement. It was magnetized along its rolling directions and orthogonal components of localized flux density and magnetic field were detected and processed to obtain the localized loss. The sheet had previously been decoated so the grain structure could be observed. The measurement system shown in the block

diagram in Fig. 1 has three main sections: the magnetising circuit, the power supply to the X-Y-Z-precision position control system and the signal conditioning circuit.

Fig. 2 shows the magnetizing and scanning systems. The magnetizing coil (wound on the C-core), the specimen and the platform on which the specimen was placed can be seen. A three-dimensional i.c. Hall effect sensor (for measuring x , y and z components of magnetic field), whose magnetic sensitive surface area was $6.25 \times 10^{-2} \text{ mm}^2$ was located $35 \mu\text{m}$ above the surface of the steel. It had a field range of $\pm 477 \text{ Am}^{-1}$ and sensitivity of 275 mVT^{-1} in both x and y axes (the z component was not used for power loss calculations). Its output and that of orthogonally located needle probes to detect the components of dbx/dt and db_y/dt were fed through the signal conditioning circuit. The needle probe technique is an alternative method which is more convenient for localized flux density measurement than conventional use of enwrapping

search coils wound through small holes drilled through the sample [8].

The needles detecting the x and y components of db/dt were spaced 7.3 mm and 6.3 mm apart respectively. The output of two isolating transformers connected to 240 V supply through a circuit breaker were fed to the Compumotor AT6400 4-axes indexer and the three Compumotor micro step drives; these are the three components that directly control the positioning system. A carrier, on which the Hall sensor and needles were mounted, was stepped automatically at $50 \mu\text{m}$ intervals over the selected regions using the precision control system. At each step the sensors were lifted off the surface to avoid scratching the needles on the steel the sample. Orthogonal components of h and db/dt were detected at each measurement points and the computed average loss in each region was measured.

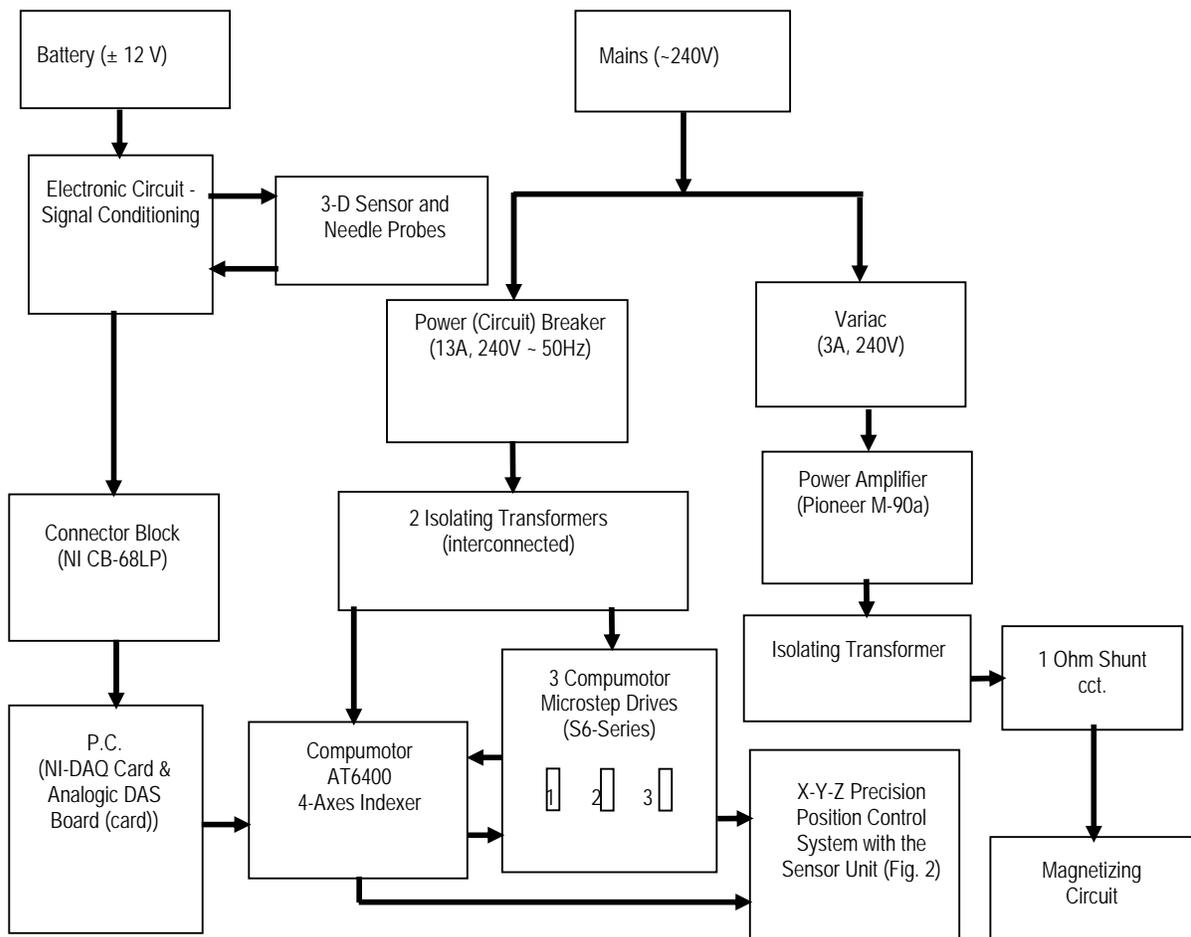


Fig. 1. Block diagram of the magnetizing and measurement setup.

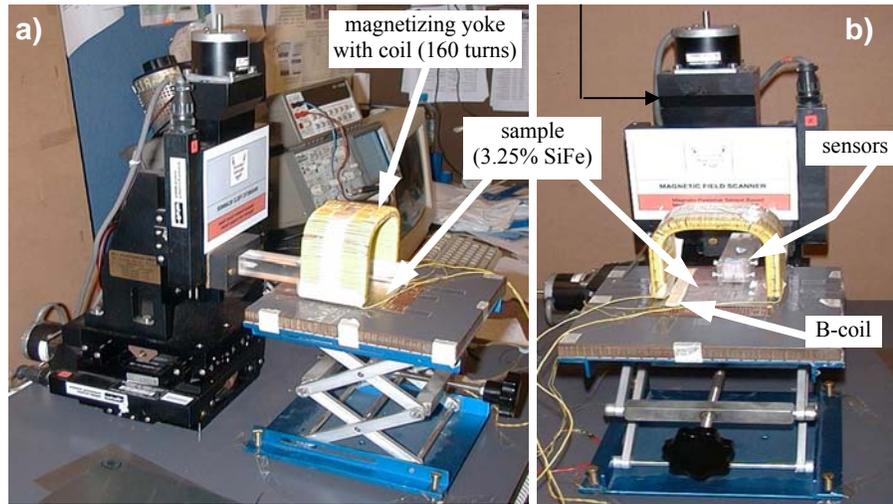


Fig. 2. Main components of the magnetising and scanning systems: a) side view, b) front view.

Fig. 3 shows regions over which the scans were performed and corresponding grain boundaries and static domain patterns. The three regions “A”, “B” and “C” have

surface areas of about 140 mm², 60 mm² and 90 mm², respectively.

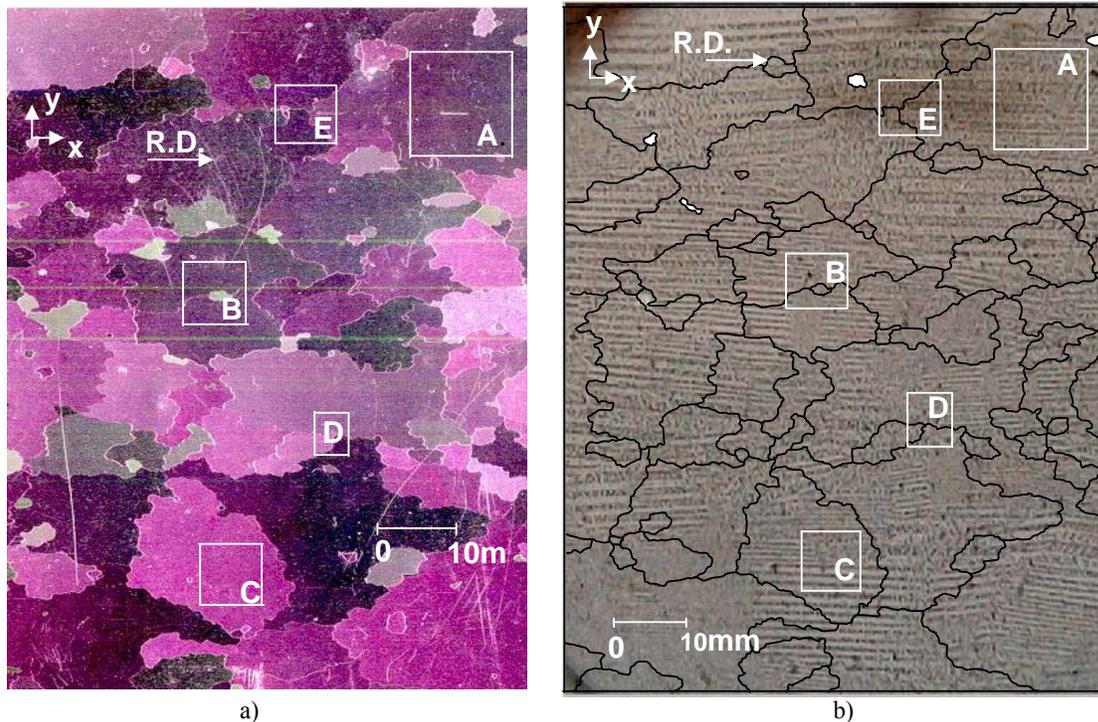


Fig. 3. Part of the sample surface showing scanned regions “A”, “B”, “C”, “D” and “E”: a) photograph of the decoated sample, b) grain outlines superimposed on the static domain structure.

The total loss (per unit mass) at each point in each measurement regions was calculated from,

$$P = \frac{1}{T\rho} \int_0^T (H_x \frac{dB_x}{dt} + H_y \frac{dB_y}{dt}) dt \quad (\text{W/kg}) \quad (1)$$

where the subscripts x and y denote components of the vectors in directions x and y respectively T is the magnetization period and the density term (ρ) converts the loss to per unit mass rather than unit volume.

Each data point was obtained after averaging of 25 iterations of measurements performed over a 1 sec interval. The x and y loss components in equation 1 were obtained at each measuring point and averaged across each rectangular region.

3. Results

The sensor head was scanned over the sample when it was magnetised at 1.5 T, 50 Hz and the local orthogonal components of h and db/dt were measured and the loss in each region of interest was calculated as explained in the previous section. The overall average value of peak flux density, B_p , across the sample which was magnetized at 50 Hz was obtained from a search coil, which enveloped the sample. Figure 4 shows the variation of the averaged x and y components of measured loss with flux density in regions "A", "B" and "C". The localized flux density values in Fig. 4 were obtained from the needle probes measuring the x component.

The local loss due to the transverse component of magnetization is relatively low as would be anticipated, but it is not negligible compared with the loss calculated from the x components of b and h . There is no apparent correlation between the grain structure and transverse loss. The longitudinal component of loss is lowest in region "B" which includes grain boundaries but quite well oriented grains. Region "C" has the highest transverse loss, but it is in the central region of a well oriented grain. Clearly a more detailed study is needed to understand these unexpected results.

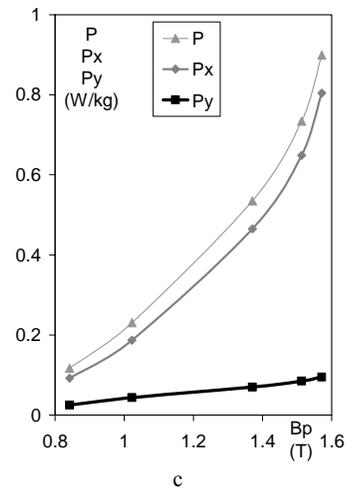
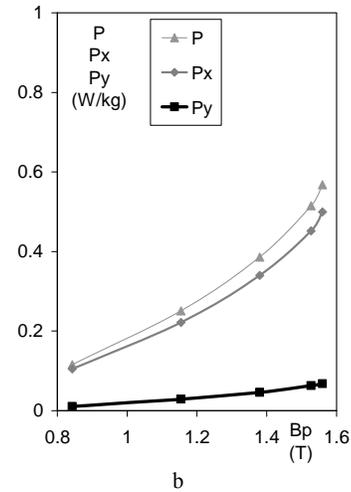
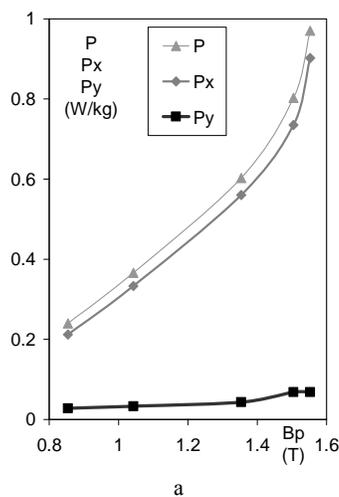


Fig. 4. Variation of localized power loss ($P = P_x + P_y$) with flux density (B_p) in: a) region "A" within a single grain, b) region "B" across grain boundaries, c) region "C" within a single grain (see also Fig. 3).

A localized iron loss tester (Soken type DAC-TR-1) which detects the average loss over an area of 13 mm by 25 mm was used to measure the average iron loss in regions "A", "B" and "C" at peak localized flux densities of 1.0 T and 1.5 T. The error in the value of iron loss given by the Soken tester is claimed to be less than $\pm 5\%$. The high losses shown in table 1 occur because the sample is in a decoated condition.

Table 1. Localized losses measured using a Soken tester.

Region	Iron loss (W/kg)	
	B = 1.0 T	B = 1.5 T
A	0.80	1.32
B	0.60	1.30
C	0.80	1.30

The values found with the sensors follow similar region to region trend but they are far smaller than those indicated by the Soken tested. The Soken test detects the loss due to the x component of magnetization but closer agreement with the values in Fig. 4 was expected. Some difference would occur because the Soken tester measures the local loss over a far larger area than the sensors different measurement areas and the magnetisation conditions would be different since in the Soken measurement the sample is only magnetized in the loss measuring region so actual magnetisation conditions would be different. The losses measured by the Soken tester are more than double those measured using the sensor method at 1.0 T and around 50 % higher at 1.5 T. These cannot be explained by differences which might occur due to the points just mentioned.

4. Discussion and conclusion

The existence of the loss, P_y , due to the perpendicular components of h and db/dt in grain oriented electrical steel should be recognised in grading materials or attempting to estimate the absolute loss. Conventional loss measurements using the Epstein square or single sheet/strip testers do not detect this component and hence may underestimate the loss by as much as 10%. The effect is expected to occur in non-oriented steel perhaps to a greater extent. The phenomenon will also occur in the steel when used in transformer cores so absolute losses may be underestimated by a similar amount although the core building factors should not be affected. The measurement technique used here is difficult and it is difficult to assess its accuracy. Poor agreement was found with Soken tester results which might be due to different magnetising conditions in each case due to differences in mobility of domain walls under the different conditions but clearly more work is necessary to confirm the size of the effect.

In theory, localised loss can be measured absolutely using a thermal method (thermometric) based on the principle that the localised loss is proportional to the initial rate of rise of temperature at the measuring point [9]. In the past the thermometric method has not proved as accurate as the use of orthogonal b and h sensors and measurements made using the two techniques generally do not agree well. However, recently very good agreement between the techniques for rotational loss measurement has been reported [10].

Alternating and rotational power losses at 50 Hz have been measured successfully at different flux densities for 3% grain oriented silicon iron materials using the thermometric method [9]. Orthogonal sensors (fieldmetric method) are used for rotational loss measurement systems and provided they are very accurately aligned reliable results can be obtained [11] [12]. It is interesting to note that apparent transverse loss components measured with orthogonal sensors in rotational magnetization systems, in which material is only magnetized along the x direction, have largely been largely ignored and put down to

experimental errors, but perhaps this is another manifestation of the phenomenon.

Interesting contours of localized power loss have been reported using the *Magnetovision* system [13]. These were obtained by scanning a 1-D sensor over a sample surface so it would be interesting to incorporate a set of orthogonal sensors to see whether taking the y components of h and db/dt into account would affect the global results.

In conclusion the loss due to transverse flux appears to be present although it might not be accurately quantified here. It is perhaps timely to follow up the work to get a fuller understanding of the mechanisms and the size of the errors over a wider range of materials and measurement conditions (fieldmetric and thermal) to assess their practical importance.

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