Analysis of Magnetic Fields on the Surface of Grain Oriented Electrical Steel

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Abstract. *Magnetic properties of grain oriented electrical steel are often measured using well established surface field sensors. Use of magnetic domain observation, magnetic force microscopy (MFM) and Barkhausen noise measurement for studying magnetic properties and microstructure is demonstrated. It is shown that uncertainty over the region in which Barkhausen noise is detected needs clarification. It is further shown that different domain observation techniques appear to identify different types of micro structural features and that uniaxial magnetic field sensors may not reveal the total loss occurring in the steel. The origin of unusual MFM images is discussed.*

Keywords: Electrical Steels, Magnetic Domains, Barkhausen Noise, Magnetic Losses, Magnetic Force Microscopy, Magnetic Field Detectors

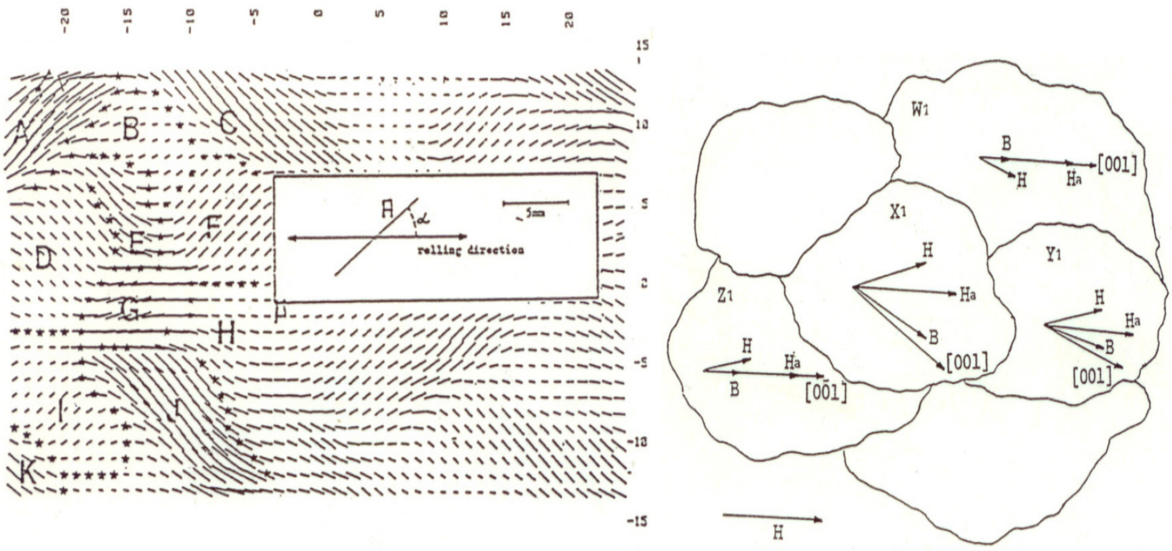
1. Introduction

Grain oriented electrical steel (GOSI) is a key component of electrical machine cores. It is produced in thin strip form, typically 0.30 mm thick following a complex sequence of rolling and heat treatment schedules together with application of electrical insulating coatings [1]. The steel comprises large grains (up to around 100 mm^2 surface area) with a strong {110}<001> texture. When laminations are magnetised at power frequencies along their rolling directions, as in transformer cores operating in electrical power systems, magnetic losses occur during domain wall motion [2]. Such losses are responsible for up to 10% of all electrical energy generated [3]. More knowledge based measurement and interpretation of losses is necessary to quantify metallurgical and processing parameters which control the losses.

The underpinning dependence on composition, internal stress, thickness, impurities, grain size and texture cannot be fully quantified without a deeper knowledge of magnetisation processes. Two measurable physical features closely associated with the loss process are magnetic domain motion and Magnetic Barkhausen emission (MBE). Although an IEC standard for loss measurement for commercial grading of GOSI is well established [4], its use as a research tool for investigating loss mechanisms is limited. Other methods based on surface magnetic field sensors are commonly used for localised loss evaluation. Magnetic domain observation (MDO) and magnetic force microscopy (MFM) are useful tools for surface magnetic field characterisation. Domain images obtained from the commonly used Bitter technique and the Kerr magneto optic (KMO) effect are presented to show how these techniques can imply the presence of different domain structures. It is shown that a better understanding of MBE measurements is needed to develop quantitative relations between microstructure and magnetic properties.

2. Anomaly of loss measurement using surface sensors

The energy loss in a sheet of GOSI under ac magnetisation is dependent on the tangential component of surface magnetic field (H) and spatial rate of change of flux density along the magnetising direction (*dB/dt*). Sensors are commonly used to measure H and *dB/dt* along the magnetising direction but transverse components of B and H are present in GOSI as illustrated in Fig.1. On application of an external field H_a, magnetisation within individual grains remains predominantly parallel to their [001] directions. Demagnetising effects within grains results in a localised field distribution which is the resultant of H_a and the demagnetising field whereby H in each grain is not parallel to the rolling direction [5]. Ignoring this, as is the case in localised measurement and IEC testing, leads to loss underestimations of up to 10 % [6].



(a) (b)

Fig. 1. (a) Measured field pattern on a GOSI surface showing location of grains and transverse components of H, (b) Schematic representation of effect of demagnetising field in misoriented grains.

3. Intepretation of domain observations

It is important to study the effect of grain boundaries on the localised domain pattern in order to understand loss processes. Figure 2 shows static domains, separated by 180^{o} walls, observed on the same GOSI surface using KMO and a modified Bitter pattern technique [7]. A low angle grain boundary cannot be seen using the KMO method. Although the true magnetic structure is identical for each observation technique, the Bitter technique detects surface stray field whereas KMO senses the surface magnetization component and in this case they yield different domain patterns.Under AC conditions, KMO does reveal the presence of the grain boundary due to domain wall refinement and nucleation. Static images are often used to deduce loss processes so it is important to anticipate the phenomenon.

Few surface observations on GOSI have been reported using the MFM because its resolution is often too high for investigating the predominant 180^{o} walls. An attempt was made to see if the grain boundary in Fig 2 (a) could be observed by the MFM but its presence is not obvious in the image shown in Figure 3. On close inspection a fine *finger print* pattern is present on either side of the region where the boundary is located. The cause of this pattern is not yet known. It may be simply an aberration of the MFM measurement method or image processing although it was not found on samples of non-magnetic material. If it is magnetic in origin, it could lead to an additional source of MBN although the curved nature of the pattern is not expected in steel.

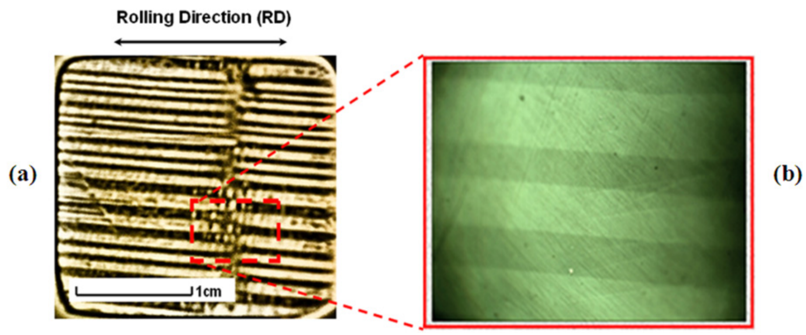


Fig. 2. Static domains observed on a 25 mm x 25 mm GOSI surface (a) Image obtained using a modified Bitter technique (b) magnified KMO image over the dashed box area.

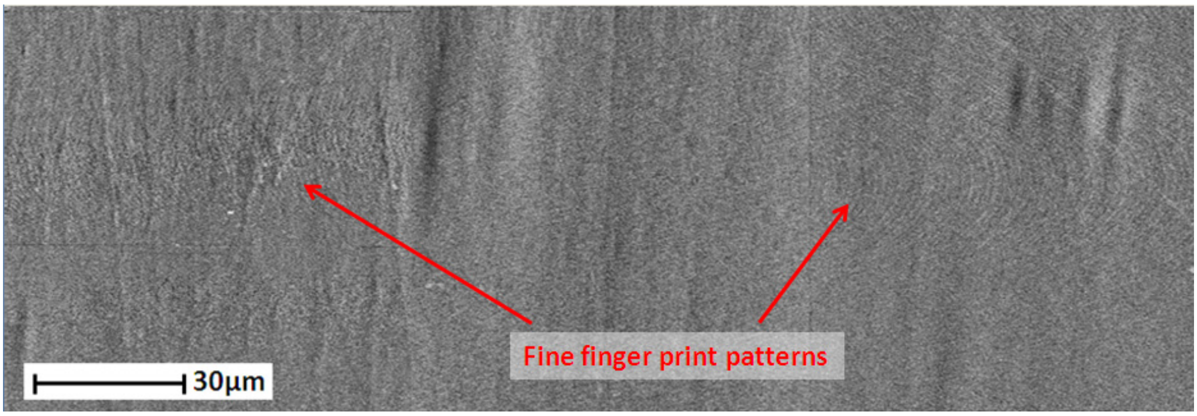
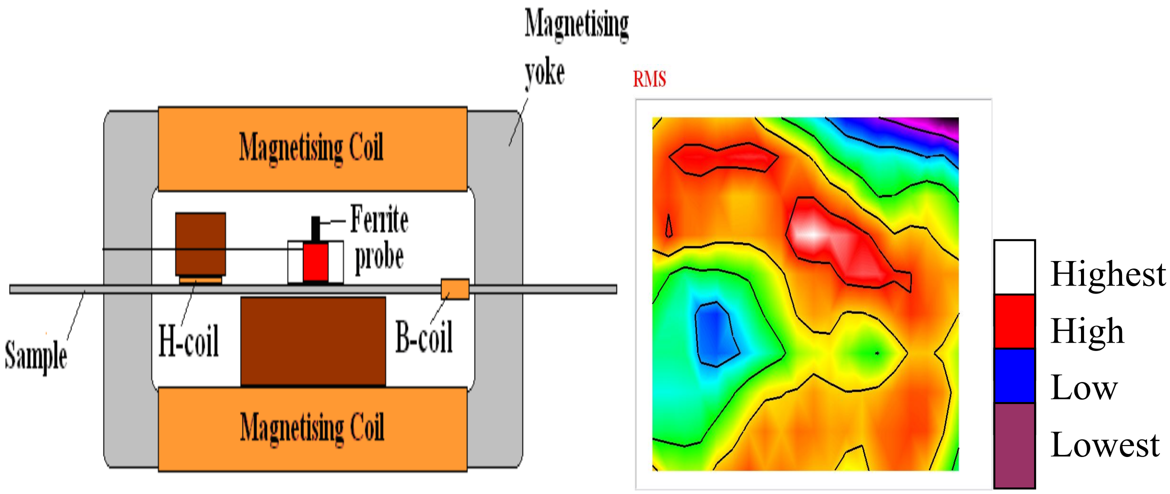


Fig. 3. MFM image over a 270 µm (horizontal) by 90 µm (vertical) region showing finger print patterns (vertically directed grain boundary across central region is not apparent).

The MBN referred to above can be measured in many ways [8]. The detected Barkhausen noise voltage pulses are due to emissions occurring when moving domain walls pass through material inhomogeneities close to the surface of the steel. MBN, at 50 Hz excitation, has been measured using the system shown in Figure 4 (a). Figure 4 (b) shows regions of high and low rms MBN in GOSI detected by scanning a 1000 turn, 2 mm diameter ferrite probe over the surface. No correlation with grain or domain structures is apparent. Further measurements show that, above around 0.2 T, the MBN is higher in well oriented GOSI than in the conventional steel but this reverses at low flux density. This is thought to be because domain wall motion in both at low fields is jerky and produces relatively more Barkhausen jumps whose cumulative effect is higher in amplitude in less well oriented material because the domain wall pinning effect of the greater number of grain boundaries is not so influential [9].

4. Conclusions

MDO, MFM and MBN measurements, combined with localise loss measurement are powerful tools for investigating relationships between microstructure and magnetic properties of GOSI. However, both loss measurement using surface field sensors and MDO using static KMO must be interpreted cautiously. If unexplained, MFM patterns are magnetic in origin they might help identify links between MBN and magnetic properties of GOSI. The regions over which MBN emissions are detected need to be quantified in order to help correlate localised MBN measurements with grain structure.



(a) (b)

Fig. 4. (a) Schematic of MBN measurement system (b) MBN profile over a 20 mm by 35 mm GOSI surface.

Acknowledgements

Two authors N. Chukwuchekwa and X. Xu are grateful to the EPSRC and Cogent Power Ltd respectively for sponsorship of their PhD projects related to this investigation.

References

[1] Littman M F. Grain-oriented silicon steel sheets. *JMMM.* 26 (1-3) 1-10 1982.

[2] Nozawa T, Mizogami M, Mogi H, Matsuo Y. Magnetic properties and dynamic domain behavior in grain-oriented 3% Si-Fe. *IEEE Trans. Mag.* 32 (2) 572-589 1996.

[3] Moses A J. Opportunities for exploitation of magnetic materials in an energy conscious world. *Interdisciplinary Science Review.* 27 (2) 100-113 2002.

[4] International Electrotechnical Commission. IEC 404-2: (3) 1996.

[5] Moses A J. Detection and importance of magnetic surface fields on steels. *Grain Boundaries*: *their characterisation and Influence on Properties* (Ed. I R Harries and I P Jones). IOM Communications Book 743 187-196 2000.

[6] Moses A J, Konadu S N and Zurek S. Losses due to the transverse component of flux density in grain oriented electrical steels. *J. Optoelectronics and Ad. Mats.,* 1110-1114 2008.

[7] Xu X T, Moses A J, Hall J P, Williams P I and Jenkins K. A comparison of magnetic domain images using a modified bitter pattern technqiue and the Kerr method on grain oriented electrical steel. Submitted to *IEEE Trans. Mag.* Jan. 2011.

[8] Moses A J, Patel H V and Williams P I. Challenges in quantifying Barkhausen noise in electrical steels, *Electromagnetic Non-destructive Evaluation (S Takahashi and H Kikucki Eds,* IOS Press. 178-185 2007.

[9] Chukwuchekwa N, Moses A J and Anderson P I. Barkhausen noise in grain-oriented 3% Si-Fe at 50 Hz. *J. Elec. Eng.*. 61 7/s 69-72 2010.