Correlation between Angular dependence of A.C. Barkhausen Noise and Hysteresis Loss in a Non-Oriented Electrical Steel

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Abstract. Hysteresis loss and Barkhausen noise have been measured in non-oriented electrical steel strips cut at various angles to the rolling direction. Both parameters followed similar trends with changing angles to the rolling direction and peak flux density at 25Hz and 50Hz magnetisation and are related to a low and high flux density interpretation of hysteresis loss.

Introduction

Texture in non-oriented electrical steel causes a small anisotropy of magnetic properties in the plane of laminations with respect to the rolling direction. It is now widely recognized that better control of the texture can lead to improved directional magnetic properties which will be very beneficial in reducing loses of a.c. motor stator cores.

Barkhausen noise (BN) occurs when domain walls interact with microstructural inhomogenuities such as grain boundaries, inclusions and defects and the phenomenon is well understood qualitatively [1]. The so-called “Barkhausen jumps” in magnetic materials can be due to microscopic effects due to irregular motion of well defined domain walls or at a fine scale due to stochastic microscopic motion of segments of walls although both are closely dependent [2].

Magnetic losses are traditionally split into hysteresis, eddy current and excess loss components. The hysteresis loss is generated as domain walls are pinned and released at inhomogenuities in a material. Hysteresis loss per cycle is generally believed to be independent of magnetising frequency although early work still throws doubt on this assumption [3] [4]. Nevertheless, it is widely assumed that there is a close correlation between Barkhausen and hysteresis phenomenon although excess losses are also related to Barkhausen jumps [5]. In grain-oriented electrical steel, correlation has been found between the power spectra of Barkhausen noise over a cycle and total loss showing the possibility of relating crystal structure to magnetic behavior at microscopic and macroscopic levels [6].

It has been shown that the anisotropy of losses in non-oriented steels is mainly confined to the hysteresis component [7]. Furthermore, it has been proposed that the hysteresis loss can be split into two components, a high induction component which follows the texture behavior and a low flux density component which increases monotonically with angle from the rolling direction [8]. It is supposed that there are different energy dissipation mechanisms acting on these two different regions of the hysteresis loop: in the low induction region (below μ_{max}) it is well accepted that domain wall motion is the major source of loss, but in the high induction region (above μ_{max}) the main energy dissipation mechanism is not clear, whether it be irreversible domain rotation, domain annihilation and nucleation or simply more domain wall movement. Domain rotation, predominantly reversible, should not contribute to power losses. The usefulness of this approach has recently been demonstrated in grain-oriented electrical steel [9]. In addition, it has been claimed that the texture is not the only source of magnetic anisotropy in electrical steels since coercive force increases monotonically with angle from the rolling direction and is probably related to an anisotropy in the mean inter-inclusion distance at a microscopic scale [10].

In this paper we have attempted to correlate the directional variation of hysteresis loss in non-oriented electrical steel with the corresponding variation of BN in order to help clarify the dominant phenomena controlling the magnetic anisotropy of the material.

Measurements

Epstein strips of a 0.47mm thick non-oriented steel were cut at 10° intervals to the rolling direction of a sheet for BN and loss measurements. The fully processed 3.85% Si steel had been stress relief annealed at 700°c. Its saturation magnetisation was around 1.97T, resistivity 55 μΩcm and its mean grain diameter was 130μm. Texture measurement revealed a strong [001](110) component.

The BN was measured in a single strip tester over a peak flux density range of 0.1T to 1.4T at 25Hz and 50Hz magnetising frequency. The output signals from two multi turn search coils were connected in series opposition prior to digital signal processing to obtain a BN signal [11]. BN under a.c. conditions can be analysed in several ways. In this case it was found most accurate to measure the amplitude sum (over 20 cycles) effectively averaged per cycle of magnetization. Repeatability measurements confirmed that the values obtained in this way at a given flux density and frequency in any one strip varied by less than 3%.

Fig.1 and Fig. 2 show the variation of BN amplitude with flux density in strips cut at 10° angles to the rolling direction (the last digit in each case refers to the rolling direct '0' being along RD and '9' being at 90° to the RD). It can be seen that up to around 0.9T there is little difference of the BN in samples cut between 60° and 90° to the RD, whereas it increases with angle at any flux density in samples cut between 0° and 50° to the RD. Above 0.9T the BN follows the pattern illustrated in Fig. 3 showing the peak around 60° at both 25Hz and 50Hz. Clearly there is a different texture dependence above and below this critical flux density.

Total losses were measured in stacks of each material cut at each angle to the rolling direction in a standard Epstein frame. Hysteresis loss was calculated based on the area of the quasi-static B-H loop, eddy current loss was calculated from the classical Maxwell equation and the excess loss was calculated as the difference between total loss and the other two components. The anisotropy index (maximum loss – minimum loss divided by average loss) at 1.5T was 0.19. The absolute difference between maximum and minimum total and hysteresis loss was 0.64W/kg and 0.53W/kg respectively indicating that much of the loss anisotropy was due to the hysteresis component [8].

The hysteresis loss was subdivided graphically into the "high induction" and "low induction" components. The hysteresis loop is divided into two regions bounded by the value of induction at maximum permeability (μ_{max}). This value can be taken from the hysteresis curve, as the magnetization curve joins the lower branch of the hysteresis curve around that point. The "low induction" hysteresis component is the area between the two values of induction at maximum permeability, while the "high induction" hysteresis component is the sum of the two symmetrical areas from maximum permeability up to maximum induction.

Fig.4 shows the variation of these components with angle to the rolling direction demonstrating the monotonic increase in the low induction component and a peak in the high induction component. occurring at around 50°.

Discussion

The Barkhausen data presented in Fig. 1 and Fig. 2 represents the average activity over one magnetising cycle. It is well known that if this were further analysed most of the activity would be found to occur at the time in the a.c cycle when the flux density is changing rapidly, i.e. close to the coercive point.

It is interesting to note the frequency dependence of the Barkhausen activity. There is almost a direct proportionality. It is generally stated that BN is independent of frequency but it is probable that the 'fine' level activity is independent but the macroscopic, or "course level", activity is frequency dependent and contributes to the excess losses.

The difference between the low induction variation of BN with angle of magnetisation and the high induction case is not surprising. At low induction magnetization in non-oriented steel occurs mainly by 180° domain wall motion and hence even a small [001](110) texture present will not cause any angular variation of properties. The BN does however increase with angle at low induction and this could be attributed to the anisotropy in the mean inter-inclusion distance [10]. This phenomenon is not well understood but it would be expected to cause a monotonic increase in BN since the low-induction hysteresis component increase monotonically.

At high induction, typically above 0.9T, 90° domain wall motion comes into play and a higher amount of rotation will also occur. These are both texture dependent and produce additional BN of the 'fine' type. Because of the dominance of the [001](110) texture it is not surprising that the high flux density BN versus angle characteristics is similar to magnetostriction, loss and coercivity characteristics of Goss oriented electrical steel which are well documented [12].

The anisotropy factor of the BN at 1.2T, 50Hz and 1.2T, 25Hz was 0.21 and 0.31 respectively. The corresponding anisotropy factor of the hysteresis loss was 0.33. There is insufficient data here to draw any firm conclusion but it is interesting that the anisotropy factor of the BN at 25Hz and hysteresis are very close whereas the anisotropy factor of the BN is lower at 50Hz. This could indicate that as the frequency drops there is a closer correlation of the two because the BN does not include such a large component due to the macroscopic frequency dependent events.

Conclusion

This study shows definite correlation between BN and the high and low induction hysteresis components in non-oriented electrical steel. It appears to verify the influence of anisotropy of inter-inclusion distances on angular dependence of losses in non-oriented steel. The role of the phenomena which cause excess losses in producing a frequency dependent BN component should be noted. In the future, it would be of value to carry out further studies to verify these conclusions apply to material with different textures and to attempt to quantify the relationship, if any, between BN and the flux density and frequency dependence of excess loss as well as further verifying the correlation with hysteresis components in other materials. This would provide a better understanding of the effects of texture on loss which could help in the development of new grades of low loss motor steels.

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Figure 1:

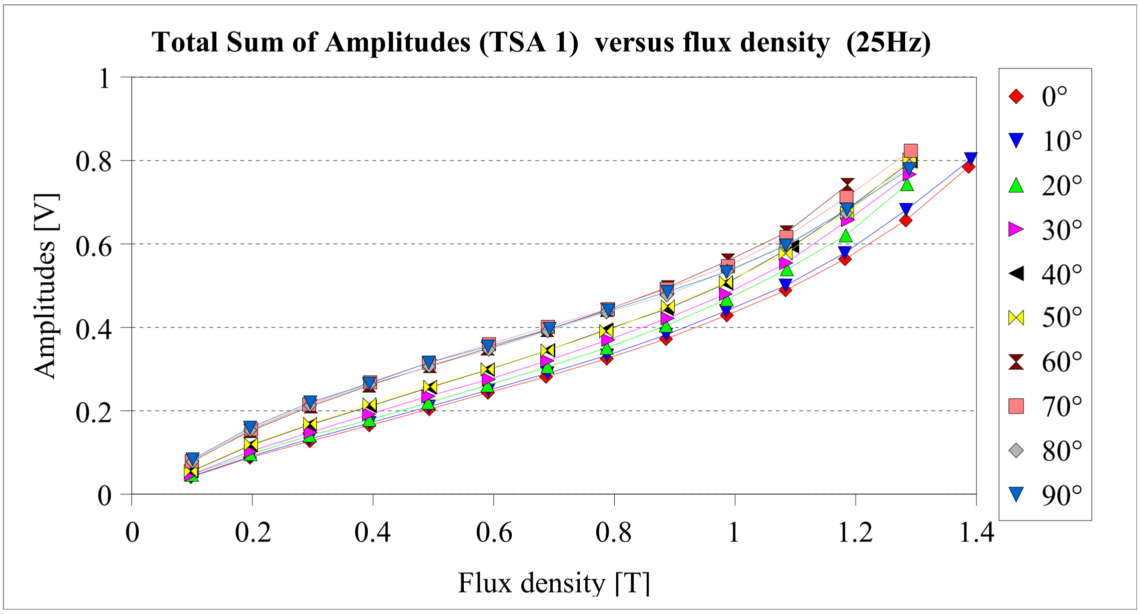

Figure 2:

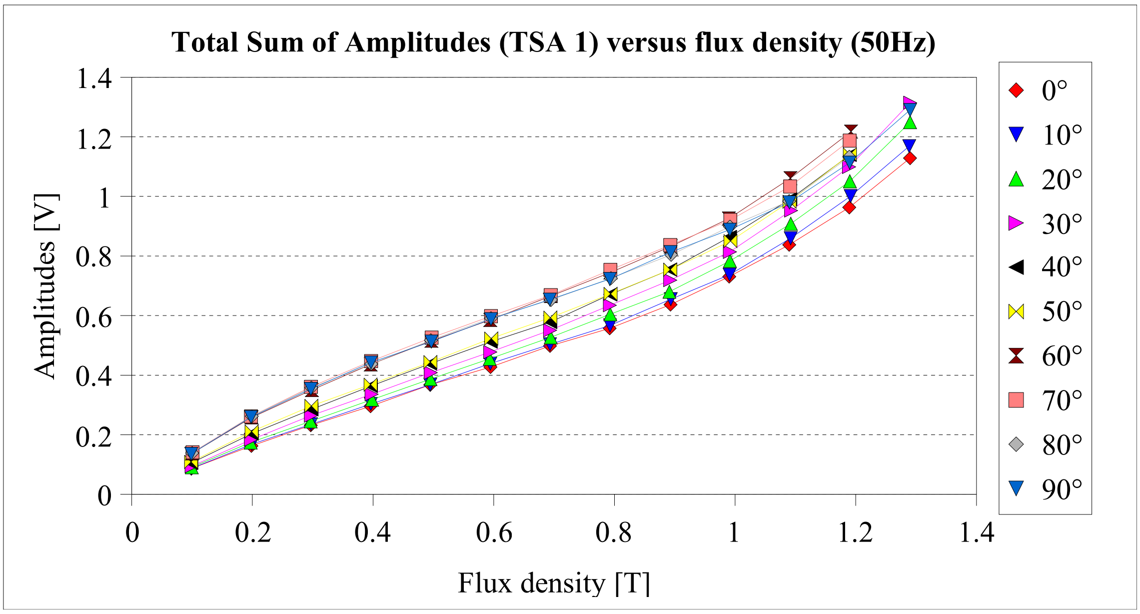

Figure 3

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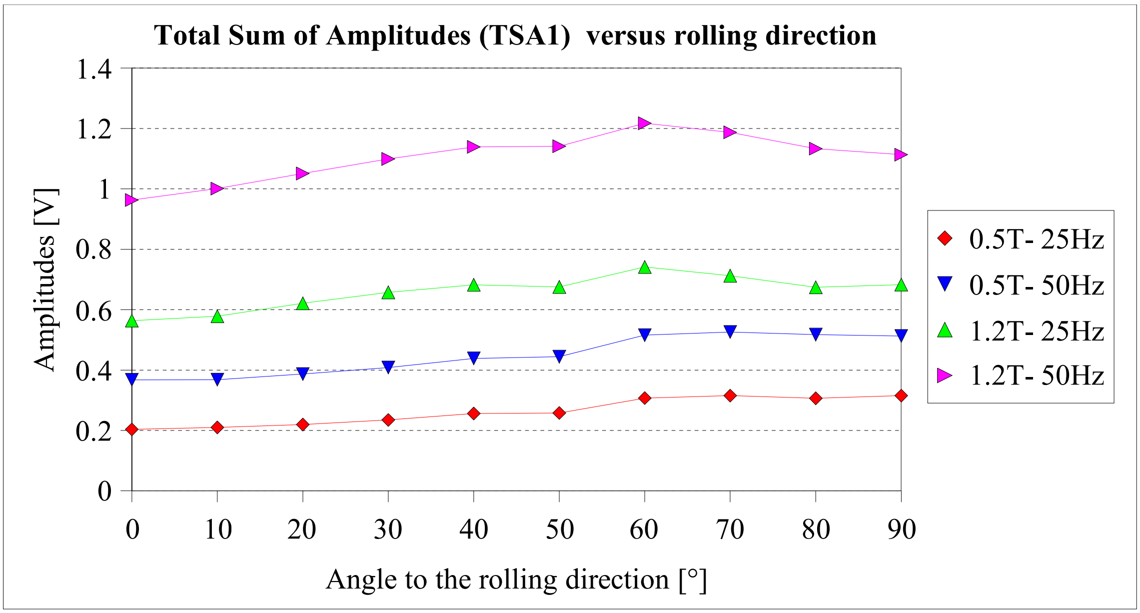

Figure 4

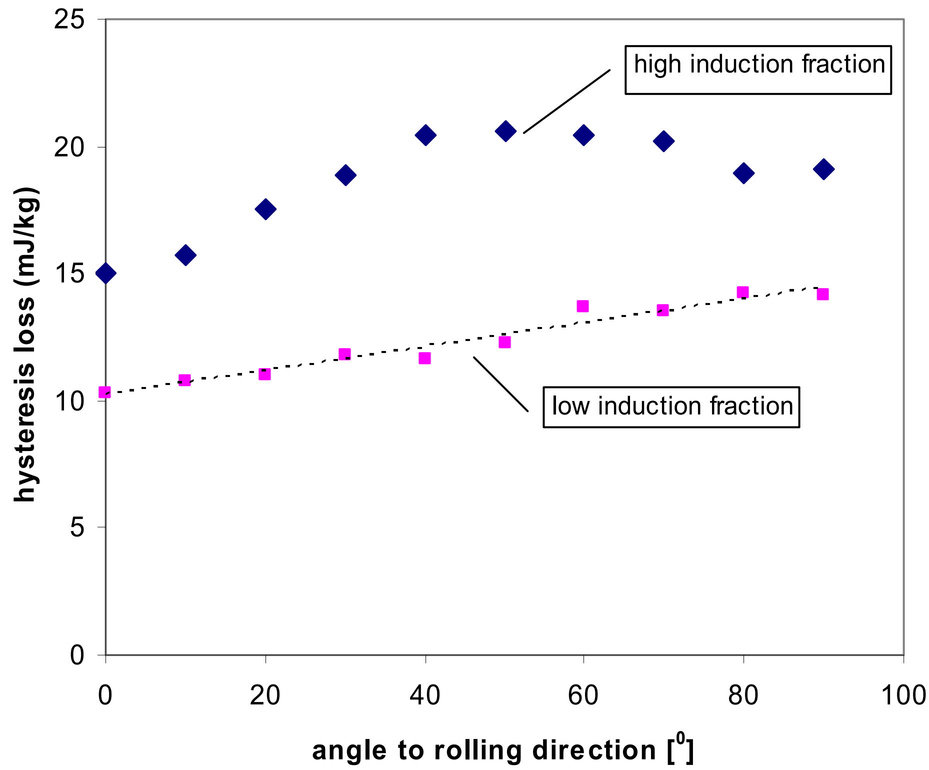

Figure 4. Angular behaviour of high and low induction fraction of quasi static hysteresis loss