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Development and application of measurement techniques for evaluating localised magnetic properties in electrical steel

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ABSTRACT

This paper reports the development of a measurement probe which couples local flux density measurements obtained using the needle probe method with the local magnetising field attained via a Hall effect sensor. This determines the variation in magnetic properties including power loss and permeability at increasing distances from the punched edge of 2.4% and 3.2% Si non-oriented electrical steel sample. Improvements in the characterisation of the magnetic properties of electrical steels would aid in optimising the efficiency in the design of electric machines.

1. Introduction

The development of electric vehicles (EV) and hybrid electric (HEV) has been driven in recent years by the desire to be more environmentally friendly. Requirements by governments and consumers for decreases in carbon emissions, improvements in air quality and reduced reliance on fossil fuels has placed an onus on motor manufacturers to improve the fuel efficiency of their vehicles and subsequent reduction of exhaust gas. One method of achieving this in HEVs is through improvement of the efficiency of the EV's traction motor. The functional material in the core of the motors is required to have many and often competing properties outlined in Table 1.

Few materials satisfactorily weigh the different requirements for an electric motor more economically than non-oriented electrical steel (NOES). Mechanical punching, which is low cost and suitable for high volumes, is the most popular cutting method. Therefore, the laminations, used in motor cores are largely produced by punching from NOES sheets.

Electrical steel sheets are measured under conditions of no applied stress, uniform alternating field, in a given direction with a sinusoidal flux waveform as prescribed by international standard IEC60404-2. Many of these assumptions are undermined by the manufacturing process and in particular, the punching of the laminations which introduces plastic and elastic stress/strain resulting in an increase in power loss. The greatest impact is on the narrowest parts such as the teeth where the proportion of the width of the degraded zone at the cut edge to the total width is high, unlike the Epstein, which is stress-relief annealed, or SST test samples which can be as wide as 500 mm.

Punching induces plastic strain which peaks in a region of the order of the sample width from the edge but can extend up to 10 mm from the edge if plastic flow isn't limited [1]. These combine with residual stresses due to the non-uniform distribution of plastic strains, potentially extending over the entire width of the sample. These residual microstresses hinder the motion of domain walls and increase power loss. [2]

The cutting of electrical steel is known to affect the magnetic properties negatively with a pronounced effect in the region close to the cut edge [3–6]. Investigations into the effect of cutting have produced varying estimates for the degradation region depth as the depth varies with material properties, cutting type and methodology [7]. Optical microscopy [8–10] shows clear grain deformation in the first 0.5 mm from the edge of punched samples. Altered domain patterns over 1–5 mm were observed [11] using Kerr microscopy. Micro-indentation showed increases in hardness, which can be used to estimate residual stress, pronounced in the first 0.5–1.0 mm [12,13], but with a gradual increase extending up to 10 mm. Naumoski [14] using the MOKE method, noted changes in domain structure over the first two to three grain rows

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Table 1
Driving properties and related core material requirements.

Driving property	Material requirements
High torque for starting	High permeability
Compact and lightweight	Low loss under high frequency
Small rotor/stator air gap	Good workability
High fuel efficiency	Low loss in typical driving ranges
High revolutions	High strength

near the edge. Estimations for the degradation depth can be obtained by dividing samples, to increase the number of cut edges per unit width. Gmyrek [15] divided rings 200 mm OD, 160 mm ID into concentric rings and estimates the depth to be 1.87 mm.

Measurement of the local flux density have been made using search coils with the degradation depth extending up to 10 mm from the edge [16,17]. However, this involves damaging the sample and altering the stress field with the drilling of holes. Non-destructive methods include the needle probe methods or the use of capacitors proposed by Zurek [18]. This method uses conductive paint which cannot be moved easily between measurement locations.

There have been several methods proposed to model the magnetisation profile within a sample taking cutting into account. Vandenbossche et al. [19] used the drop in permeability at the edge and a parabolic function, both experimentally determined from strips cut with a guillotine to increase the number of cut edges. Peksoz [20] used Matlab to find the best fitting function with input parameters obtained with search coils from eight experimental data sets. Siebert [5] who used neutron grating interferometry and the so-called dark field image technique, looked at the flux density across the width of 5 mm wide 2.4% NOES (material grade M330-35A) samples, with the B profile calculated for punched samples having a symmetric parabolic shape and notably different from laser cut samples. Elfgen [21] used the mathematical description of the permeability described in [19] to produce a continuous model to describe the local magnetic properties with model parameters identified from SST measurements on M330-35A samples. These are however laser cut which will have a different distribution profile.

As there is such a variance in both degradation depths and flux density profile due to material, geometry and cut method, being able to validate and compare profiles would be of great importance to designers of electrical machines in the optimisation of their designs as well as refining loss models.

2. Measurement principles

Methods to measure both local B and H include a needle probe and H-coil sensor by Enokizono [22] and Hall sensors have been used to measure the local magnetic field [23,24]. The ease of constructing devices using Hall sensors coupled with their simplicity of use and small sensitive area make them suitable for the measurement of local magnetic field.

Measurements of local flux density have included using search coils, which is based on Faraday's law of induction. The main disadvantage of this method is that it requires the drilling of holes in the sample which can induce significant additional stress and cause local variation in flux density distribution.

The needle probe method which was initially proposed by Werner [25] helps to alleviate some of these concerns by not requiring any drilling of the sample. The needle probe method works by calculating the voltage between two points on the surface of a sample, with the measured voltage assumed to be proportional to the rate of change of the flux density within the sample, between the needle tips. For this to be true several assumptions are made; firstly, that the flux distribution within the sample is symmetrical with regards to the centre axis parallel to the surface on which the needles are placed; secondly that the spacing between the needles is large compared to the sample thickness so that the sample thickness can be neglected [26,27]. This is rarely an issue in electrical steel where the lamination are usually 0.5 mm or less thick. However, due to the grain structure there will not be exact symmetry between top and bottom halves, the best that can be achieved is a similar distribution in number and size of grains. An increase in average grain size and decreases in needle spacing will result in increased errors.

Studies have shown the needle method can produce local flux density measurements in good agreement with search coils [28] although errors can be introduced if the distance between the needle and the edge doesn't exceed half the lamination thickness [29].

The combining of a needle probe and Hall effect sensor along with an accurate and precise positioning system allows a reproducible non-destructive method that also has flexibility in being able to move the measurement location.

The power loss, measured in W/kg is calculated by integrating the area of the loop and is given by the following equation.

$$P_t = \frac{1}{\rho T}\int_0^T H\frac{dB}{dt}dt \tag{1}$$

where H is the instantaneous tangential component of the field at the surface (A/m) and, in this case measured by a Hall effect sensor. B is the instantaneous value averaged over the cross sectional area of the material. ρ is the density of the material (kg/m^3) and T is the period defined as $T = 1/f$ where f is the frequency.

3. Experimental setup

A system was developed to measure the local magnetic properties of punched electrical steel ring samples. This consisted of a computer controlled, AC magnetising system, developed at Cardiff University, consisting of a desktop PC, National Instruments DAQ PCI 6120, power amplifier and isolation transformer [30].

The local magnetising field, power loss, flux density and permeability of 0.35 mm thick 3.2% Si non-oriented punched electrical steel rings with various inner diameters (ID): (150 mm, 160 mm, 170 mm, 180 mm and 190 mm) and constant outer diameter (OD) 200 mm was measured. Rings were chosen as they more closely replicate motor stators but have a simpler geometry which could be more easily magnetised and by keeping the OD fixed and increasing the ID the proportion of degradation depth, which was assumed to be constant to sample width, was increased.

The samples were placed inside Polyamide PA 2200 cases each additively manufactured to suit the various ring diameters although not in direct contact with the sample as to reduce compressive stress and increase air cooling (Fig. 1).

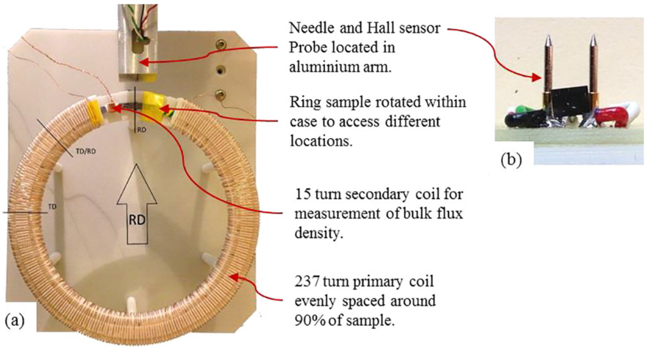

Fig. 1. (a) Plan view of magnetising system for 190 mm ID sample and (b) local measurement probe consisting of Hall effect sensor and needles.

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