Determination of the Demagnetisation of Electrical Steel Strips

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***Abstract*— Using basic principles and fundamental equations for calculating the average demagnetising field at the mid-plane of a completely saturated magnetic strip, demagnetising effect was estimated and confirmed by measurements made on various samples. Using the formula, the saturation magnetisation of a group of steel strips, measured using an open magnetic circuit tester, was corrected. The accuracy in determining saturation magnetisation using this method was investigated.**

***Keywords*— demagnetising field, electrical steel, saturation magnetisation**

I. Introduction

There is a well known and well understood fact that there is a difference between the magnetic field inside a magnetised body and the field applied to it. This is the so called demagnetising field. The demagnetising field is related to the shape, dimension and magnetic properties of the body [1-5].

The demagnetising field is present in all magnetic measurements and is normally reduced to near zero by using a closed magnetic circuit. In such cases as the measurement of electrical steel strips using an open magnetic circuit or an on-line yoke type tester with air gaps between the sample and the yokes, the demagnetising field cannot be entirely eliminated. Concerted effort has been dedicated on determination and computation of demagnetising effects [6-10]. The actual magnetic field in the sample can be accurately measured using the Rogowski-Chattock potentiometer or an H-coil. The magnetic flux on the other hand is normally measured using a B-coil wound on the former of the exciting coil, enclosing the sample under test. This includes a flux component caused by the demagnetising field of the sample. For general purpose measurements, it is usually acceptable to neglect the effect of this field, but, in order to precisely measure the magnetic properties of the sample, a detailed study of the demagnetising field of the sample is necessary.

Since the study on the demagnetising field in the shape anisotropic magnetic materials for example described by authors such as Chikazumi [11] and other experts, significant efforts have been directed at the study of the demagnetising field in non elliptical samples by Becker and Kasten [12], Bertram and Steele [13], Simkin and Trowbridge [14], McWhirter [15], Joseph and Schlomann [16], and the use of fictitious magnetic poles has been universal. Most of these however assume that the samples were uniformly magnetised and that the magnetisation in the samples was constant. Such an assumption is acceptable only for non-magnetic and diamagnetic materials.

Ruehli and Ellis [17] used a field-dependent magnetisation with the assumption that the susceptibility was constant and the contribution from the magnetic poles in the sample volume was negligible. On the other hand, Normann and Mende [18], using a field-dependent susceptibility, determined how the distribution of magnetisation changes as a function of the applied field for the short rectangular prisms, but the magnetic poles in the sample volume were neglected.

A method that involved dividing the volume of a magnetic sample into uniformly magnetised elements was used by Brug and Wolf [19] for the case of thin disks that undergo magnetic phase transitions. But a demagnetising matrix for interacting volume elements in cylindrical geometry was used there.

Soinski [20] used a one-dimensional summation method to calculate the demagnetising coefficients of standard rectangular electrical steel strips (300 mm × 30 mm) used in the Epstein testers, magnetised in a homogeneous applied field. However, no consideration was made here for the influence of the magnetic poles in the sample volume, but to some extent, this is a study that is relevant to the current investigation since the sample sizes are very similar.

Generally the method for measuring the demagnetising field of a body is based on the same foundation that the tangential component of magnetic intensity is continuous at the boundary of two media. Foster [21], using double search coil connected in series opposing, measured the ballistic demagnetising factor of circular cylinders. Tejedor [22], using two flux meters, measured the demagnetising factor of both circular cylinders and plates, but, determining the magnetic properties of the samples was needed.

The calculated applied magnetic field was produced by a comparably longer rectangular coil, and the results were then compared with those of measured values on actual samples using the computerised experimental set-up, previously described in [23,24].

II. DEMAGNETISING FIELD IN AN OPEN MAGNETIC TESTER

Figure 1 shows the basic structure of an open magnetic circuit tester used for the measurements. The magnetic flux Φ induced inside a B-coil wound around the longitudinal centre of the former is:

$$\Phi = \mu_0 A_t(\overline{H}_a - \overline{H}_d) + A_s M_s \tag{1}$$

where $\overline{H}_a$ and $\overline{H}_d$ in equation (1) are the average applied field and the average demagnetising field in the cross-sectional area of the B-coil, $A_t M_S$ is the saturation magnetisation in the sample cross-sectional area A_S. After air flux compensation, the magnetic flux of equation (1) is then:

$$\Phi' = A_s(\overline{M}_s - \mu_0 \frac{A_t}{A_s}\overline{H}_d) \tag{2}$$

The first part of equation (2) is related to the saturation magnetisation, while the second part to the demagnetising field of the sample. The influence of demagnetising field on saturation magnetisation determination depends on the demagnetising field strength as well as the ratio of the cross-sectional area of the B-coil to the sample. To obtain the same accuracy ΔM_S in saturation magnetisation of different size of samples, the accuracy in determining demagnetising field is:

$$\Delta\overline{H}_d = \frac{A_s}{A_t} \cdot \frac{\Delta\overline{M}_s}{\mu_0} \tag{3}$$

For example, in our tester, the cross-sectional area of the B-coil is fixed at A_t = *360 mm*^{2}. To determine the saturation magnetisation of the strip (A_S = *18 mm*^{2} *(= 30 mm (width) × 0.6 mm (thickness))*) with an accuracy of 0.002 T, using equation (3), the accuracy in determining the demagnetising field should be *0.08 kA/m*. If the strip thickness goes down to *0.2 mm*, the accuracy should be around *0.03 kA/m*.

The magnetic behaviour of the samples in Figure 1 can be described by the total magnetic field $\vec{H}$ inside the strip, and is determined by:

$$\vec{H} = \vec{H}_a - \vec{H}_d \tag{4}$$

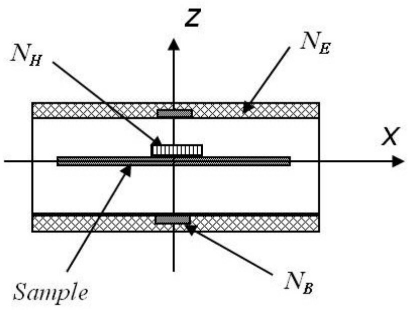

Fig. 1. Structure of an open magnetic circuit tester, showing positions of the B-coil (N_B), the H-coil (N_H), inside the main Excitation coil (N_E).

III. EXPERIMENTAL SET-UP

Figure 2 shows the experimental set-up for the measurement of the magnetic properties of an electrical steel strip [21]. The applied field to the sample is produced by a rectangular coil energised by a sinusoidal voltage at 50 Hz from the mains power supply. The strength of the applied field is obtained by measuring the exciting current in the coil using a Hall Effect current transducer. The magnetisation of the sample is measured by integrating and then sampling the differential induced voltage between the B-coil $\boldsymbol{N_B}$, wound inside the exciting coil, and an air flux compensating mutual inductor M_B located outside. The demagnetising field is measured by putting an H-coil adjacent to the sample at the longitudinal centre. The e.m.f. induced by the applied field in the H-coil is compensated by another external variable mutual inductor M_H. The instantaneous values of the demagnetising field, related to the respective values of the applied field, are obtained by sampling them simultaneously.

IV. DEMAGNETISING FIELD OF AN ELECTRICAL STEEL STRIP

To determine the actual demagnetising field, two similar characteristics but different lengths of 0.1 % silicon non-oriented electrical steel strips, originally supplied by a well known Steel works, were prepared. To eliminate the influence of the demagnetising field, sample properties were measured on the longer coil using the experimental set-up shown in Figure 2. The dc susceptibilities of the samples were approximated by calculating the ratio of the magnetisation of the samples to the applied field (i.e. $\chi = M/H_a$). Figure 3 shows the variation of demagnetising field against the lengths of a group of 0.65 mm thick, 0.1 % silicon steel strips, cut from the same origional sheet. When the sample is longer than 150 mm or the length to width ratio is greater than a critical value of 5, the difference between the demagnetising field calculated and that measured is less than *0.07 kA/m*, the accuracy estimated earlier. This means that, as long as the length to width ratio of a sample is more than 5, the accuracy in estimating demagnetising field and that of the saturation magnetisation could be ensured. Figure 4 shows the distribution of magnetisation inside the 0.1 % silicon strip, calculated at different values of applied field.

The linear increase of the demagnetising field against the

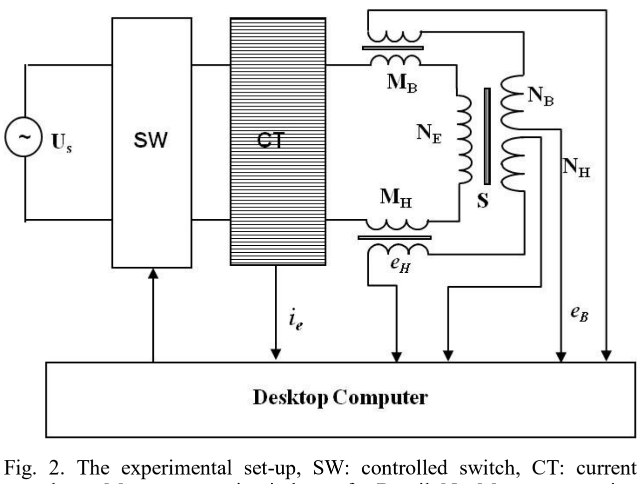

Fig. 2. The experimental set-up, SW: controlled switch, CT: current transducer, M_B: compensation inductor for B-coil, N_B, M_H: compensation inductor for H-coil, N_H, N_E: exciting coil.

saturation magnetisation, as shown in Figure 5, was also measured on the samples having different percentages of silicon content, yielding in alike.

Figure 4 shows that when the applied field is lower than a crucial value H_C=*5 kA/m*, the sample works in its unsaturated condition as the curves for H_a=*2 & 4 kA/m* in the same figure. In this case, a small increase of the applied field results in a large increase of the magnetisation at the centre of the sample and a comparatively slight increase at the two ends. According to the definition of magnetic poles by equation, such a variation in magnetisation is equivalent to a greater increase of the magnetic poles in the sample volume and a small increase of the magnetic poles on the boundary. It is due to the former that the demagnetising field increases proportionally to the applied field.

The ballistic demagnetising factor shown in Figure 6 was obtained by dividing the average demagnetising field of Figure 4 by the average magnetisation of the midplane of the sample, magnetised in different strengths of applied fields.

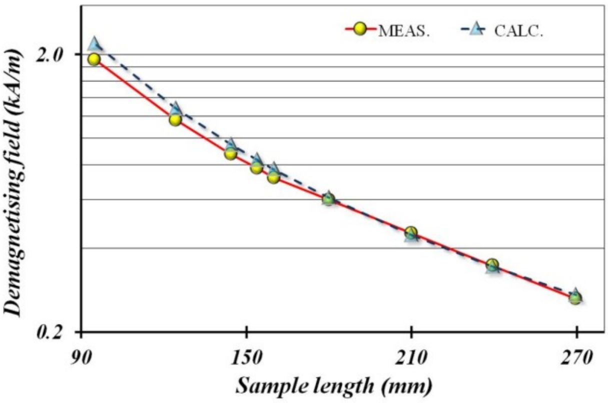

Fig 3. Variation of the demagnetising field against the length of a group of 30 mm wide, 0.65 mm thick non-oriented electrical steel strips.

The curves for in Figure 4 show that, when the applied field is increased further, the central region of the sample becomes saturated, and only the area of saturation increases with the applied field. Such a variation is equivalent to a movement of the magnetic poles in the sample volume towards the ends, and a small increase of the magnetic poles on the boundary. Hence, the exponential decrease of the demagnetising field is still dominated by the movement of the magnetic poles in the sample volume. Only after the sample becomes fully saturated throughout, the demagnetising field can be solely determined by the magnetic poles on the boundary.

V. INFLUENCE OF THE DEMAGNETISING FIELD ON THE MEASUREMENTS USING A B-COIL

Although the maximum demagnetising factor is only around 4×10^{-4} for thin electrical steel strip such as the one considered here (see Figure 6), the influence of the demagnetising factor

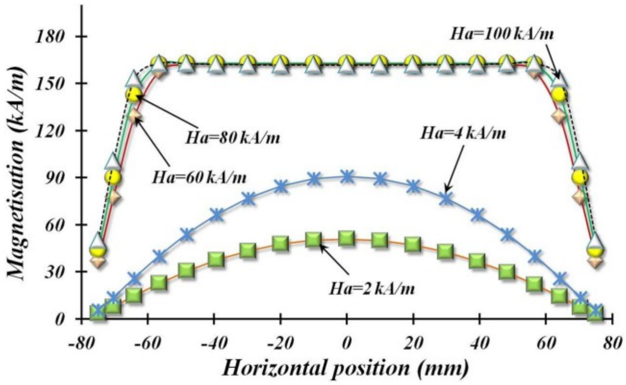

Fig. 4. Distribution of magnetisation inside the 0.1 % silicon strip, calculated at different values of applied field.

could be significant if the cross-sectional area of the B-coil is obviously larger than the cross-sectional area of the sample.

Figure 6 also shows the crucial H_C value of 5 kA/m, which results in the maximum demagnetising effect in the sample. This influence is normally defined by the ratio of the demagnetising flux $H_d\times A_t$ to the magnetisation flux $M\times A_S$ of the sample as:

$$R = \frac{H_d\ A_t}{M\ A_s} = N_d \frac{A_t}{A_s} \tag{5}$$

The demagnetising flux can be approximated by assuming its uniform distribution in the cross-sectional area A_t of the B-coil, A_S being the cross-sectional area of the sample, and the demagnetising factor.

For example, in the measurement of the magnetisation of the 150 mm sample using an open magnetic circuit similar to that shown in Figure 2, the cross-sectional area of the B-coil, which is determined by the dimension of the former of the exciting coil, is $A_t = 35\times10\ mm^2$, while the cross-sectional

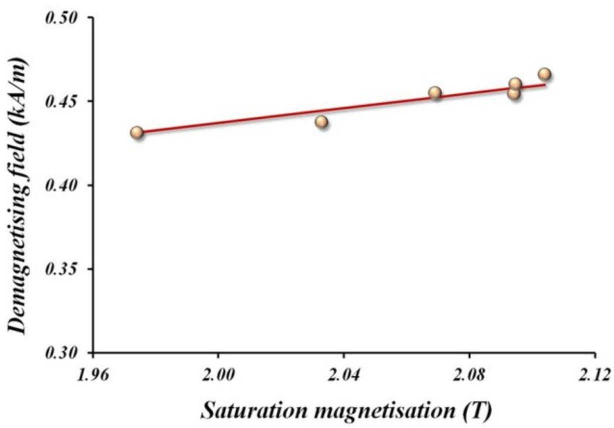

Fig. 5. Demagnetising field produced by the samples having different values of saturation magnetisation.

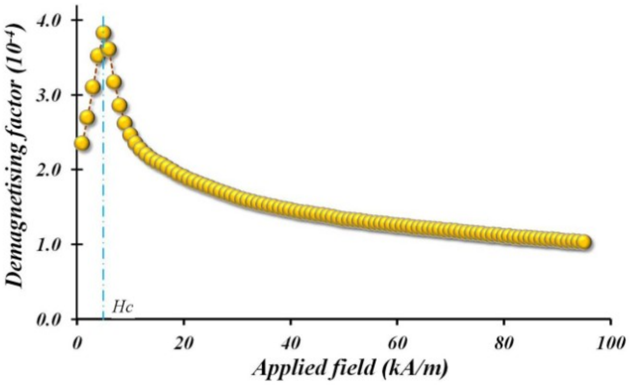

Fig. 6. Variation of the demagnetising factor against the applied field at the mid-plane of the 0.1 % silicon sample. The crucial value for the H_C, of 5 kA/m, is clearly shown to result in maximum demagnetising effect in the sample.

area of the sample is $A_S = 29\times0.63\ mm^2$. In accordance with Figure 6 and equation (5), the maximum influence of demagnetising field, which occurs at the crucial point, is around 0.7%. Even when saturated, the influence is still as high as 0.2 %.

VI. Conclusion

The small thickness of the electrical steel strip results in the demagnetising field produced by the magnetic poles in the sample volume to be greater than that produced by the magnetic poles on the boundary. The influence of the magnetic poles in the sample volume can be eliminated only when the sample becomes fully saturated throughout.

Being dependent on both the dimension and the magnetic properties of the strip material, the demagnetising field of a thin electrical steel strip varies with the strength of the applied field. Although the demagnetising factor of the thin electrical steel strip is small, its influence on the measurement of the magnetic properties of the sample could be significant, if the cross-sectional area of the B-coil is comparatively much larger than that of the sample.

It is however reassuring that the measurements carried out during investigation of magnetisation near saturation, reported previously, that the demagnetising fields were negligible. For stability of the system and measurements, no closure yokes could be employed for these measurements, and since the samples were in near deep saturation, the demagnetising effects were minimal.

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