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Assessment of the effect of lift-off on a magnetic flux injection technique for detection of residual curvature in electrical steel

***Abstract**. A magnetic flux injection technique developed to assess the residual curvature in non-oriented electrical steel strip has been assessed for its suitability for an on-line application with a study of the effects of lift-off between the pole faces of the magnetising/sensing yoke and strip surface. It has been found that changes in the lift-off appear to have very little effect on the differences in loss values measured at each of the surfaces which are correlated to the residual curvature.*

***Streszczenie.** Technika "flux injection" jest niekiedy stosowana do badania materiałów magnetycznych bez możliwości bezpośredniego pomiaru indukcji. W metodzie tej ważne znaczenie ma kształt nabiegunników rdzenia i ich przyleganie do powierzchni blachy. Zbadano możliwość pomiaru krzywizny powierzchni blachy. (**Ocena efektu uniesienia rdzenia w technice „flux injection" stosowanej do badania krzywizny blachy**)*

Keywords: Electrical steel, residual curvature, lift-off, power losses.
Słowa kluczowe: blachy elektrotechniczne, straty magnetyczne.

Introduction

Residual curvature can occur in strip steel due to various causes in the rolling process in which a cross-sectional stress profile in the longitudinal direction leads to a latent strain in steel laminations. A magnetic flux injection technique, based on a localised, single sided measurement of total loss, has been developed to assess the residual curvature (or, strictly, the latent strain in material held flat) in non-oriented electrical steel strip in the semi-processed condition [1]. This paper reports how the technique has been assessed for its suitability for an on-line application with a study of the effects of lift-off between the pole faces of the magnetising/sensing yoke and strip surface.

Description of technique

The technique is based on differences found in apparent values of the total loss from measurements made on the obverse surfaces of strip material using a single yoke, flux injection type of magnetisation system. The single yoke consists of primary and secondary electrical windings wound onto a laminated, soft magnetic C-shaped core made using wound grain-oriented steel. This yoke is placed on, or near, the surface of the strip material (which is held flat in a non-magnetic, non-conducting jig, as shown in figure 1) and losses associated with obverse surfaces of the strip assessed in turn.

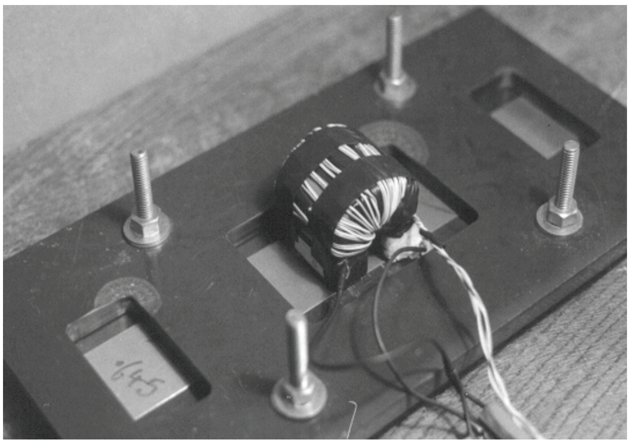

Fig. 1. The C-core, with primary windings visible, placed on a strip specimen held flat in a non-magnetic jig.

It has been reported that the differences in values of loss measured with the energised yoke placed on each surface have previously been found to be dependent on the degree of residual curvature held within the strip material for given values of flux density and magnetising frequency [1]. It is important to know the effect of introducing an air gap (lift-off) between the pole faces and the strip on the differences in loss associated with residual curvature.

Experimental procedure and results

The technique described above was previously carried out with the pole faces of the magnetising yoke placed directly onto the strip surface. In this study, controlled values of lift-off were achieved by inserting 0.5 mm thick, solid polystyrene sheets between the pole faces and strip surface. Up to three sheets of plastic were used to study the effects of values of lift-off of 0.5, 1.0 and 1.5 mm as illustrated in figure 2.

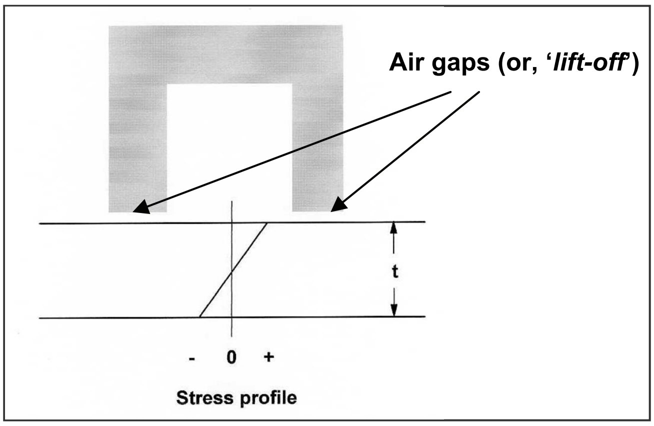

Fig. 2. Schematic diagram showing the C-core soft magnetic yoke, without primary and secondary windings visible, placed on a greatly exaggerated strip specimen held flat and containing a stress profile due to residual curvature, with air gaps introduced between the pole faces of the magnetic yoke and the surface of the strip. For clarity, the non-magnetic plastic spacers used to create the air gaps are not shown.

A value of peak flux density of B = 1.3 T was selected since previous results showed that the technique was optimal with peak flux density in the range 0.9 – 1.4 T.

The width of the C-core was 50 mm and the distance between the inner edges of the pole faces was 18 mm. The flux density was checked using an enwrapping search coil and a correction factor applied to the value measured by the secondary coils mounted on the yoke. A correction factor was applied to the path length (since the H-field was measured using the magnetising current) and a corresponding correction factor was applied to the values of power losses measured by the single yoke to give values in agreement with a Single Epstein Strip Test (SEST) system [2] using similar material in the same as-cut condition without air gaps. (The SEST was itself calibrated for agreement with a full four-limb Epstein frame [3].)

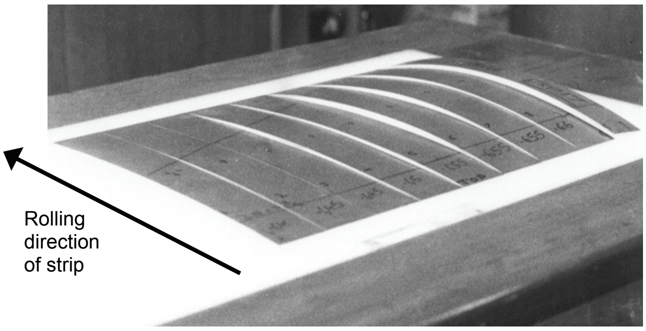

Fig. 3. Residual curvature in a slit steel sheet (note that such material was selected specially for study and would not be supplied to customers).

Measurements were made using 50 mm wide strips (the same width as the yoke to constrain flux in the direction of magnetisation) of semi-processed, non-oriented, 0.65 mm thick electrical steel sheared from a single sheet, shown in figure 3. This material was specially prepared for this study as it exhibited a range of residual curvature across the width of the strip. The material was tested in the as-cut condition and not stress relief annealed, hence the extra-ordinarily high values of power losses exhibited by the material. The strips selected exhibited retained radii of curvature of up to 2.086 m.

Figure 4 shows the values of specific total loss versus radius of curvature measured using the yoke on each surface of the sheared strips for each value of lift-off. Figure 5 shows the differences in these values of specific total loss for each value of lift-off.

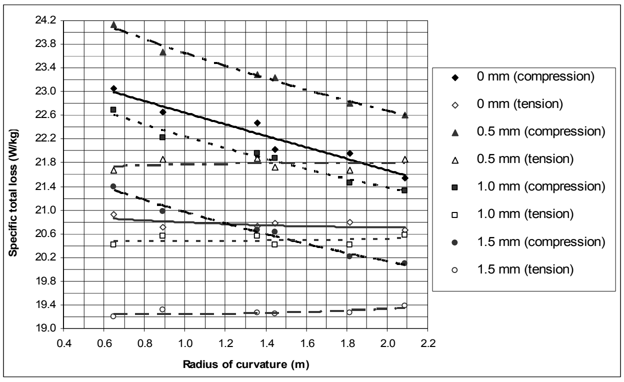

Fig. 4. Specific total loss vs. radius of curvature at B = 1.3T, f = 50Hz. Losses measured on obverse surfaces of strip containing residual curvature and held flat in a non-magnetic frame. The nature of the stress at the surface for each set of measurements and the magnitude of the lift-off of the yoke from the surface is indicated in the key.

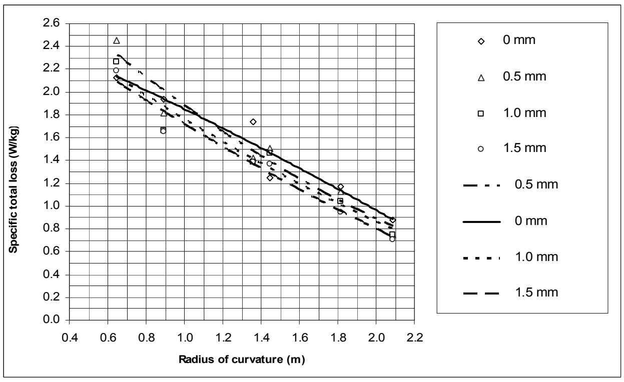

Fig. 5. Difference in specific total loss vs. radius of curvature. Trend lines for each value of lift-off are shown.

Discussion

In an industrial environment, control of the air gap between a magnetising fixture and the moving strip surface (in which the fixture and strip surface must not be in contact in order to avoid possible damage to either the strip or the fixture itself) is likely to be subject to some degree of variation.

It is well known that permeability based techniques developed to assess residual stresses in ferromagnetic materials are notoriously susceptible to the variation in lift-off since any variation greatly affects the reluctance of the magnetic circuit. Losses, however, are associated with physical phenomena in the material (hysteresis and eddy current effects) and not the air gap. Therefore, other than the effect of changes in flux direction with respect to the plane of the strip, which most likely account for the variation in values of total losses measured using the yoke and shown in figure 4, changes in the lift-off appear to have very little effect on the technique of assessing differences in losses between surfaces, as shown in figure 5.

These results suggest this method could be suitable in an on-line application where the yoke is held off the surface of the material during a process of continuous assessment.

Conclusion

A magnetic flux injection technique developed to assess the residual curvature in non-oriented electrical steel strip in the semi-processed condition has shown that an air gap between the pole faces of the magnetising/sensing yoke and strip surface have very little effect on the differences in values of loss measured at each surface, potentially making the technique suitable for an on-line application.

REFERENCES

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