EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN LEP-MA/83-36

COERCIMETER FOR NON-DESTRUCTIVE MEASUREMENT OF THE COERCIVITY OF STEEL SHEETS

by

J. Billan

Presented at 8th International Conference on Magnet Technology,
Grenoble, France, 5 - 9 September 1983

Geneva, Switzerland
September 1983

Résumé - Cet instrument spécialement conçu pour mesurer la coercivité de tôles d'acier sans découper d'échantillon, sera utilisé pour faire les 8000 mesures de coercivité nécessaires au contrôle de la production des 11'000 tonnes de tôles d'acier pour les dipôles LEP. Le coercimètre effectue des mesures locales et directionnelles de la coercivité avec une précision de 3 % et une reproductibilité de 1 %. La perméabilité peut aussi être mesurée avec une précision comparable. Description et performances sont présentées.

Abstract - A special instrument has been built to measure the coercivity directly on steel sheets without having to cut samples. It will be used to perform the 8000 coercivity measurements which will be needed during the production of the 11'000 ton of steel sheets for the LEP dipole magnets. The coercimeter allows local and directional coercivity measurements to be made on a steel sheet with an accuracy of 3 % and a reproducibility of better than 1 %. The permeability can also be measured with similar precision.

I - INTRODUCTION

The 3304 dipole magnets of LEP require the production of 11'000 tons of 1.5 mm thick decarburized steel sheet. As explained in a previous paper [1], this steel, besides having a low coercivity and a high permeability, must also have a very low spread of coercivity. The maximum dispersion of ± 11 $A\ m^{-1}$, guaranteed by the manufacturer, is still too large and a controlled mixing of the steel is necessary. To this end, about 8000 coercivity measurements will have to be performed during production. For such a large number of measurements, classical permeameters (ring or Epstein frame) requiring preparation of samples are excessively time- and steel-consuming, hence the idea to build a "coercimeter" measuring the coercivity directly on the steel sheets without having to cut samples.

II - PRINCIPLES

The steel sheets are of rectangular dimensions, 1.0 x 0.5 m. Magnetization is provided by an excitation coil and is concentrated by using a pair of flux return yokes placed on each side of the sheet. The yokes also serve to minimize the excitation. The flux in the sheet is measured by means of a detection coil as shown in Fig. 1. Also shown in this figure are the auxiliary excitation and detection coils placed on the yokes, which are used to estimate the mean air gap of the yoke contacts by measuring the magnetic flux circulating only between yokes.

The basic principle of the measurement is as follows: considering a closed flux line passing through the steel sheet and one of the return yoke, by definition the coercive field is calculated from the number of ampère-turns ($N\ I_c$) which give a zero induction along this flux line. According to Ampère's law:

$$N\ I_c = H_{c_s} \times l_s + H_{c_y} \times l_y \qquad (1)$$

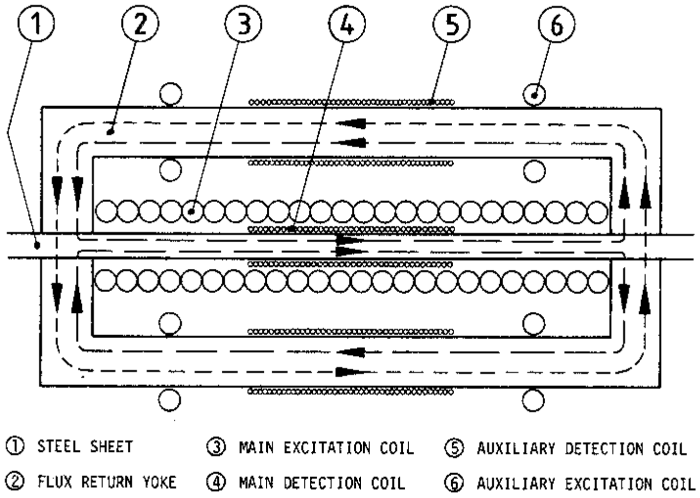

Fig. 1 - Schematic cross-section of the coercimeter

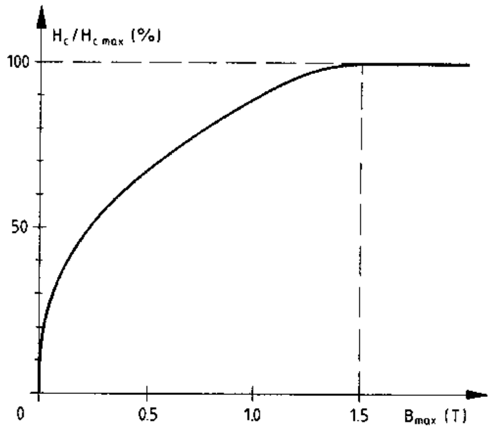

Fig. 2 - Typical variation of H_c vs. maximum induction

(at zero induction, there is obviously no drop of ampère-turns due to the reluctance of sheet, yoke and air gap), hence

$$H_{c_s} = \frac{N\ I_c - H_{c_y} \times l_y}{l_s} , \qquad (2)$$

where:

H_{c_s} = coercive field of the steel sheet,
H_{c_y} = coercive field of the yoke,
l_s = flux line length in the sheet,
l_y = flux line length in the yoke.

From eq. 2 it can be seen that for $H_{c_y} \ll H_{c_s}$, the measuring precision is largely determined by the precision of l_s. The detection coil measures the total flux in the sheet, but due to the width of the yoke contacts, each flux line has a different length. Nevertheless, a mean length has been computed under the condition that the flux lines do not wander in the sheet but pass from one contact to the other in straight lines in the plane of a cross-section of the coercimeter (two-dimensional problem hypothesis). For this reason, the following considerations guided the design:

a) The excitation field must be as homogeneous as possible, hence the choice of an excitation coil of one layer placed in close contact with the sheet and covering all the free space between yoke contacts.
b) The yokes should be good magnetic short-circuits, hence the air gap of the contacts must be as small as possible and the material of the yoke must have the highest possible permeability.
c) The yokes should cover completely one of the dimensions of the sheet in order to avoid "end effects" increasing the mean length of the flux lines in the sheet.
d) The yokes should be laminated in order to prevent the flux in one of the yoke laminations from passing into an adjacent one: this helps to limit the influence of variations of the air-gap contacts (e.g. due to sheet surface irregularities).

Another important consideration in designing a coercimeter is that it is not necessary to magnetize the steel sheets up to complete saturation: to reach the maximum value of H_c, 1.5 T is sufficient (see Fig 2). This limits the maximum field to approximately 1200 A m^{-1}, thus simplifying the design of the excitation coil.

Some results of the computations of the mean length of the flux lines in the sheet are given in Fig. 3, and the coercive field variation in the sheet under the yoke contacts, deduced from those computations, is given in Fig. 4 for a 1.5 mm thick steel sheet.

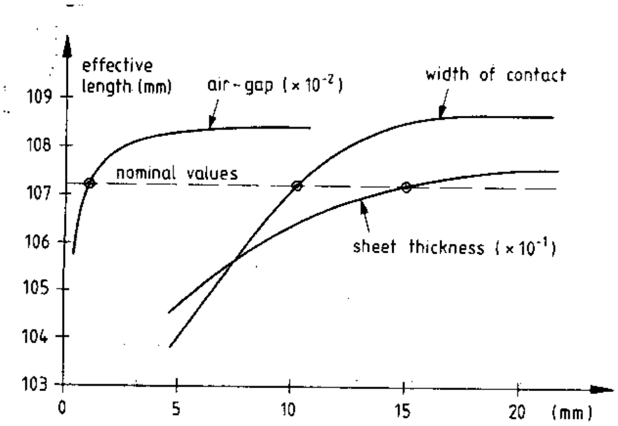

Fig. 3 - Variation of the effective flux line length

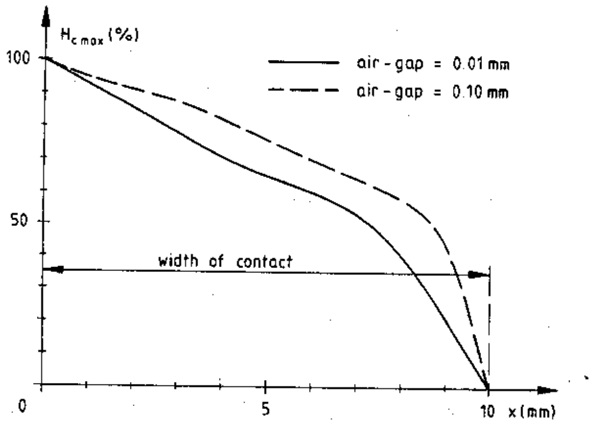

Fig. 4 - Variation of H_c under yoke contact

III - DESCRIPTION

1. Main components

The yokes are the most important component of the coercimeter. They are made by stacking 0.9 mm thick mumetal laminations having a filling factor of 0.95. At the maximum induction in the yoke (0.12 T), the mumetal coercive field is smaller than 1 A m^{-1} and μ is of the order of 10^5. The overall length of the stack is slightly more than the width of the sheet (520 mm), the lamination and contact width are 10 mm and the free space between contacts 100 mm.

The excitation coils, made of 2.5 mm^2 flexible copper wire, have 24 turns for the main coil and four turns in total for the auxiliary coils. The detector coils have 50 turns for the main coil and also 50 turns for each of the auxiliary coils. The latter are connected in such a way as to be in series for a flux circulating only in the yokes and in opposition for the return flux of the sheet.

The yokes are pressed against the sheet with of force of 3000 N by use of a pneumatic jack. A system of rollers guides the sheet for an easy and safe introduction into the coercimeter. This is shown in Fig. 5.

2. Electronic and control equipment

Once the sheet is in place in the coercimeter, the sequence of measurements is automatic, controlled by microcomputer. The results are displayed on the screen, logged on paper and stored on a mini-cassette tape for statistical treatment.

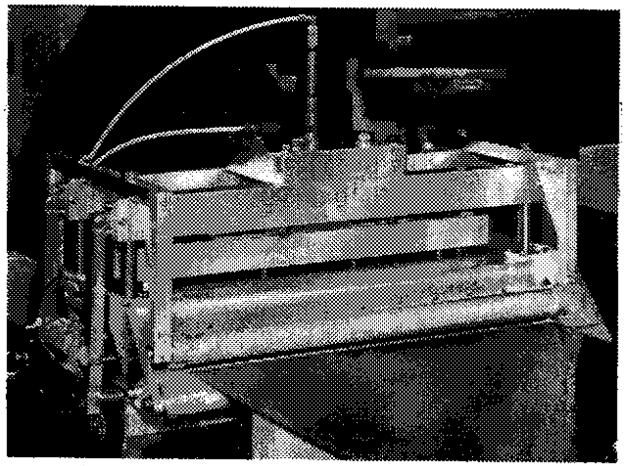

Fig. 5 - Introduction of a sheet in the coercimeter

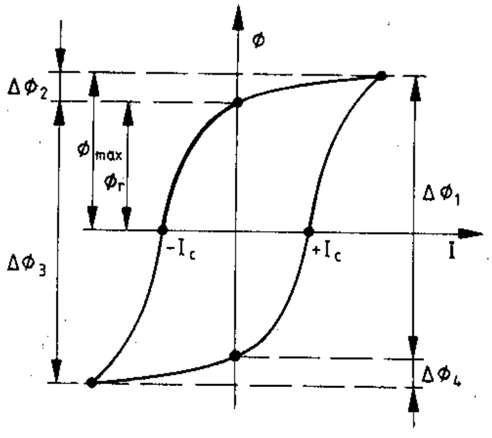

Fig. 6 - Flux measurement on a hysteresis cycle

Excitation currents are supplied by a precise bipolar power supply with a resolution of 0.3 mA ($\simeq 10^{-3}$ of I_c), and flux variations in detector coils are measured by integrators having a resolution of 1 µVs, a maximum drift of 5 µV and a maximum nonlinearity of 0.015 %.

IV - MEASUREMENT PROCEDURE AND PERFORMANCE

First, an average value of the four air gaps is calculated by measuring the flux in the yokes when magnetized by the auxiliary excitation coils. This value is used to calculate the effective flux path length in the steel, l_s. After demagnetizing the yokes, the power supply is commutated on the main excitation coil and a stable hysteresis cycle is established. The four flux variations along this cycle are measured as indicated in Fig. 6 and the remanent flux, ϕ_r, is calculated:

$$\phi_r = \frac{1}{4}\left[\left|\Delta\phi_1\right| - \left|\Delta\phi_2\right| + \left|\Delta\phi_3\right| - \left|\Delta\phi_4\right|\right] . \qquad (3)$$

Then, the current, I_c, necessary to cancel ϕ_r is measured on both sides of the cycle and H_c is calculated from the mean absolute value of I_c taking into account the coercive field of the yoke according to eq. 2. One measurement lasts about four minutes.

The coercimeter accuracy has been evaluated analytically and results have been compared with measurements performed on a ring permeameter [2]. The differences were of the order of typically 1 % and maximum 3 %.

The reproducibility is well within 1 % as long as the parameters influencing the coercivity are kept reasonably constant, particularly the temperature (10^{-3}/°C).

V - PERMEABILITY MEASUREMENT

Permeability can be deduced from the measurements of the maximum flux in the sheet, ϕ_{max}, and the calculation of the drop of ampère-turns in the free part of the sheet between the yoke contacts (e.g. 96 % for 1200 A m^{-1} excitation field and 0.01 mm air gaps). At such a field level, the permeability of this steel is slightly superior to 1000 and the measuring accuracy is about 2 %.

CONCLUSION

Designed to be operated in a simple and reliable way by non-specialists, two coercimeters have been installed at the steel works. Since the beginning of 1983, about 1000 coercivity measurements have been performed satisfactorily.

ACKNOWLEDGEMENTS

This work was initiated by J.P. Gourber who launched the idea of a single sheet tester. Thanks are due to K.N. Henrichsen, H. Depierre and G. Turcato who designed and built most of the electronic equipment, to C. Sanz for his skillful work in the yoke fabrication and to G. Erskine for his helpful participation in program computations.

REFERENCE

[1] GOURBER J.P., BILLAN J., LAEGER H., PERROT A., RESEGOTTI L., CERN LEP-MA/83-9 - presented at 1983 Part. Acc. Conf., Santa Fe, N.M (March 1983).

[2] HENRICHSEN K., CERN AR/Int. SG/65-7 (1965).