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PRODUCTION OF THE SOFT MAGNETIC STEEL LAMINATIONS FOR THE LEP DIPOLE MAGNETS

by

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Abstract: By January 1987, Cockerill has produced 10 000 t of soft magnetic steel sheets and Styner & Bienz has precision-punched 3 500 000 laminations for the 3 370 steel-concrete cores for the LEP dipole magnets. Systematic quality controls were performed to ensure uniform magnetic and geometric characteristics over the three and a half years production period. The paper describes briefly the production methods and presents statistical data and some correlations on measured characteristics, including impurity analyses, carbon contents, coercivities, permeabilities, ageing behaviour and geometry of the steel sheets and the laminations.

Introduction

The bending field in LEP, CERN's large electron positron collider, will be created by magnets with C-shaped laminated cores which will have to operate at low field levels and therefore have been built with a filling factor of 0.27. The arguments and implications of this choice have been presented previously [1,2,3].

The requirements for the soft magnetic steel laminations have been defined in 1982, following closely the specifications of the steel for the ISR and the SPS magnets but adapting them to the particular experience gained when building the prototype steel-concrete cores for LEP. The main differences with respect to the former two productions are:

- no insulation treatment has been applied,
- controlled steel mixing to reduce the spread in remanent field between cores has been introduced,
- the specifications for flatness and internal stresses had to be tighter and those for crown effects could be looser, because the laminations for the LEP cores are not stacked under high compression but are only loosely spaced by their indentations before the concrete is poured between these laminations.

After an initial production of 1500 t of steel sheets in 1983, the mean coercivity for the entire production has been fixed at 43 A m^{-1} . The sheets and laminations were produced at a monthly rate of 330 t from 1984 to 1986; the time lag between sheets and laminations was about two months.

Production of the Steel Sheets

The production sequence for the steel sheets followed, in principle, a well-established pattern:

- elaboration of low impurity steel in 150 t converters,
- casting of 15 t ingots,
- hot forming to 15 t slabs (840°C),
- hot rolling to coils, 3.5 mm thick and 1 m wide (660°C),
- pickling in an acidic bath,
- cold rolling to 1.55 mm thickness,
- open-coil decarburization at 700°C to $C < 0.005\%$,
- cold drawing for critical stress to 1.5 mm thickness which corresponds to approximately 3 % elongation,

- open-coil heat treatment at 820°C for grain growth to size ASTM 0,
- flattening and cutting to sheets of $980 \text{ mm} \times 1010 \text{ mm}$, then halving to size $980 \text{ mm} \times 505 \text{ mm}$,
- oiling for 6-month corrosion-free storage and packing to sea-transport criteria in 3-ton palettes.

Several other procedures were added to this standard production sequence in order to ensure the specified characteristics over the entire production period. Some of the most relevant of these procedures were:

- The melts were selected according to certain impurity conditions; the 132 melts thereafter used for the LEP steel sheets had average impurity contents of (weight percent): 0.064 C, 0.342 Mn, 0.010 P, 0.011 S, 0.002 Si, 0.0023 N, 0.018 Cu, $< 0.001 \text{ Al}$, $< 0.001 \text{ Nb}$.
- The production was organized in campaigns, always ensuring that several entire melts ran without interruption from the beginning to the end of the sequence. Thus, tool settings and verifications, especially those which were particular to the LEP steel sheet, could be properly implemented and maintained.
- The existing quality insurance system was extended to systematic measurements of the carbon content after decarburization (average: 0.0015 %), the grain size, the coercivity and the ageing behaviour after grain-growth treatment but before cutting, in order to permit a corrective treatment or a diversion to other productions if the set values had not been obtained.
- Deliveries of the palettes to the punching works were grouped in 200-ton batches where in each batch the coercivity classes had to be balanced; due to the fluctuations of the coercivity and to limited stock at the steel works, on few occasions corrections had to be applied. The coercivity in a palette of sheets could either be increased by an additional skin-pass of 0.5 % after the grain-growth treatment, or it could be decreased by the exclusion of coil parts which originated from the top of an ingot, where the impurity levels, and hence the coercivities, were higher than average.

Magnetic Measurements

For each melt, two distinct sets of ring samples were cut from sheets, $490 \text{ mm} \times 505 \text{ mm}$, for permeability measurements according to the method described in Ref. 4. The total span of magnetic excitation between 0.1 and 15 Oe was divided into 14 equal percentage intervals, the induction B was measured and the relative permeability μ calculated from $B(H)$. The magnetization curve $B(H)$ and the relation $\mu(B)$ are shown in Figs. 1 and 2, respectively. In these figures, the central curve represents the mean values of the measurements, the two boundary curves being distant by one standard deviation (σ) from the central one.

All samples have been submitted to an accelerated ageing treatment at 150°C for 100 h and then re-measured. The average increase of the coercivity due to this treatment is 0.26 A m^{-1} at a standard deviation of 1.1 A m^{-1} .

Systematic large-scale coercivity measurements on the steel sheets have been performed at the steel

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Fig. 1 Magnetization Curves $B = f(H)$
 a) for excitation range 0 to 2.5 Oe
 b) for excitation range 2.5 to 15 Oe

works with the sheet coercivity meter described in Ref. 5. This enabled the classification of batches of 172 sheets with dimensions of 490 mm × 505 mm (corresponding to one sixth of a magnet) for controlled mixing in order to reduce the spread in remanent field between finished magnet cores. Figure 3 shows the histogram of the initial coercivity, its division into the five classes for the batches and the resulting spread in coercivity for the final cores.

When correlating coercivities and permeabilities of steel samples, we notice excellent correlation at induction levels up to about 1 T as can be seen in Figs. 4 and 5. Thus, the controlled mixing of the steel for a reduction of the coercivity spread, which is particularly important at the low bending field used at injection, results in a supplementary benefit for a reduction in permeability spread for all particle energies up to 100 GeV in the collider.

At the prevailing low levels of impurities, there is no correlation between any impurity and a magnetic characteristic of the steel.

Fig. 2 Relations $\mu = f(B)$ and $\nu, B = f(E_{LEP})$

Fig. 3 Histogram of H_c in Batches and Cores

Punching of Laminations

Fig. 4 Correlation (H_c, μ) with μ ($H = 0.624 \text{ A m}^{-1}$)

Fig. 5 Correlation Coefficient $k(H_c, \mu) = f(B)$

Fig. 6 Lamination for LEP Dipole Core

Some basic procedures for punching the laminations, shown in Fig. 6, from the soft magnetic steel sheet had been determined by systematic investigations made at the time of punching for the prototype steel-concrete cores:

- Tests were made in order to determine whether the fabrication of the laminations could be rationalized by delivering the steel in form of 500 mm wide coils to the punching works, where the sheet is unwound, flattened and punched in one operation. It turned out, however, that the required precision in flatness and gap height could not be obtained by far, especially because equipment able to adequately flatten this type and size of material is only installed at the steel works.
- It was established that the pole gap had to be punched in two successive steps; first, the C-shape had to be cut open which liberated internal stresses altering the gap height and then, the final precision punching could be performed by taking into account that the lateral punching forces had to be in equilibrium.
- Because of the spaced laminations, the burr height in the pole gap became a critical quality factor of the finished cores. The limit specified for the burr height could be obtained by using sharp tools and small clearances between punch and die. Tool steel with 12 % Cr required resharpener every 30 000 punches, whereas the use of tungsten carbide extended the intervals between resharpener to 300 000 punches. Typical evolutions of burr height are shown in Fig. 7.

Fig. 7 Evolution of Burr Height

A fully automatic, micro-processor controlled production line was set up for punching and conditioning the 3 500 000 laminations. Its layout is shown in Fig. 8 and some of its features are enumerated below:

- The punching line was set up so as to diminish the effect of the variations in steel thickness on the stacking density of the cores. To achieve this, 172 sheets of dimensions 490 mm × 505 mm were piled up on a balance and the average thickness of the batch was determined. The height of the indentations, which defines the spacing between adjacent sheets, was then adjusted to obtain an equal steel density for each batch. The precision thus obtained was mainly only limited by the precision of the dimensions to which the sheets could be cut before weighing.
- All indentations had been arranged in pairs, with one dent protruding at the front, and the other at the back of the lamination such that the distance between both determined the elasticity upon stacking. As all

Fig. 8 Production Unit for Punching Laminations and Conditioning Batches

laminations had their indentations formed identically, every second laminations had to be turned so that always the front dents of one sheet met the front dents of its neighbour, and the same applied for the back dents. In order to achieve this, a piling carriage for 172 laminations was installed at the press' outlet. Every second position of this carriage was filled with the indentations oriented in one direction, then the carriage was turned and the free positions were filled with indentations oriented in the opposite direction. This procedure created the additional benefit to distribute equally the milling crown of the basic steel sheet.

- The weight of a prestacked batch of 172 laminations was checked on another balance and adjusted to $\pm 0.8\%$ by adding or withdrawing one or two pairs of laminations. This batch of 172 ± 4 laminations was then compressed on a vibrating table and its density under identical compression verified to be within the specified tolerance of $\pm 0.15\%$.

Characteristics of Batches of Laminations

In total, 20 280 batches of 172 ± 4 laminations have been punched, stacked and conditioned for equal density, weight and length; some characteristic data on these batches are given below.

- The average number of laminations per batch is 171.75 with a standard deviation of one;
- the average mass per batch is 362.85 kg, $\sigma = 1.20$ kg;
- the average mass per lamination is 2.113 kg, $\sigma = 0.011$ kg;
- from this data, the relative variation of the average sheet thickness of the batches can be determined to be 0.5 % for one standard deviation;
- without adjusting the height of the indentations, the variations in filling factors would have corresponded to that of the sheet thickness; by spacer height adjustments, this variation was reduced by a factor 3.

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References

- [1] J.P. Gourber and L. Resegotti, "Implications of the Low Field Levels in the LEP Magnets", *IEEE Trans. on Nucl. Sci.*, Vol. NS-26, No. 3, pp. 3185-3187, June 1979, and Div. Report CERN ISR-BOM/79-14.
- [2] J.P. Gourber and C. Wyss, "Prototypes of LEP Bending Magnets with Steel-Concrete Cores", *IEEE Trans. on Nucl. Sci.*, Vol. NS-28, No. 3, pp. 2867-2869, June 1981, and Div. Report CERN ISR-BOM/81-07.
- [3] J.P. Gourber, J. Billan, H. Laeger, A. Perrot and L. Resegotti, "On the Way to the Series Production of Steel-Concrete Cores for the LEP Dipole Magnets", *IEEE Trans. on Nucl. Sci.*, Vol. NS-30, No. 4, Part II, 1983, pp. 3614-3616, and Div. Report CERN LEP-MA/83-9.
- [4] K.N. Henrichsen, "Permeameter - A Semiautomatic Device for Magnetic Testing of Ring Samples at Fields up to 30 oersted", *Proc. 2nd Int. Conf. on Magnet Technology*, Oxford, 1967, pp. 735-739, and Div. Report CERN AR/Int. SG/65-7.
- [5] J. Billan, "Coercimeter for Non-Destructive Measurement of the Coercivity of Steel Sheets", *Journal de Physique*, Vol. 45, Colloque C1, C1-965 - C1-968, January 1984, and Div. Report CERN LEP-MA/83-36.