Toward the Production of 50 000 Tonnes of Low-Carbon Steel Sheet for the LHC Superconducting Dipole and Quadrupole Magnets

Simon Babic, Santo Comel, Francis Beckers, Francis Brixhe, Giuseppe Peiro, and Theodore Verbeeck

***Abstract*—A total of 50 000 tonnes of low-carbon steel sheet has been ordered for the LHC main magnets. After three years of production, about 10 000 tonnes of steel sheet have been produced by Cockerill-Sambre Groupe Usinor. This paper gives a summary of the manufacturing process and improvements implemented as well as an overview of the difficulties encountered during this production. Preliminary statistics obtained for the mechanical and magnetic steel properties are presented.**

***Index Terms*—Ferromagnetic materials for S. C. magnets.**

I. Introduction

LOW-CARBON steel sheet is used to manufacture the yoke laminations which provide the return path for the magnetic flux and concur to the mechanical rigidity of the LHC dipole and quadrupole structure. Moreover, the iron yoke laminations contribute to the accuracy of the mechanical assembly and are used to trim the magnetic length. For these reasons the high precision and tight tolerances required for critical dimensions are obtained with a fine-blanking process. For the dipole magnets, the shape of the laminated iron yoke is split in two parts in the vertical symmetry plane, whereas the quadrupole yoke laminations are made in one single piece (Fig. 1).

The dipole yoke is contributing to about 17% of the field strength at the injection field. For the 1248 dipole and 392 main quadrupole magnets to be assembled, about 6 250 000 yoke laminations will have to be produced [1] by the European Industry.

The technical requirements for the low-carbon steel followed closely those defined previously for the ISR, SPS and LEP magnets [2], [3]. The major differences are related to:

- the sheet thickness, which has been increased from 1.5 mm to 5.8 mm giving the best optimization between magnetic characteristics of the steel, number of pieces to be fine-blanked and related cost per piece,
- the coercivity value, which should remain within a range of ±10 A/m with respect to a target nominal value of 75 A/m,
- the flatness, the internal stresses and the thickness spread measured perpendicular to the rolling direction were all defined in view of the tight tolerances to be achieved during the fine blanking process and assembly of the yoke laminations.

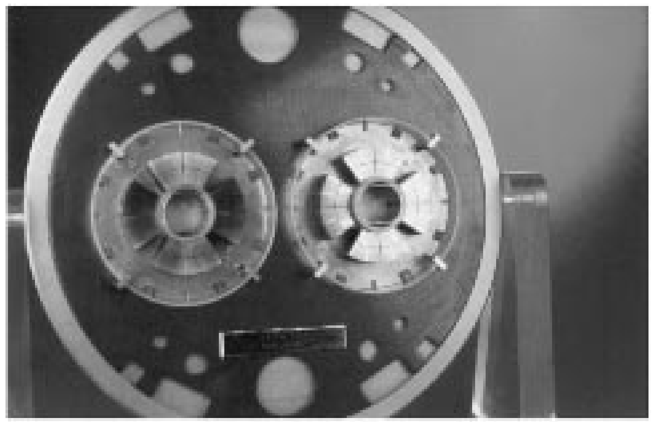

Fig. 1. Mock-up cross section of quadrupole magnet with single yoke lamination structure.

II. Production Process of the Steel

A. General Aspects

The steel production for the LHC main magnets, known under the trade name MAGNETIL BC 5.8™, differs with respects to the standard steel production process in the following:

- the low-impurity content and in particular the residual carbon content (around 30 ppm) are obtained by transferring the melt after conversion through a vacuum furnace (1350 °C, in batches of 200 tonnes) where the alloying elements are also added,
- continuous casting in slabs of about 25 tonnes,
- hot rolling mill with a precise control of the rolling temperature; the size and the homogeneity of the grain structure are obtained and preserved by a well defined thermo-mechanical process. The final thickness of the strip is obtained during this operation (5.8 mm ± 0.15),
- during the cool-down of the coil, a controlled and stable coating of milling scale is formed with an uniform thickness of 3 to 5 μm (layer of Fe_3O_4, similar as for the blue steaming process),

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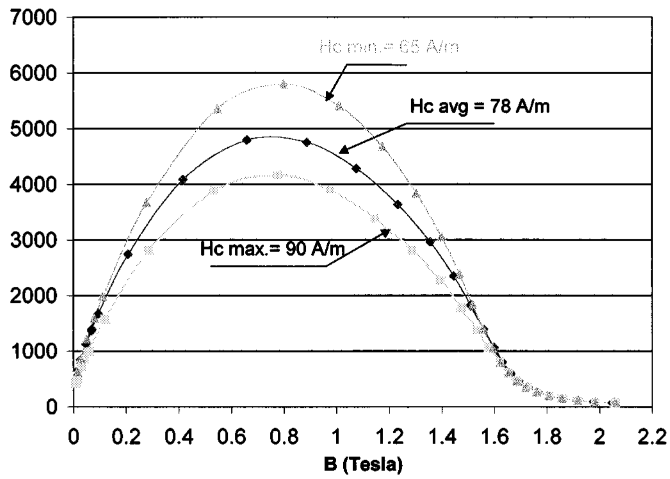

Fig 2. Relation $\mu = f(B)$ at room temperature.

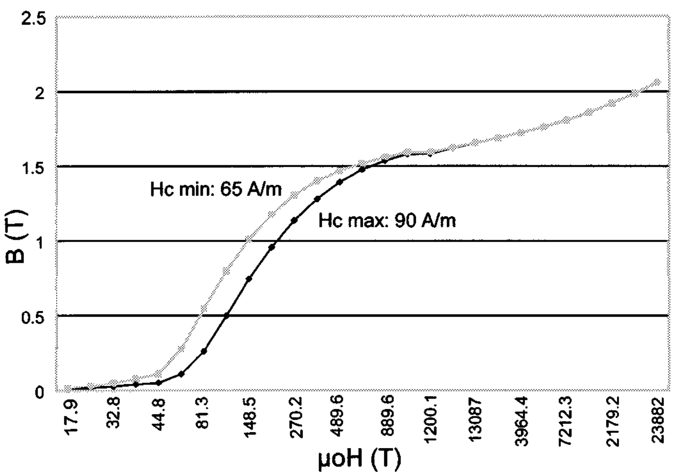

Fig. 3. Magnetization curve $B = f(\mu_0 H)$.

- final annealing process of the coils in a bell oven where a grain growth and a grain homogeneity to size ASTM 3 is further obtained.

The finished coils have a mass between 20 and 25 tonnes.

B. Technical Issues During Production

The standard production process for the first 1000 tonnes included a pickling operation performed before the annealing process. This imposed several constrains for the protection against oxidation not only for the produced coils during storage but also after cutting them into sheets. The technical specifications required the sheets to be protected by a thin oil layer, whereas the final fine-blanked yoke laminations had to go through a phosphating coating treatment. In order to optimize the steel manufacturing process and the production costs of the fine-blanked pieces, an intensive study program was initiated by Cockerill-Sambre to check whether the milling scale appearing after the hot rolling operation could be kept as a protection agent against oxidation throughout the production of fine-blanked pieces, thereby avoiding both the oil protection and the expensive phosphating process. The various imposed tests were all successfully completed and resulted in the approval of the process for the further production.

Moreover, by adding this thin oxide layer into the process, major problems encountered during the initial production phase could be eliminated. These difficulties were mainly related to adherence of the coil layers due to a strong shrinking effect during the annealing process; important coil breaks were developed during the coil unrolling operation destroying thereby the mechanical and magnetic properties of the sheet produced.

The sheet cutting and slitting process was performed automatically on a high performance cutting line specially developed and installed for this production. From an initial coil width of 1200 mm, the sheets are slit to a 580 mm width and to a length of 4015 mm. A daily sheet cutting rate of about 150 tonnes of coils could be attained. The sheets are automatically stacked in 3-to 5-ton packets and wrapped with a recyclable multi layer plastic film ready for shipment.

The production is organized in campaigns of 800 to 1000 tonnes so to ensure that the steel manufacturing process and the delicate cutting line adjustments could be properly implemented and maintained during the whole production.

As the steel yoke contribution is not a major factor for the magnet field strength, no controlled steel mixing to reduce the spread in remanent field between steel lots has been considered.

III. Mechanical and Magnetic Measurements

The production sequences for the required mechanical and magnetic measurement checks follow a well defined procedure:

- during the sheet cutting process, three samples of coupled sheets, with a reduced size (580 mm $\times$ 600 mm), are taken in the beginning, the middle and the end of each coil,
- each couple of samples is checked for the flatness and the internal stresses,
- the thickness spread is measured over five equidistant positions perpendicular to the rolling direction.

For each middle sample of a coil representing the melt, the usual internal quality assurance checks were extended to systematic measurements of the major chemical components of the melt, the grain size, the yield and tensile strength as well as the elongation.

Magnetic measurements are performed in two steps:

- with a coercimeter [4], the three sheet samples are measured and, in a few minutes, direct values of the coercivity in the longitudinal rolling direction is obtained for each coil. A check is also made on one of the samples in the transverse rolling direction.
- The limit for the acceptance criteria was set to a maximum coercivity value of 90 A/m with respect to a target average value of $\sim$75 A/m for the whole steel production.
- For the three sample sheets, a circular ring sample was prepared by mean of a water cutting method and used for permeability measurements made with a split coil permeameter [5].

Measurement results are first stored locally in standard Excel® spreadsheets and thereafter loaded in an centralized Oracle® database structure designed with a Web interface system.

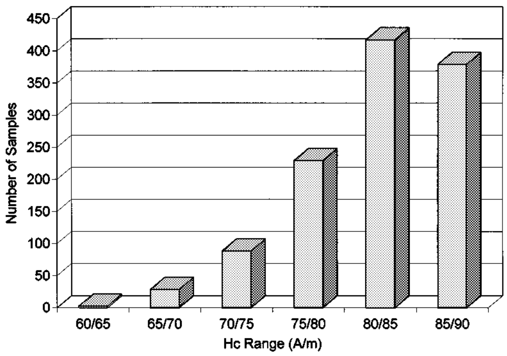

Fig. 4. Spread of coercivity taken in longitudinal rolling direction.

IV. Results of Measurements and Statistics

A. Magnetic Measurements

Figs. 2 and 3 show respectively the permeability in function of the induction and the magnetization curve $B = f(\mu_0 H)$.

The spread is representative of the minimum and maximum coercivity values recorded with the permeameter.

Coercivity and permeability measurements have been performed on three samples taken from each coil and measured at the steel cutting plant. For the permeability measurements, one of the samples was submitted to the total range of magnetic excitation between 18 and 24 000 A/m in 29 steps. The two remaining samples were measured at three standard reference excitation points of 40, 1200 and 24 000 A/m for which the requested minimum induction was respectively set to values equal to or higher than 0.04, 1.5 and 2 Tesla.

The influence of ageing on both coercivity and permeability was investigated by submitting one sample for each coil to an accelerated ageing process (100 h at 150 °C) and then re-measured. In most cases, very little or no variation is observed for the coercivity and the permeability after this process.

The coercivity distribution measured on the sample sheets is given in Fig. 4; the peak distribution is presently located in the 80 to 85 A/m range. When samples exceeded the acceptance limit criterion of 90 A/m, the concerned steel production was rejected. As the production process is now well under control, it is expected that in the future, better and more stable characteristics for the magnetic properties will be obtained.

B. Mechanical Characteristics

In order to obtain the high precision of the final pieces to be produced, the steel mechanical properties have an important impact on the design of the fine-blanking tools. The limits for the yield and tensile strength were respectively set to >120 MPa (σ 0.2%) and <300 MPa, whereas the thickness spread measured across the rolling width had to be lower than 1.5%. Flatness and internal stresses were fixed (respectively set to lower than 0.5% and 0.25 mm according to ISO 7452 standards) so as to limit their influences on the tight geometrical tolerances imposed on the yoke laminations. The distribution obtained for the tensile and yield strength values are shown in Figs. 5 and 6.

As rather good and stable values were maintained during the two first years of steel production, the sampling rate for these two last parameters could be reduced from one sample per coil to one sample per melt.

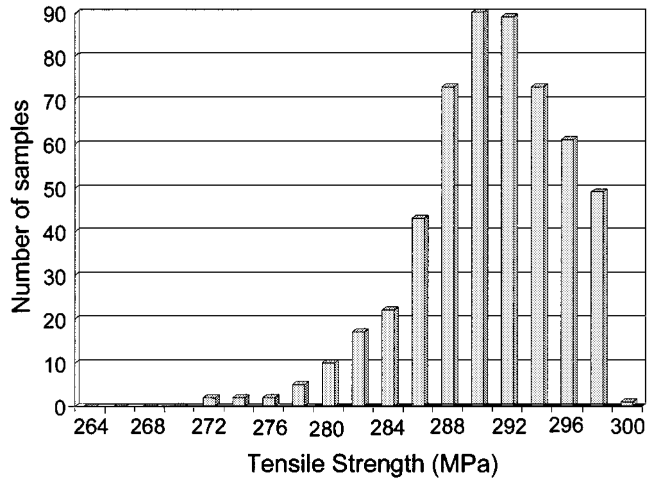

Fig. 5. Distribution of tensile strength values.

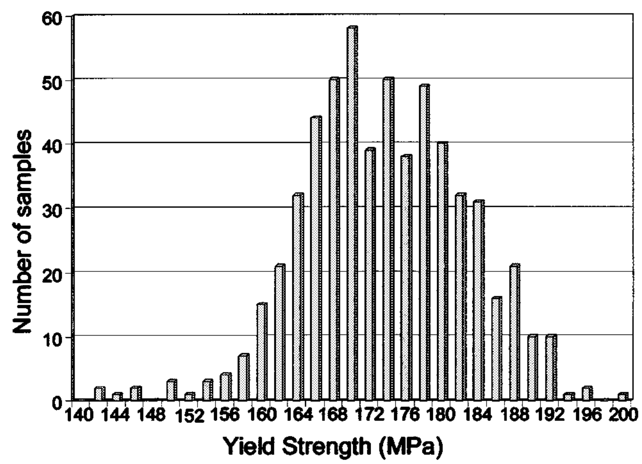

Fig. 6. Distribution of yield strength values (σ 0.2%).

V. Magnetic Measurements at LHe Temperature

In order to compare the steel magnetic characteristics with respect to the measurements made at ambient temperature, a small number of samples were measured at the LHe cryogenic temperature of 4.2 K.

A. Experimental Set-Up and Procedure

The circular ring specimen, which is exactly the same as the one used at room temperature, is prepared with three windings; the first two reproduce the split coil permeameter [5] with:

- N search coil/N excitation coil = 90/180 turns

and the last winding Nb, about 3000 turns are used as a much stronger excitation coil. The two excitations coils are made from a 0.31 mm outer diameter superconducting wire while for the search coil a 0.2 mm constantan wire is used. The large excitation coil gives an excitation field of about 380 000 A/m at a maximum current of 40 A. Such a high excitation level allows to get measurements in the saturation region of the steel and especially to measure the saturation polarization (Js) at 4.2 K. A specimen after winding is shown in Fig. 7.

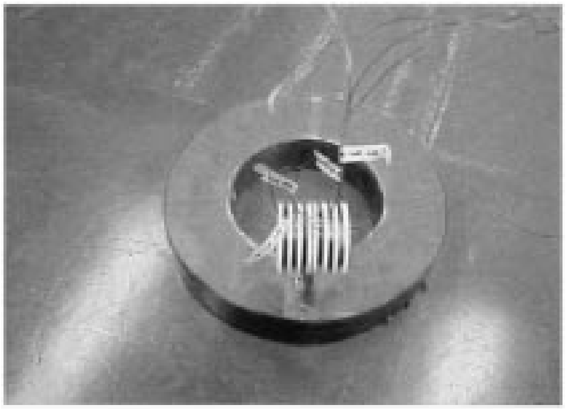

Fig. 7. Sample after winding.

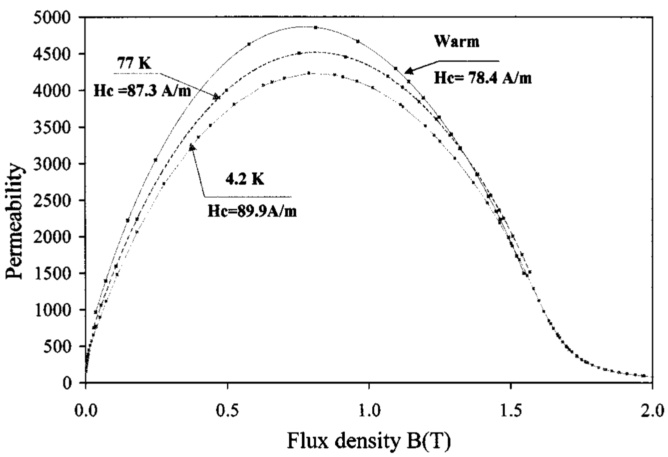

Fig. 8. Relation $\sigma = f(B)$ at 77 K and 4.2 K.

The sample is positioned in a LHe cryostat and connected to the outside with a pair of independent current leads while the search coil is available through a sealed connector. The power supply used is bipolar: ±40 A, 15 V. Up to now, five samples were measured at 77 K and two at 4.2 K [6].

B. Results of Magnetic Measurements

A typical permeability curve is given in Fig. 8. The data is related to a sample having an average coercivity of 78.4 A/m at room temperature and which corresponds quite well to the average target to be obtain over the whole production.

The results are showing a drop in the maximum permeability of about 6% at 77 K and 12% at 4.2 K while for the coercivity, an increase of respectively 10 and 15% is observed. The saturation polarization Js obtained at 4.2 K is 2.162 T.

More measurements are expected to be performed in the near future to confirm these values.

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REFERENCES

[1] D. Perini, C. Lanza, P. Fessia, and T. Verbeeck, “First experience in the mass production of components for the LHC main dipoles,” *IEEE Trans. Appl. Superconduct.*. MT–17 Conf., submitted for publication.

[2] T. M. Taylor, “Production of the steel sheet for the laminations of the ISR main magnet cores,”, Divisional Report ISR-Mag/69-41.

[3] H. Laeger, F. Beco, S. Comel, J. Hostettler, R. Luthi, and L. Vuffray, “Production of soft magnetic steel laminations for the LEP dipole magnets,”, Divisional Report LEP-MA/87-52.

[4] J. Billan, “Coercimeter for nondestructive measurements of the coercivity of steel sheets,” Journal de Physique, Divisional Report CERN LEP-MA/83-36, vol. 45, Colloque C1, January 1984.

[5] K. N. Henrichsen, “Permeameter—A semiautomatic device for magnetic testing of ring samples at fields up to 300 oersted,” in *Proc. 2nd Int. Conf. Magnet Technology*, Oxford, 1967, Divisional Report AR/Int. SG/65-7, pp. 735–739.

[6] J. Billan and G. Peiro, “Preliminary results on permeameter measurements at LHe temperature,” CERN/LHC-MMS, Internal Report, to be published.