# Production of Low-Carbon Magnetic Steel for the LHC Superconducting Dipole and Quadrupole Magnets

F. Bertinelli, S. Comel, P. Harlet, G. Peiro, A. Russo, and A. Taquet

***Abstract*—In 1996 CERN negotiated a contract with Cockerill Sambre—ARCELOR Group for the supply of 50 000 tonnes of low-carbon steel for the LHC main magnets: this was the first contract to be placed for the project, and one of the single largest. In 2005—after nine years of work—the contract is being successfully completed.**

**This paper describes the steel specifically developed, known as MAGNETIL, its manufacturing and quality control process, organization of production, logistics and contract follow-up. Extensive statistics have been collected relating to physical, mechanical and technological parameters. Specific attention is dedicated to magnetic measurements (coercivity and permeability) performed at both room and cryogenic temperatures, the equipment used and statistical results. Reference is also made to the resulting precision of the fine-blanked laminations used for the magnet yoke.**

**The technology transfer from the particle accelerator domain to industry is ongoing, for example for the screening of high voltage cables buried in the ground.**

***Index Terms*—Ferro-magnetic materials for S.C. magnets.**

## I. INTRODUCTION

LOW-CARBON steel is the material used for the yoke laminations that provide the return path for the magnetic flux and contribute to the mechanical rigidity of the LHC superconducting dipole and quadrupole cold masses [1]. 50 000 tonnes of steel are supplied as sheets to produce over 6 700 000 laminations for 1278 dipoles, 414 main quadrupoles and 140 insertion quadrupoles. These laminations are produced by three European suppliers using fine-blanking technology, allowing to achieve the specified geometric precision for large series quantities at competitive costs.

The steel production has extended over a period of nine years, and was described after the initial start-up period in [2], [3]. In this paper we report on the overall experience and present extensive statistics on physical, mechanical and technological properties, specifically to monitor the stability of production.

## II. STEEL PRODUCTION

### A. The MAGNETIL Low-Carbon Steel

The low-carbon steel—known under the trade name MAGNETIL [4]—is a special production of Cockerill Sambre—ARCELOR Group. In 2004 ARCELOR produced 42.8 Mtonnes of steel (4.4% of the world output and second largest producer): the MAGNETIL production, essentially for CERN, represents 0.03% of this amount.

MAGNETIL is an ultra low carbon steel with specific magnetic characteristics—low coercivity, high permeability at low field, high saturation induction.

The low carbon content—below 0.0025%—avoids aging due to carbide precipitation: it is obtained by conversion of the melt through a vacuum furnace (1 mbar).

Hot rolling in the ferrite region ($\sim$ 800°C) allows to obtain a crystallographic texture type 110 at the surface and 100 in the core (i.e. the optimal orientation for magnetization). Hot rolling at this lower temperature reduces rollers wear and fabrication costs, improves steel surface quality and flatness, and allows the formation of a stable, protective layer of mill scale.

During the annealing heat treatment, the energy stored in the steel with hot rolling allows grain size growth.

The unwinding of a coil of annealed MAGNETIL can easily degrade its magnetic characteristics if it is not performed correctly. Cockerill uses a special "anti-coil break" technology to smoothen and control this operation and only delivers in sheet format.

MAGNETIL can to date optimally be produced in the thickness range 2.5 to 8 mm: higher thickness allows better flatness and lower production costs, lower thickness allows better coercivity, typically reduced by 20 to 25 $\mathrm{Am}^{-1}$.

A production campaign requires a minimum quantity typically of 600 to 1200 t. Other thickness values and quantities can be negotiated with Cockerill. In comparison, magnetic steels containing Si are cold rolled and typically limited to a thickness 1 mm.

### B. The LHC Production of Magnetil

The final sheet thickness of 5.8 mm is a compromise between magnetic characteristics and costs of steel production, fine-blanking and magnet assembly.

In order to minimize scrap at fine-blanking, different end formats of sheets were produced, see Table I.

The production process involves several operations performed in different sites:

- Production of cast iron and transfer in 125 t torpedo ladles;
- Steel conversion, typically with 210 t melts (190 t cast iron and 35 t scrap), including refining treatment in the vacuum furnace;

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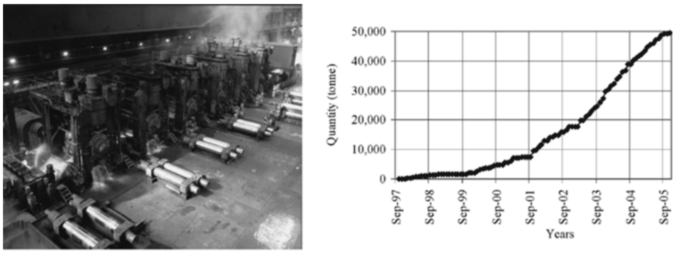
TABLE I
DIFFERENT MAGNETIL FORMATS PRODUCED, INCLUDING FOR OTHER LHC PROJECTS AND FOR LEP

| | Thickness (mm) | Format (mm) | Quantity (tonne) | Scale protection | Final production process |
|---|---|---|---|---|---|
| MB dipoles (plus prototypes and MQT/MQTL corrector magnets) | 5.8 | 580 x 4015 | 29 200 | yes | hot-rolling |
| | 5.8 | 580 x 3975 | 15 300 | yes | hot-rolling |
| | 5.8 | several | 1 100 | yes | hot-rolling |
| | 5.8 | 580 x 3890 | 650 | no | hot-rolling, pickling |
| MQ main quadrupoles | 5.8 | 470 x 4600 | 2300 | yes | hot-rolling |
| MQM, MQY insertion quadrupoles | 5.8 | 490 x 4820 | 1000 | yes | hot-rolling |
| length compensation | 1.5 and 2 | several | 100 | yes | hot-rolling |
| Total | | | ~50 000 | | |
| LHC conventional, resistive magnets | | | | | |
| MQW (Canada) | 1.5 | 910 x 395 | 1200 | yes | hot-rolling |
| MBW, MBXW, MCBW (Russia) | 1.5 | 1083 x 393 and others | 1200 | - | cold-rolling ("blue-steaming") |
| LEP dipoles | 1.5 | 980 x 505 | 10 000 | no | cold-rolling, "open-coil" heat treatment |

- Continuous casting with vertical start, producing typically 24 t slabs, width optimized according to format.
- Hot rolling on a line over 515 m long, see Fig. 1(a). The slabs are reheated in a gas furnace at ~ 1200°C. A hot rolling campaign for CERN typically produces 1200 t and lasts one 8-hour shift. In order to achieve the specified quality, special precautions are taken: new rollers are fitted and pre-heated, cooling times are longer, and consequently overall productivity is 50% lower.
  The width of the produced coils is optimized according to format, e.g. 1180 mm for the 580 mm sheet.
- Unevenly wound coils are re-processed by a skin pass: the coils are re-wound using only minimal tension, without affecting the magnetic characteristics;
- Annealing heat treatment in a bell furnace under protective atmosphere. This is a precision operation requiring accurate monitoring, and proved to be the bottleneck in production.
- Slitting of coils into sheets is performed at Oxybel—the ARCELOR Steel Service Centre dedicated to sheet cutting—on a new, dedicated line equipped with an anti-coil break. Oxybel typically processes 7 coils per day (150 t), working one 8-hour shift. The edges are removed and the coil is slit longitudinally in the centre, producing 6 pallets of flat sheets each of mass 3.4 t. The thicker side—by 0.03 to 0.06 mm—is identified by red paint, subsequently used by fine-blankers to orient laminations. A careful alignment of the sheets within each pallet was important for the fine-blankers.
- Extensive sampling for quality control is performed during slitting, typically at the start, middle and end of each coil (i.e. within ~10 m from these positions): coil start is defined as the outermost layer when Oxybel starts the slitting operation. About 12% of steel is scrapped at this stage, combined from the slitting and the quality control.
- Each of the ~14 000 pallets is uniquely identified and full traceability—both for technical and logistic features—is ensured by Cockerill, CERN and the fine-blankers.



(a) (b)

Fig. 1. (a) Hot rolling line (Chertal); (b) Production curve from 1997 to 2005.

A specific feature of the LHC application is the mill scale protection—a 3 to 5 $\mu\mathrm{m}$ layer of $\mathrm{Fe_3O_4}$ oxide. The original specification required pickling to remove the scale developed during the hot rolling, an oil protection for the sheets, and a phosphate coating of laminations after fine-blanking. Cockerill proposed to maintain the original mill scale and demonstrated its adherence and effectiveness as protection. Cockerill hence benefited from avoiding pickling and oil coating and CERN benefited from avoiding the phosphate coating, an exemplary win-win situation.

A major effort of logistics was required to coordinate internally within ARCELOR the different production sites. A large amount of quality control and administrative data required to be managed and communicated between Cockerill, CERN and the fine-blankers. With hindsight, more generalized use should have been made of barcodes for pallet identification in usage.

Several thousand tonnes of pallets required storage in different sites. Transport of the steel alone to CERN and the fine-blankers required over 2300 trucks, representing a cost of 5 to 8% of the ex-works steel price. After analysis, road transport still proved to be—sadly for the environment—a significantly cheaper option than rail.

## III. PHYSICAL AND CHEMICAL MEASUREMENTS

### A. *Magnetic Measurements*

CERN provided the equipment—a coercimeter and a permeameter—with procedures for the measurements at room temperature: over 12 600 and 6800 measurement cycles were made respectively at Oxybel to follow production.

The coercimeter [2],[3] uses steel samples simply cut from the slitting line. Each measurement cycle lasts 15 min, so this is a simple, fast tool for production. Coercivity—as measured with the coercimeter—was the main acceptance criteria, specified as a maximum value of 90 $\mathrm{Am^{-1}}$. Measured at start, middle and end of each coil, unacceptable values resulted in the scrapping of the associated third of coil length: this is another advantage of delivering in sheet format.

Fig. 2 shows statistics on coercivity in the longitudinal rolling direction, for three periods of production and for start, middle and end coil positions. Care is needed in the exact identification of the coil start, since some coils were rewound with the skin pass operation. Over the full production (average $= 81.4\ \mathrm{Am^{-1}}$, $\sigma = 6.1\ \mathrm{Am^{-1}}$), the distribution is stable. A lower coercivity was found in samples from the end coil position, most likely due to the different effect of cool-down on the coil mass after hot rolling (which cannot be

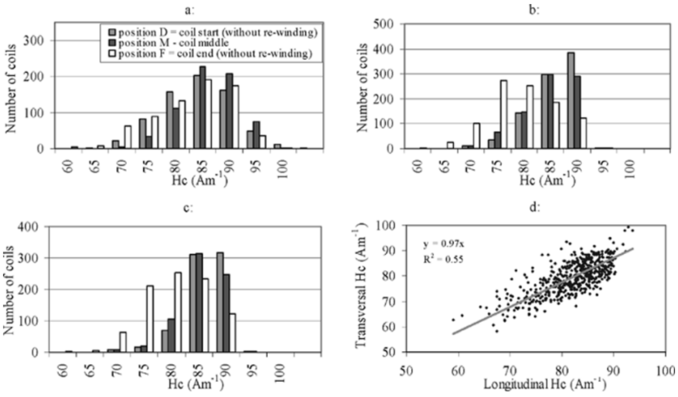


Fig. 2. CERN coercimeter at Oxybel: longitudinal coercivity at room temperature, 3 coercimeter measurements (start, middle and end) from each coil, thickness 5.8 mm. (a) Coercivity (period 1997 to 2001); (b) coercivity (period 2002 to 2003); (c) coercivity (period 2004 to 2005); (d) coercivity dependance on direction.

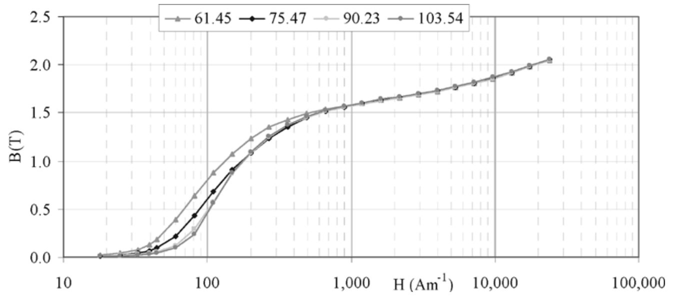


Fig. 3. CERN permeameter at Oxybel: permeability curves at room temperature, measuring different coercivity values $(\mathrm{Am}^{-1})$, thickness 5.8 mm.

completely compensated by the subsequent heat treatment). The skin pass was used in ∼12% of the coils in the period 2002–2005 with no effect on coercivity noted for these coils.

The coercivity of the 1.5 and 2 mm production was also measured $(\text{average} = 69.0\ \mathrm{Am}^{-1}, \sigma = 9.2\ \mathrm{Am}^{-1})$.

Longitudinal coercivity L is theoretically higher than transversal coercivity T: Fig. 2(d) compares actual L and T measurements from the same coil samples.

The permeameter [2],[3] requires sample rings cut by water jet. The complete permeability curves—the measurement cycle lasts 60 min—were recorded for ∼500 samples, see Fig. 3.

A simpler measurement cycle, lasting 25 min, records only three points on the curve (at 40, 1200 and 24 000 $\mathrm{Am}^{-1}$) and was used systematically for all coils. Only the portion of the permeability curve between 30 and 700 $\mathrm{Am}^{-1}$ varies depending on coercivity. The correlation between permeability (at 39.6 $\mathrm{Am}^{-1}$) and coercivity is shown in Fig. 4(a).

The effect of aging 100 h at 150°C in air was also investigated on ∼400 samples. The same samples were measured with the permeameter before and after aging, see Fig. 4(b). The effect of aging is to slightly increase coercivity, but not systematically $(\text{average} = 0.8\ \mathrm{Am}^{-1}, \sigma = 1.9\ \mathrm{Am}^{-1})$.

CERN made measurements with a permeameter at both room and cryogenic temperatures. The precision of Cockerill measurements was monitored throughout production by re-measuring 50 samples: the repeatability on coercivity values is on average 0.8%.

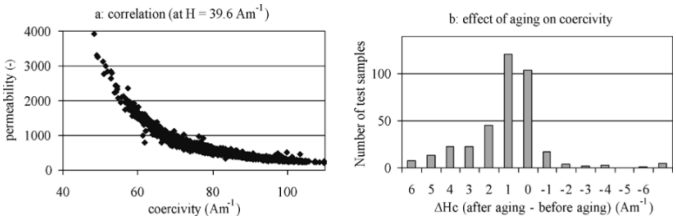


Fig. 4. (a) Correlation between permeability (at $\mathrm{H} = 39.6\ \mathrm{Am}^{-1}$) and coercivity at room temperature; (b) Effect of aging on coercivity at room temperature.

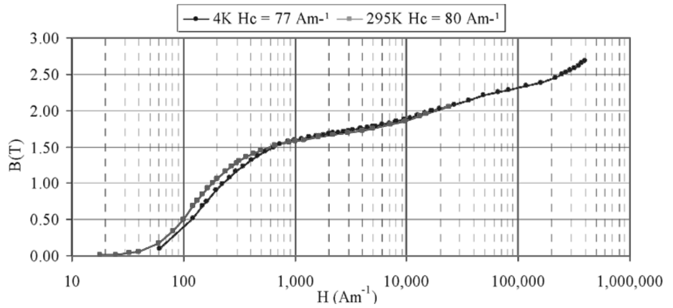
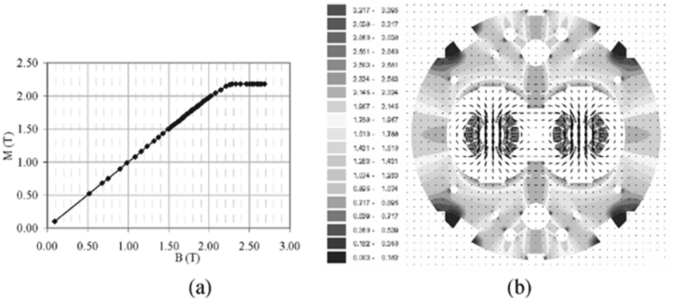


Fig. 5. CERN permeability measurements at room and cryogenic temperatures, thickness 5.8 mm.



(a) (b)

Fig. 6. (a) Saturation magnetization at 4.2 K (2.186 T); (b): ROXIE model of dipole cross-section—1.9 K, 12.84kA—showing areas of saturation [6].

Comparison of measurements at room and cryogenic temperatures is shown for the same sample in Fig. 5. The saturation magnetization is shown in Fig. 6(a), with the dipole saturation levels shown for comparison in Fig. 6(b).

The effect of fine-blanking on the magnetic characteristics has been tested at CERN with the permeameter at room temperature: fine-blanking pressure has no measurable effect, while locally ∼2 mm in correspondence of the cut edge there is an increase of 40% in the coercivity.

Analysis of field quality of the magnets at CERN does not show any effect dependent on the magnetic properties of the yoke steel. Common to superconducting magnets, the steel yoke contributes only 18% to the field [5]. With a dipole magnet requiring 33 t of MAGNETIL, typically from 10 different random pallets, no steel mixing was necessary.

### *B. Other Physical and Chemical Measurements*

The chemical composition is measured three times per melt (at 50, 100 and 150 t remaining) with a spark spectrometer, and

TABLE II
CHEMICAL COMPOSITION (% WEIGHT)

| period | C | Mn | S | P | Si |
|---|---|---|---|---|---|
| **1997-2001** | 0.003<br>(σ = 0.001) | 0.238<br>(σ = 0.012) | 0.009<br>(σ = 0.002) | 0.012<br>(σ = 0.002) | 0.003<br>(σ = 0.001) |
| **2002-2003** | 0.002<br>(σ = 0.001) | 0.231<br>(σ = 0.020) | 0.009<br>(σ = 0.003) | 0.011<br>(σ = 0.003) | 0.004<br>(σ = 0.001) |
| **2004-2005** | 0.002<br>(σ = 0.001) | 0.234<br>(σ = 0.017) | 0.009<br>(σ = 0.002) | 0.011<br>(σ = 0.002) | 0.004<br>(σ = 0.001) |

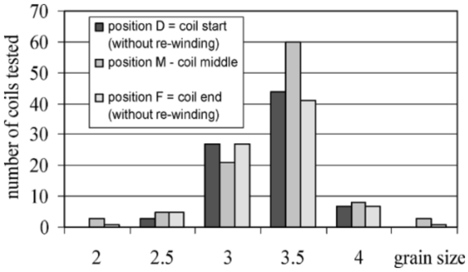


Fig. 7. Statistics on grain size—start, middle and end of coils.

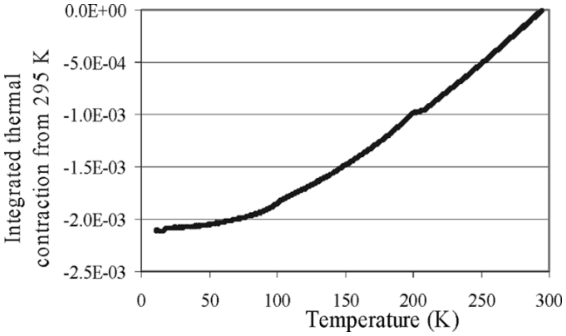


Fig. 8. Thermal contraction curve for a steel sample (from pallet 944 076 0006).

median values recorded per melt. Table II summarizes results for some important elements. The balance of Fe is 99.66% weight.

Grain size has been measured on ~300 samples according to the standard ASTM Method E112 (average = 3.3), see Fig. 7. The middle coil position has a slightly higher grain size (i.e. finer grain), again most likely due to the different effect of cool-down on the coil mass after hot rolling.

Density is an important, often neglected parameter linking the basic requirement of physics—a "volume" of steel inside magnets—with the normal requirement of steel industry—to sell by "mass". This was measured at CERN to be 7.858 $\mathrm{kg.dm}^{-3}$ at $24.5^{\circ}\mathrm{C}$.

The integrated thermal contraction—measured at CERN with dedicated equipment in the temperature range 295 K to 11.5 K—is typically $2.1 \times 10^{-3}$, see Fig. 8.

The transversal electrical resistance between stacked laminations was measured: data is available for different conditions of current, surface cleanliness and contact pressure.

## IV. MECHANICAL MEASUREMENTS

Tensile tests at room temperature are performed on samples taken from the middle of each coil, in the longitudinal direction. Fig. 9 shows statistics for the yield strength (average $= 180.0$ MPa, $\sigma = 10.4$ MPa), tensile strength (average $= 288.4$MPa, $\sigma = 9.3$ MPa) and elongation (average $= 45.8\%$, $\sigma = 5.8\%$). The highest stress levels in the lamination structure are shown for comparison in Fig. 10, ~90 MPa at RT and ~150 MPa at 1.9 K.

Tensile tests performed at cryogenic temperatures are summarized in Table III: fracture mechanics test data performed at 7 K are also available.

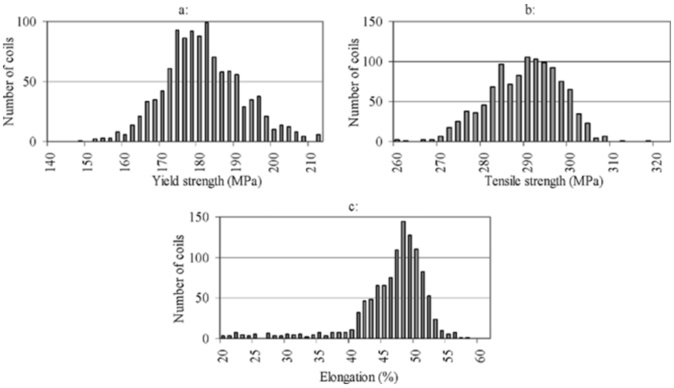
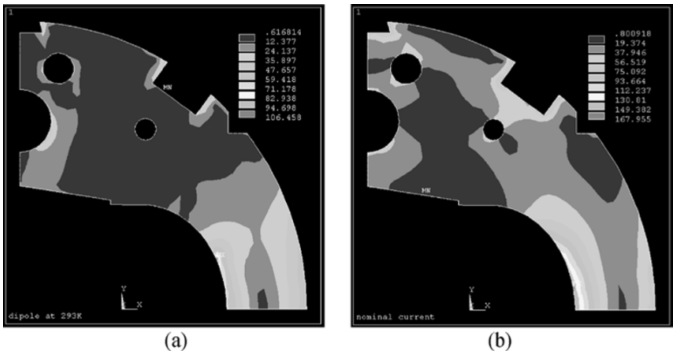


Fig. 9. Statistics on yield strength, tensile strength and elongation, L direction, room temperature. (a) Yield strength (from 1107 coils); (b) tensile strength (from 1107 coils); (c) elongation (from 1107 coils).



(a) (b)

Fig. 10. CERN FEA model of dipole lamination showing stress values [8]: (a) assembly at RT; (b) nominal 11.85 kA current at 1.9 K.

TABLE III
TENSILE TESTS AT DIFFERENT TEMPERATURES, SAMPLES FROM LONGITUDINAL AND TRANSVERSAL ROLLING DIRECTIONS (FROM PALLET 956 030 0001 IN [7])

| | Temperature | Young's Modulus | Yield Strength | Ultimate Tensile Strength | Uniform Elongation | Total Elongation |
|---|---|---|---|---|---|---|
| | (K) | (GPa) | (MPa) | (MPa) | (%) | (%) |
| L direction | 295 | 205 | 115 | 249 | 32 | 52 |
| T direction | 295 | 200 | 123 | 282 | 26 | 44 |
| L direction | 233 | 196 | 151 | 260 | ~25 | ~50 |
| T direction | 90 | 210 | 642 | 653 | 5.9 | 20 |
| - | 77 | 221 | 821 | 828 | - | 10.1 |
| L direction | 7 | 200 | - | 723 | 0.5 | 0.5 |
| T direction | 7 | 211 | - | 926 | 0.5 | 0.5 |

## V. TECHNOLOGICAL MEASUREMENTS

### A. Sheet Thickness

The specified sheet thickness is 5.8 ± 0.15 mm, with a maximum dispersion—i.e. (max-min)/average—under 1.5%.

Thickness at the centre of the coil width is measured on-line during hot rolling by an X-ray transducer, see Fig. 11. This data is used during slitting to eliminate defective lengths of the coil.

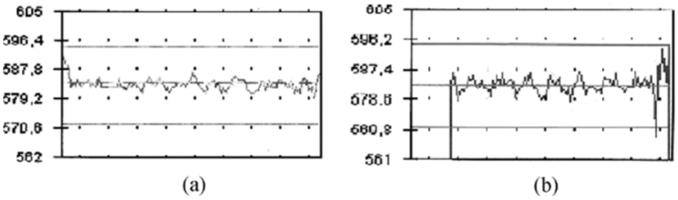


Fig. 11. On-line thickness measurements during hot rolling. (b) shows an example of out-of-tolerance detected toward the end of a coil.

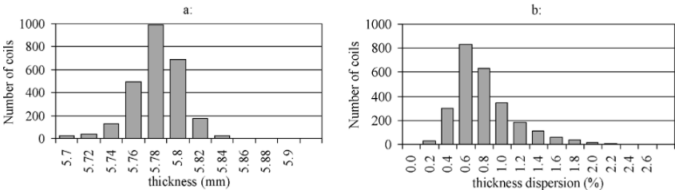


Fig. 12. Micrometer thickness measurements, middle of coil. (a) Average thickness (period 1997 to 2005); (b) thickness dispersion (period 1997 to 2005).

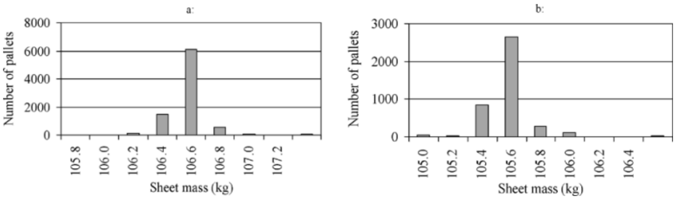


Fig. 13. Sheet mass according to format. (a) Sheet mass (format $580 \times 4015 \times 5.8$, 8425 pallets); (b) sheet mass (format $580 \times 3975 \times 5.8$, 3982 pallets).

In some exceptional cases, sheets having out-of-tolerance thickness (cases of 5.37 mm and 6.72 mm) have nevertheless been detected at the fine-blankers.

With slitting, five thickness measurements are performed with a micrometer across the coil width, on samples taken from the start, middle and end of each coil. The simple arithmetic average of the five measurements ($\text{average} = 5.77$ mm, $\sigma = 0.02$ mm) and their dispersion ($\text{average} = 0.75\%$, $\sigma = 0.33\%$) are shown in Fig. 12 for the middle coil position. During production it was shown that the middle coil position was sufficiently representative, and measurements limited to this. The largest thickness occurs predictably at the centre of the coil width: only exceptionally this was not the case.

Also available are measurement statistics on pallet mass, flatness and internal stresses. Pallet mass, shown in Fig. 13, is an important parameter for invoicing and steel consumption at the fine blankers: optimization through the sheet geometry allowed considerable savings.

### *B. Fine-Blanking*

The laminations are cut by fine-blanking technology in only one step, followed by deburring and cleaning. The geometric precision of laminations requires good stability of the material.

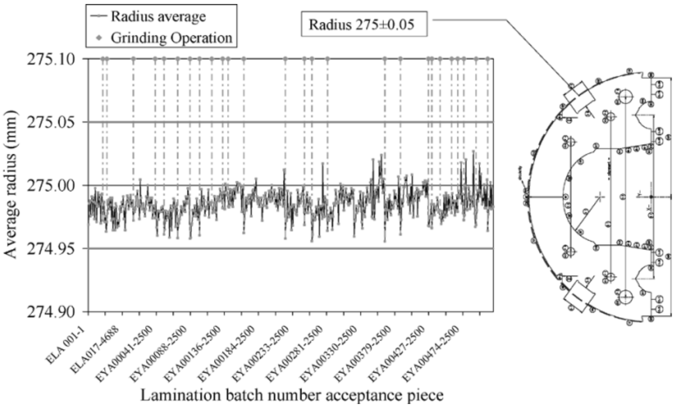


Fig. 14. Geometric stability of steel during fine-blanking: average lamination radius and effect of tool resharpening.

Fig. 14 shows how the average dipole lamination radius varies due to tooling wear in between tool sharpenings: the stability is excellent.

The surface defects encountered concern exceptionally a few sheets with local lack of the scale protection, scratches or traces of rust caused by the steel pallet straps.

## VI. CONCLUSION

The quality and stability of the MAGNETIL production throughout the nine years is remarkable. The project has allowed Cockerill Sambre to further develop their internal processes of quality control with positive outcomes in all areas of production.

Future applications for MAGNETIL are being pursued by ARCELOR and look technically promising in the areas of magnetic levitation and high voltage screening, where environmental legislation may require burying cables.

## ACKNOWLEDGMENT

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