Characteristics of the Austenitic Steels Used in the LHC Main Dipoles

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***Abstract*—The LHC dipole structure is assembled using austenitic steel collars and austenitic steel end-laminations. The collars will be fine-blanked starting from 11 000 tons of steel; the end-laminations require 1700 tons of steel.**

The procurement of the austenitic steels was divided in two phases: first, we qualified different grades from different producers, and then, we made the call for tender, adjudicated the contract and started the series production. The first part of this paper summarizes the results of the first qualification phase when extensive checks and measurements were carried out on five different grades.

The second part describes the approach used to control the series production and the results obtained. At the time of writing about 19% of the steel for collars and end-laminations has been manufactured and delivered.

***Index Terms*—Collars, steel selection.**

I. Introduction

AFTER the decision of making the LHC main dipole collars using austenitic steel instead of aluminum [1] we launched a campaign for the qualification and test of possible grades suitable for this application. In the mean while we also qualified a grade for the end laminations.

The market survey and qualification procedure lasted approximately six months. After this phase we launched the call for tenders and we concluded a contract with one producer of the steel for collars (Nippon Steel Corporation) and one of the steel for nonmagnetic yoke laminations (Kawasaki Steel Corporation).

The steel for collars represents a critical item for the correct performance of the LHC dipoles. The LHC machine requires the use of about 1250 dipoles implying the production of 11 000 tons of austenitic steel. The collars are important in the definition of the dipole field quality. Their dimensions must be extremely precise (tolerances of ± 20 μm in critical positions) obtained by means of a fine-blanking technique (precise punching) and reproducible all along the production. The collars are locally heavily stressed and work at 1.9 K. These facts call for high performance and reproducibility of the mechanical properties. The relative magnetic permeability must be as close as possible to 1.0 and constant along the production in order not to impair the field quality.

The steel for nonmagnetic end-yoke laminations is less critical since these pieces are not heavily stressed. The LHC machine requires the production of 1700 tons of this material. For this steel as well we need reproducible properties and constant dimensions of the fine-blanked parts during the whole production.

The most important feature required for this grade is its thermal contraction. It is important to have a thermal contraction as close as possible to that of the soft iron used for the yoke laminations in the straight part ($\sim 2\cdot 10^{-3}$ between room temperature and 1.9 K).

Manuscript received September 24, 2001.

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Publisher Item Identifier S 1051-8223(02)04172-6.

II. Qualification Outline

We purchased steel in various grades from different producers in order to manufacture collars for the dipole prototypes. The criteria for choosing the supplier were the availability of a grade fulfilling our technical requirements in the steel producer catalogue and his interest and good willingness to deliver material in time to respect the construction planning of our dipole magnets. The idea behind the qualification procedure was to test the complete chain from the steel production to the magnet manufacturing. We measured the steel features and behavior, we fine-blanked several thousands of collars and assembled at least one full size prototype with each given grade.

The characteristics that were systematically measured for each steel grade are the following:

1) Magnetic permeability at 4.2 K and 1.9 K,
2) Thermal contraction between room temperature and operational temperature (1.9 K),
3) Mechanical properties at room temperature and at 77 K,
4) Metallurgical features (grain size, inclusions, ferrite content etc.).

With the collaboration of the fine-blankers we tried as well to estimate the fine-blanking suitability of the different grades. We considered the precision and reproducibility of the collars, the wear of the tooling, the flatness of the collars and the quality of the cut. It is difficult or impossible to quantify all these parameters after the cutting of few thousands of collars. In principle we should have produced more collars to get better statistics. Therefore the judgment is mainly based on the experience and the know-how of the fine-blankers. The experience gained with the series production tells us that the preliminary evaluation done for a grade at the beginning is almost confirmed or achieved even better performances after the fine-blanking of several thousand of pieces when all the cutting parameters are optimized.

III. Qualification Data

During the market survey phase we were able to pre-select and test five different grades of steel as shown in the following Table I.

TABLE I
GRADES TESTED

Grade	Producer
13RM19®	Sandvik
20-7 MN®	Ugine
YUS 130 S®	Nippon
Hyform 200 mod.®	Avesta Sheffield
KHMN®	Kawasaki

TABLE II
NOMINAL CHEMICAL COMPOSITION (% OF TOTAL WEIGHT)

Grade	C	Si	Mn	P	S	Cr	Mo	Ni	N
13RM19	0.11	0.65	6.4	0.01	0.01	18.8	0.38	7.2	0.26
20-7 MN	0.03	0.22	9.12	0.02	0.002	20	0.032	6.86	0.4
YUS 130 S	0.09	0.4	10.7	0.022	0.004	18	0.1	6.6	0.32
Hyform 200 mod.	0.1	0.35	6.8	0.023	0.001	16.4	0.14	7.9	0.26
KHMN	0.1	0.6	28	0.022	0.004	6.7	<0.1	0.02	0.1

TABLE III
RELATIVE MAGNETIC PERMEABILITY μ_r (ACCURACY BETTER THAN 1%) AT DIFFERENT TEMPERATURE AND DIFFERENT MAGNETIC FIELD VALUES

Grade	μ_r at 4.2 K	μ_r at 4.2 K	μ_r at 1.8 K	μ_r at 1.8 K
	B=0.1T	B=3T	B=0.1T	B=3T
13RM19	1.003	1.0028	1.0029	1.0028
20-7 MN	1.0021	1.0019	1.0021	1.002
YUS 130 S	1.0022	1.0019	1.0019	1.0019
Hyform 200 mod.	1.0026	1.0026	1.0025	1.0025
KHMN	1.0015	1.0011	1.001	1.001

TABLE IV
THERMAL CONTRACTION ($\Delta L/L$) BETWEEN ROOM TEMPERATURE AND 1.9 K

Grade	Thermal contraction $\Delta l/l$
13RM19	$2.7 \cdot 10^{-3}$
20-7 MN	$2.7 \cdot 10^{-3}$
YUS 130 S	$2.6 \cdot 10^{-3}$
Hyform 200 mod.	$2.7 \cdot 10^{-3}$
KHMN	$1.8 \cdot 10^{-3}$

TABLE V
SPECIFIED VALUES

	Characteristic	reference value for the collars	reference value for the end-laminations
Room temperature	Yield strength $\sigma_{0.2}$	400-600 MPa	280-350 MPa
	Tensile strength σ_R	700-800 MPa	580-680 Mpa
	Elongation A_5	≥ 40%	≥ 40%
	Hardness HBS 5/750	≥ 180	≥ 100
At 77 K	Yield and Tensile strengths	superior to the room temperature ones	superior to the room temperature ones
	Elongation A_5	≥ 10%	≥ 10%

TABLE VI
MECHANICAL PROPERTIES AT ROOM TEMPERATURE

Grade	$\sigma_{0.2}$ [MPa]	σ_R [MPa]	A_5	E [GPa]	HBS 5/750
13RM19	440	800	52%	200	260
20-7 MN	460	795	50%	183	234
YUS 130 S	445	795	53%	194	250
Hyform 200 mod.	390	763	54%	188	277
KHMN	320	630	67%	186	220

TABLE VII
MECHANICAL PROPERTIES AT 77 K

Grade	$\sigma_{0.2}$ [MPa]	σ_R [MPa]	A_5
13RM19	1113	1634	66%
20-7 MN	1136	1650	46%
YUS 130 S	1023	1595	48%
Hyform 200 mod.	936	1533	65%
KHMN	1050	1600	50%

TABLE VIII
METALLURGICAL ANALYSIS

Grade	grain size	residual ferrite	max
13RM19	8-9	low	1%
20-7 MN	7-8	low	1%
YUS 130 S	6	no residual ferrite	
Hyform 200 mod.	7-8	low	0.002
KHMN	6	no residual ferrite	

The chemical composition of each grade is given in Table II.

Concerning the magnetic permeability, the specified value defined in the technical specification is $\mu_r \leq 1.003$ at 1.9 K with a magnetic field excitation of $H \geq 8 \times 10^4$ A/m ($\mu_0 H \sim 0.1$ T) for the collar grade and $\mu_r \leq 1.005$ in the same conditions for the end-yoke lamination grade. Table III shows the obtained results under different magnetic field values.

In the technical specification the required value for the thermal contraction between room temperature and 1.9 K is $2.2 \cdot 10^{-3} \leq \Delta l/l \leq 2.6 \cdot 10^{-3}$ for the collar grade and $1.6 \cdot 10^{-3} \leq \Delta l/l \leq 2.2 \cdot 10^{-3}$ for the end-yoke lamination grade. The Table IV shows the obtained results.

The measurements were performed with an accuracy of $\pm 0.1 \cdot 10^{-3}$. A more accurate device ($\pm 0.05 \cdot 10^{-3}$) based on laser measurements through a window in a cryostat has been developed to follow the series production but we did not repeat the measurements for the nonselected grades.

The specified values for the mechanical properties are the following (Table V).

The measured values are reported in the following Tables VI and VII. There is a very good reproducibility from sample to sample (less than 5% of difference).

The specification (for both collars and end-yoke laminations) states that, at a microstructural observation, the structure have to be fully austenitic and with a maximum grain size 4, according to ASTM E112-83. Table VIII shows the results of the measurements.

Concerning the fine-blanking suitability, the judgment from the fine- blankers based on a limited number of tests can be summarized in the following Table IX.

TABLE IX
COLLARS FINE-BLANKING SUITABILITY

Hyform 200 mod. :	good flatness of the collars (both from coils and sheets) very good cut relatively low tooling wear
YUS 130 S :	good flatness of collars from sheets. Improvement is necessary for collars from coils very good cut relatively low tooling wear
20-7-MN :	large flatness variation within the same sheet delivery (even the orientation of the sheet influence the process) good cut relatively low tooling wear
13RM19 :	good flatness "difficult" to cut important tooling wear

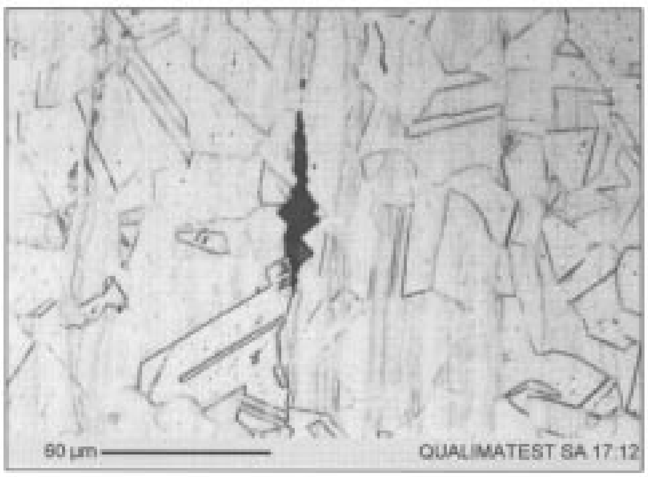

Fig. 1. Sample with the ferrite rate of 1% (the dark area).

IV. Qualification Conclusions

At the end of the qualification procedure we can conclude that all the selected grades are of good quality. Some weak points can be improved with the experience that will be gained producing a large amount of material.

The 13RM19, 20-7 MN, YUS130S and Hyform 200 mod. are good grades for the collar production. The KHMN is a good grade for the nonmagnetic end-yoke laminations.

The grade YUS130S [3] for the collars and KHMN [5] for the end-yoke laminations were finally chosen, after a call for tender, according to the best commercial offer received.

The remaining overview of this paper is mainly focalized on the steel for the collars.

V. About the Magnetic Permeability

As explained in the introduction one of the most important parameters to monitor for collars materials is the magnetic permeability of these grades. During the measurements one sample of the grade Hyform 200 mod. was found out of tolerance with a magnetic permeability of 1.0038 at 0.1 T, 1.8 K and 1.0026 at 3 T, 1.8 K. In order to understand the problem an analysis of the ferrite rate was made. The sample was cut every 0.5 mm along the width. The maximum rate of ferrite (1%) was found just under the surface (see Fig. 1). This behavior can explain the increasing of the magnetic permeability in this sample.

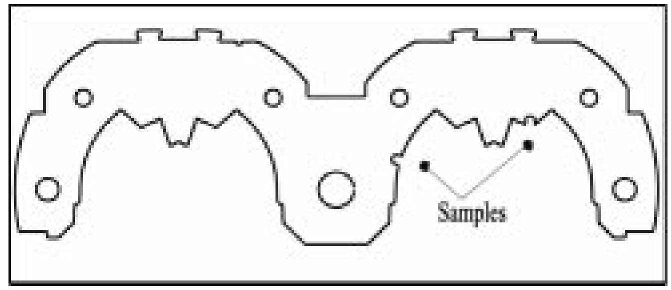

Fig. 2. Collar shape (male figure) with indicated where samples for magnetic permeability measurements are taken.

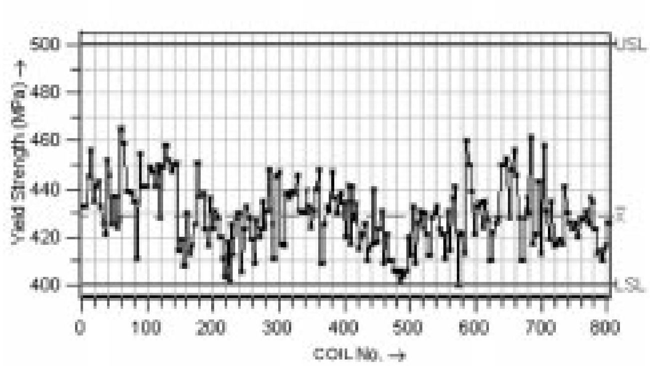

Fig. 3. Yield Strength, as a function of sequence of the coils; LSL and USL are respectively the lower and the upper specification limit.

This grade was specially developed for this application and the sample belongs to the very first melt. The producer confirmed that some parameters in the process were found to be inappropriate during the test melt and we are convinced that the implemented corrections will avoid any problem in the future.

To investigate the effect of the fine-blanking on the magnetic permeability of the collar edge, two samples (as shown in Fig. 2.) were cut and measured at 4.2 K. The collar was punched from a steel sheet of the same grade chosen for the large series production.

The result of the measurements ($\mu \sim 1.002$ as in the untouched areas) shows that there are no changes on the magnetic permeability due to the strain hardening of the steel in the boundary zone.

VI. Series Production of the Steel for the Collars

Like most of components of the LHC dipole structure [2], the series production of the austenitic steel for the collars is continuously monitored through graphical analysis of the data. The parameters, representative of the material performance, that are checked every coil (~2 tons), are: Yield Strength (Fig. 3), Tensile Strength, Elongation, Hardness, while grain size and inclusions are checked once every melt (~40 tons). For quality checks, the decision taken was to use the Quality assurance Plan proposed by Nippon Steel Corporation (NSC) with some small modification to the Technical Specification issued by CERN to adapt it to Japanese standards. All metallurgical and mechanical properties are measured by NSC in the frame of their Inspection and Test plan [3].

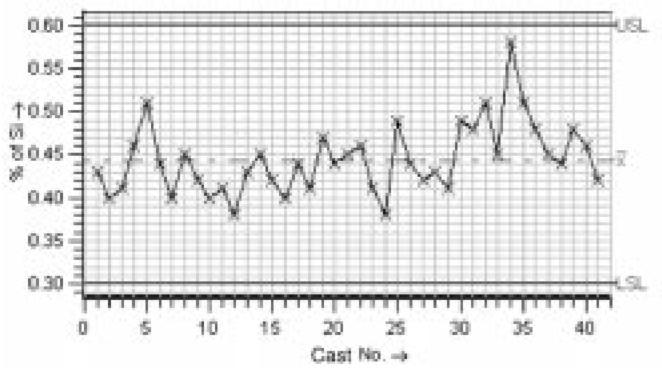

Fig. 4. Percentage of Silicon; LSL and USL are respectively the lower and the upper specification limit.

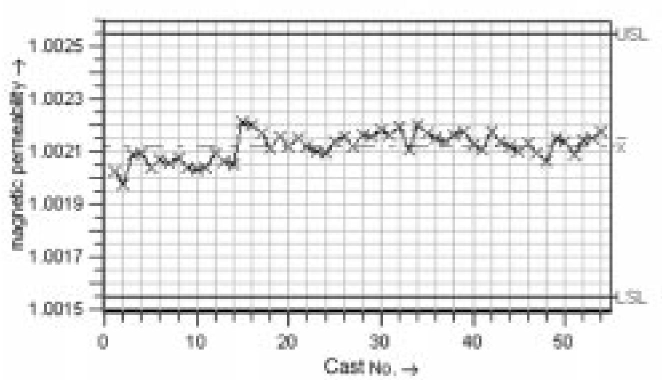

Fig. 5. Magnetic permeability at 4.2 K and at 1 T, in function of the sequence of the casts. LSL and USL are respectively the lower and the upper specification limit.

CERN measures only the magnetic permeability and thermal contraction for every melt.

The parameter representative of the cast analysis, checked every cast, is the chemical percentage in weight of C, Si (Fig. 4.), Mn, P, S, Ni, Cr, Mo and N.

Plotting all these data with their specification limits, we can monitor the series production, and by comparison of related parameters we can identify possible changes in the process of production.

Fig. 5 shows that the first 19% (about 2000 tons) of the production is extremely stable melt by melt. The most useful parameter to monitor the production is the magnetic permeability (see Fig. 5) since it is influenced by the chemical composition, the production process and the mechanical and thermal treatments of the steel. In particular at low magnetic field (before the

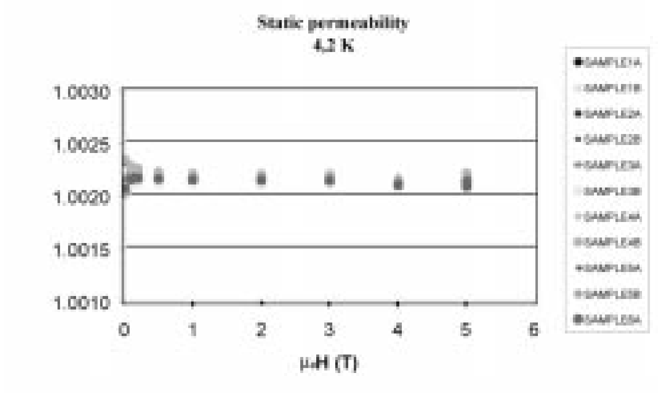

Fig. 6. Magnetic permeability, measured on different samples at different applied magnetic field and at 4.2 K. Each sample number represent a melt; the letters A and B represent two measurements performed, respectively, in perpendicular and parallel direction. The process parameters could be different from melt to melt in order to optimize the production.

saturation), this parameter is very sensitive to changes in composition or process.

VII. Conclusions

We pre-selected and measured the main characteristics of five grades of steel. After a competitive call for tenders the series production was launched with a precise monitoring of the main steel production parameters in close collaboration with the two Japanese producers involved (Nippon Steel Corporation and Kawasaki Steel Corporation).

Acknowledgment

The authors wish to acknowledge all the steel producers mentioned in this paper for their collaboration, help and their deep and genuine interest in the LHC project.

References

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