Control of the magnetic properties in very large steel pieces.

J.P. BADEAU - P. BOCQUET - J. BURLAT - A. CHEVIET - J. FOUEL - E. VARCIN
Creusot-Loire Industrie, France

Abstract
The performances of the magnetic circuits in large accelerators rely largely on the steel ferromagnetic properties. The steel producer knows how to satisfy the customer's requirements, but the best solutions are achieved through a close collaboration between producer and designers.

1. REQUIRED PROPERTIES OF STEEL

In large accelerators, magnetic circuits are big steel structures performing simultanously two functions :

- They have to carry the induction flux at a minimal expense of ferromagnetic material and of magnetic excitation field.
- They are also mechanical structures.

The steel producer has to answer two kinds of requirements :

- Magnetic impositions which can be :
  - minimum values of the induction at different values of the magnetic field .
  - high saturation induction .
  - low value of coercivity .
  - minimal magnetic ageing with time and/or temperature.
- Mechanical impositions : they generally rely on yield and tensile strengthes and sometimes toughness requirements.

But, the designer wants first homogeneous characteristics at different locations in a piece as well as in different pieces of a batch.

2. SOME SOLUTIONS

2.1. Principles

To obtain good magnetic properties, the following guidelines are generally accepted.

The chemical analysis has to be very closed to pure iron (% Fe ~ 99.99) and a very low carbon content is mandatory.

This is sufficient to achieve high saturation induction (which is a structure insensitive property), but for permeability, coercive force, residual induction, it is also necessary to get a metallurgical structure with large ferritic grain, without internal stresses and precipitates. However, few relatively coarse precipitates in the grain boundaries are less detrimental than many fine precipitates in the matrix.

2.2. Steel melting

Selected scraps are melt in an arc furnace. Refining and deassing are achieved in the laddle with a vaccum processing.

The main difficulties are :

- The control of non oxydable elements (Cu, Sn, ...) : the only practical way is the selection of scraps.
- Decarburization without oxydation of the melt with vacuum processing.
- Necessity of a very low Sulphur content if a low Mn is required (Prevention of hot shortness).
- Phosphorus is said to be not detrimental to the magnetic properties and it strengthens the ferrite. However, the segregation factor of P being very high, for large pieces, P is limited to very low values (generally < 50 ppm).

2.3. Solidification and metal working

During these stages of the processing, attention is given to the metal soundness and to the conditions of solidification to minimize the segregation and to insure the homogeneity of the product .

2.4. Heat treatment

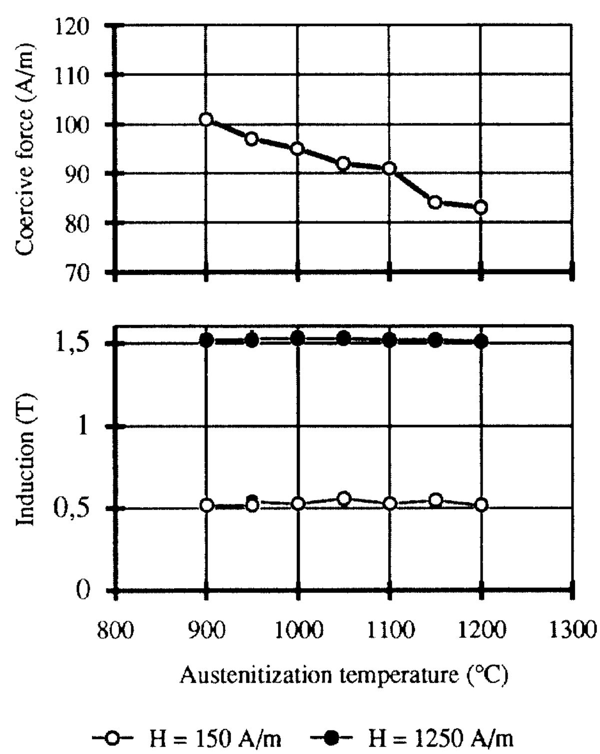

Figure 1 . Effect of the austenitization temperature on the coercive force and the induction at low fields .

The final aim being a very coarse ferritic grain, it is necessary to get first a coarse austenitic grain through austenitization at high temperatures.

The figure 1 shows the influence of the austenitizing treatment : high temperatures and long time decrease the coercive force. The effect on induction at low and medium fields is less evident.

There is two ways to get a large ferritic grain from a large gamma grain :

- A slow cooling after the austenitization, particularly during the ferritic transformation : different samples from a same plate, were austenitized at 920°C and then cooled at different rates varying from 2.5 to 100°C/h. The slowest cooling rates give the lower coercivity and the maximal values of induction at low fields (Figure2)

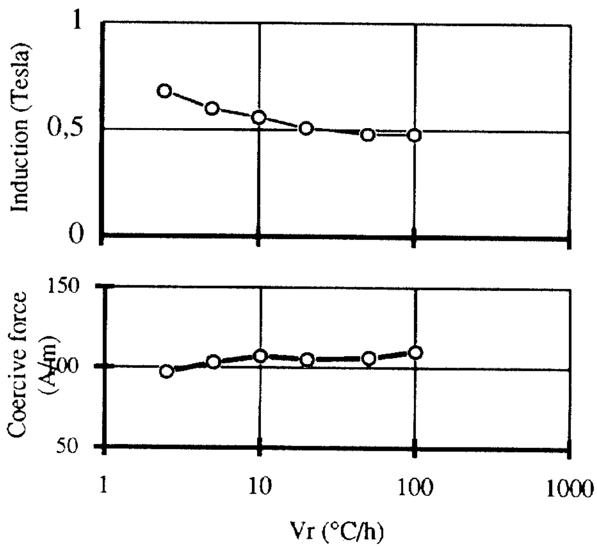

Figure 2. Influence of the cooling rate on the induction at low field (150 A/m) and the coercive force .

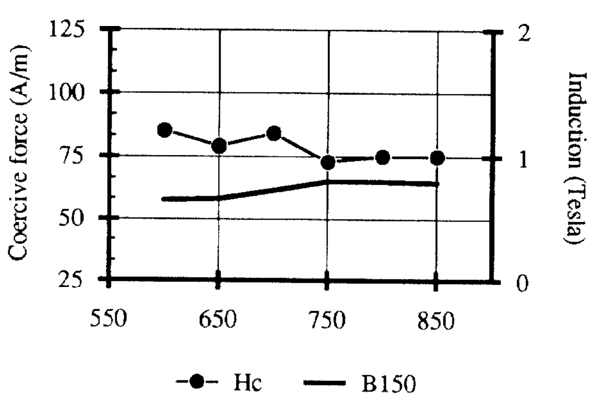

Figure 3 . Effect of the annealing temperature on B150 (Induction for H= 150 A/m) and Hc(Coercive Force).

- After air cooling, annealing just below the AC1 temperature improves the magnetic properties. The temperatures are higher than those used for tempering. The figure 3 shows the effect of the annealing treatment on a very low carbon steel (C ~ 0.004 %).

Attention must be paid to the cooling rate below the annealing temperature: a slow cooling rate gives a large improvement of the coercivity and a slight increase in permeability. But the major effect of the cooling rate at low temperatures is on the magnetic ageing phenomena.

Magnetic ageing is often characterized by the increase of the coercive force after a 100°C - 100 h treatment -. The figure 4 shows the benefit of a slow cooling rate after tempering.

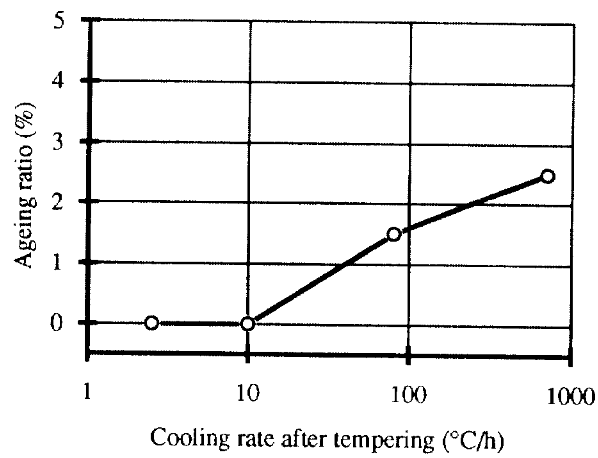

Figure 4 . Influence of the cooling rate after tempering at 650°C on magnetic ageing .

3. EXAMPLES OF APPLICATIONS

3.1. Steel castings for a cryogenic accelerator .

In the magnetic circuit of a cryogenic accelerator, castings are preferred as this solution needs fewer parts.

The larger pieces are up to 90 000 kg and 950 mm thickness.

The most stringent magnetic requirements are for pole pieces :

Intrinsic Induction ($B-\mu_0 H$) at H > 200 kA/m (approaching saturation) :

A > 2.14 T

and

Coercive force

Hc < 70 A/m.

For other parts, the specification is less severe for Hc but asks for higher mechanical characteristics :

A > 2.14 T - Hc < 100 A/m.

Preliminary tests have indicated that a 1 % Nickel addition improves both magnetic and mechanical properties

Consequently, parts with the higher mechanical specification were cast with about 1 % Ni and the other parts without volontary additions of this element (% Ni < 0.15 %) . For both cases, very low content of C, S, P and Si were achieved. All parts were annealed at 840°C for 8 hours.

The Ni addition is specially efficient for the Yield Strength (+30 %) and it decreases the coercive force but without noticeable effects on induction at low fields or on intrinsicinduction(Table1).

Table 1. Magnetic properties of large castings .
(Induction in Tesla; field in A/m)

Heats	Induction			Intrinsic Induction	Hc (A/m)
	H = 200	H = 300	H = 500		
Low Nickel					
A	0,864	1,140	1,413	2,159	66
B	0,874	1,128	1,406	2,156	61
C	0,860	1,119	1,396	2,166	64
D	0,885	1,165	1,449	2,158	69
E	0,845	1,103	1,386	2,155	63
F	0,873	1,121	1,386	2,154	60
High Nickel					
G	0,913	1,147	1,372	2,154	43
H	0,828	1,074	1,343	2,169	57
I	0,842	1,090	1,349	2,166	61
J	0,858	1,111	1,373	2,153	57
K	0,859	1,107	1,354	2,158	62
L	0,825	1,074	1,332	2,155	65

2.2. Heavy plates for two deflecting magnets .

Good results are achieved for heavy plates through the following process. After hot rolling, the hot plates are very slowly cooled under a cover of volcanic ashes : between 900 and 200°C, the cooling rate is 2°C/h. This process gives its best results with thick plates : with increasing thickness, the coercivity is lower and the dispersion is reduced (Figure 5).

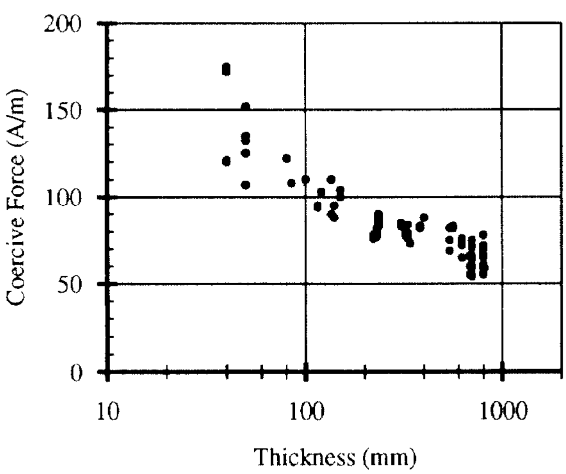

Figure 5. Reduction of the coercive force with increasing thickness in very low carbon steel plates .

Such plates have been used in two deflecting magnets of a large accelerator.

With the initial design, for each magnet, 400 tons of steel were necessary. But, after a discussion between the steel supplyer and the designer, a completely new design was adopted.

The delivery was no more plates, but semi-finished parts very close to the final dimensions : a optimized oxycutting process (called "Flame Cutting Machining") gives on 700 mm thick parts 10 mm guaranted dimensionnal accuracy and better than 20 µm RA roughness. With such performances, only fonctionnal surfaces need further machining and the total mass , for each apparatus, is reduced to 320 tons .

For this order, 19 heats were poured. The mean analysis was C ≃ 0.010 %, Mn ≃ 0.280 %, Si ~ 0.130 % and with a very low level of impurities (S < 0.010 % and P < 0.006 %).

The thickness of the plates were up to 740 mm and for each plate, four specimens from different locations were tested. The magnetization curves are very homogeneous specially for low field values (Figure 6).

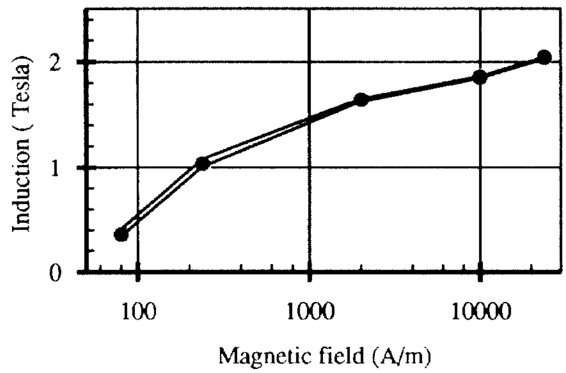

Figure 6. Magnetic properties of heavy plates :
Mean and extremal values for 19 heats .

Finally, the new design of the magnets gave very good magnetic performances but also considerable savings on machining costs.

4. CONCLUSIONS

The above examples have shown that every stage of the process has to be closely monitored in order to achieve the required magnetic properties .

They also demonstrates that the best solutions are only obtained through a close partnership between the steel supplyer and the designers of the magnetic circuits .