MATERIALS FOR FAST CYCLING ACCELERATOR SUPERCONDUCTING MAGNETS

P. Shcherbakov, I. Bogdanov, S. Kozub, L. Shirshov, P. Slabodchikov, V. Sytnik, L. Tkachenko, V. Zubko, Institute for High Energy Physics, Protvino, Moscow region, 142281

Abstract

Development of fast-cycling superconducting magnets with high field amplitudes and ramp rate makes severe requirements especially to material properties in order to improve field quality and to reduce AC losses. Analysis of experimental and literature data is fulfilled for magnetic characteristics of electric steels at different temperatures. Susceptibilities of stainless steels of different grades are examined as well as a tolerance on the value of the magnetic permeability. Mechanical, thermophysical and technological properties at room and cryogenic temperatures are presented. Comparison of steel characteristics, selected for the SIS300 quadrupole prototype, with the steels, used in the SIS300 dipole and steels, applied in the SIS100 prototype magnets is carried out. General advices to the choice of materials for electrical and stainless steels, used in a design of fast-cycling magnets, are given. *

INTRODUCTION

IHEP takes part in the development of SC magnets for SIS300 from 2001 year [1]. The substantiation of steel selection for fast cycling magnets of FAIR SIS300 and SIS100 was the one of IHEP task. Accelerator dipoles work at the field ramp rates 1 T/s and 4 T/s correspondently. The main materials of SC magnet design beside the superconductor are yoke electric steels and stainless steels for collars, vacuum pipes and other elements.

In 2003 in IHEP and GSI the study of magnetic properties of steels with 1-4% Si at different temperatures have been carried out. The anisotropy of magnetic properties has been determined and hysteresis loss have been measured in symmetric, unipolar and partial cycles [2].

Main conclusions of R&D are: a) the reducing of temperature up to 4.2 K effects on magnetic properties less than in low carbon steels; b) anisotropy, obtained on the strips of one direction (in the rolling direction and transverse one) is averaged in the ring samples, and the properties of isotropic and anisotropic steel with similar Si content are approximately the same.

In this paper the emphasis is made on the technology and possibilities of industry

The selection of stainless steels for the FAIR magnets is similar to the choice in big “slow” SC projects (Tevatron, SSC, LHC). The enormous experience in the development and study of stainless steels has been obtained during magnet development for LHC. This experience is valid for fast cycling magnets of FAIR with taking into account eddy currents at 4.2 K.

In this paper the magnetic properties of stainless steels, acceptable for the production of the collars, vacuum chambers and other elements at 300 and 4.2 K are presented.

IHEP is developing the SIS300 quadrupole, models of SIS100 magnets are developing in JINR, BINP and GSI.

ELECTRIC (ET) STEELS FOR YOKE

Severe requirements for yoke steels of SIS100 and SIS300 are given to field quality and AC losses, determined by coercivity H_c and saturation magnetization M_s, which in turn depend on Si content: H_c have to be less than 40 A/m for dipoles and 70 A/m – for quadrupole of SIS300 magnets; M_s have to be greater than 2.0 T and be as high as possible.

The carried out measurements of magnetic properties of Si steels together with analysis of literature data and steel maker catalogs allowed us to make the list of steels, which can be used as yoke material for dipole or quadrupole of the SIS 300 and SIS 100 magnets, depending on demands to field quality or acceptable AC losses. The short and full scale models of the SIS 300 and SIS 100 magnets have been made during R&D using the steels from the candidate list. The testing of these models and comparison of field quality and AC losses as well calculations with detailed models and obtained steel magnetic properties give the possibility of problem understanding and greater certainty in steel choice.

In Table 1 the steels with Si content 1.5-3% are presented [3, 4, 5]. Coercive force H_c lies in the range of 20-65 A/m, specific hysteresis loss W_h in unipolar cycles with B_{max} = 2 T at 4. 2 K is in the range of 30-60 mJ/kg, saturation magnetization Ms is in the range of 2.0-2.1 T.

Table 1: Steels with 1.5-3 % of Si content

Grade	Type	Si, %	Thickness, mm	Country
M250-50	Isotropic	3	0.5	Germany
M350-50	Isotropic	1.5	0.5	Germany
2412	Isotropic	3	0.5	Russia
2212	Isotropic	1.5	0.5	Russia
M600-100	Isotropic	3	1	Germany
M700-100	Isotropic	2.4	1	Germany
M800-100	Isotropic	1.5	1	Germany
3413/3414	Anisotropic	3	0.5	Russia

* This work was completed with financial support from Rosatom, contract H4e45.03.10.1027

It should be noted that a) isotropic steels with thickness of 1 mm are produced only in Europe in frame of standard EN 10106, b) anisotropic steels with thickness of 0.5 mm are produced only in Russia, whereas in the world the thickness is maximum of 0.35 mm.

In Fig. 1 and Fig. 2 the B-H curves and hysteresis loss dependencies, obtained on ring samples, for steels with different Si content are presented, showing the effect of Si content on magnetic characteristics. One can see that the hysteresis losses of isotropic and anisotropic steels are close, so the advantages of anisotropic steels are not obvious in the magnet circuits like dipole yoke, where there are different directions of induction with respect to rolling direction.

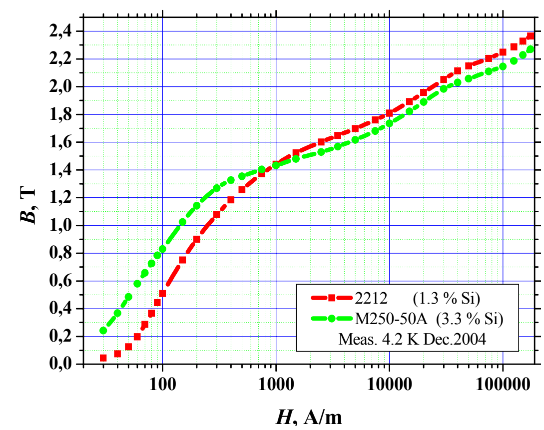

Figure 1: B-H curves of M250-50 (3% Si) and 2212 (1.3% Si) steels.

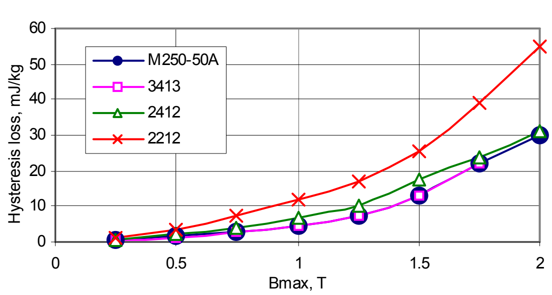

Figure 2: Hysteresis loss in unipolar cycles 0 – Bмax – 0 at 4.2 K.

In Table 2 the steel grades, used in the models of the SIS 300 and SIS 100 magnets, are presented [6, 7, 8, 9].

Table 2: Steels, used in the models of magnets for FAIR

Magnet	Accelerator	manufacturer	Steel
Dipole	SIS 300	BNL (USA)	M250-50
Dipole	SIS 300	IHEP	M700-100
Quadrupole	SIS 300	IHEP	2212
Dipole	SIS 100	BNG (Germany)	M700-100
Dipole	SIS 100	JINR	3413
Dipole	SIS 100	BINP	3413

Analisys of model test results together with calculations of fields and AC losses, as well study of steelmaker possibilities allow to make the choice of steels for model production of dipoles and quadrupoles of SIS300 and SIS100. For dipoles the steels with 3% Si (M250-50, M600-100 or 2412) are preferable, for quadrupoles – steels with 1.5-2% - 2212 or M700-100.

STAINLESS STEELS

In the design of fast cycling SC magnets the stainless steels are used in different forms for production of collars, vacuum chambers, insertion in cable, shims and so on (Fig. 3, [10]).

Main requirement to steels for collars and vacuum pipes are fully austenitic with a permeability lesser than 1.005 at 4.2 K after technological processes, the permeability of cable core and structural elements has to be lesser than 1.02.

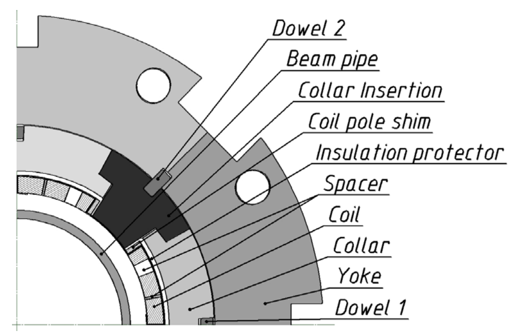

Figure 3: Main elements from stainless steels in the SIS300 quadrupole (IHEP).

Field ramp rate in the stainless steels at 4.2 K effects only on eddy currents, which restrict the thickness of sheet steels for collars and vacuum pipe. For magnets of LHC the careful selection and development of stainless steels for collars, pipes, nonmagnetic yoke end plates, beam screen has been carried out. This experience can be used for the FAIR magnets.

The main elements from stainless steels are the collars and vacuum pipe, placed near working aperture with high field homogeneity.

Collars

Stainless steels for collars have to be fully stable austenitic steels. There are two steels of this quality, Nitronic-40 and P506. Widely used at low temperature steel 316LN can show higher magnetic susceptibility at 4.2 K; steel YUS130S, used in the LHC magnets, is similar to Nitronic-40.

In Fig. 4 the dependences of permeability μ of steels Nitronic - 40 and 316LN at 300 and 4.2 K are shown [11].

In Table 3 the chemical composition, mechanical, magnetic and electric properties of studied and selected steels at 300 and 4.2 K are presented [12, 13].

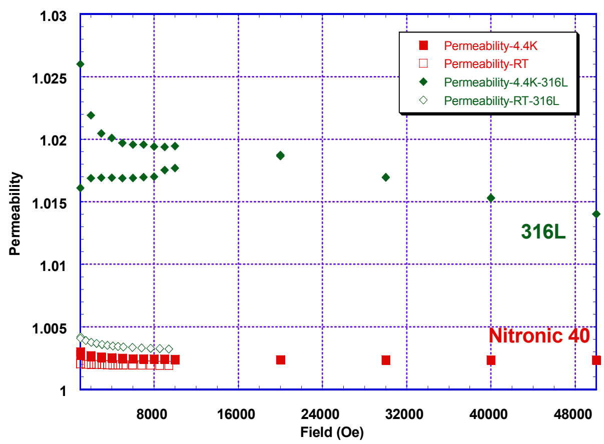

Figure 4: Magnetic permeability of steels Nitronic-40 and 316L at 300 k and 4.2 K.

Table 3: Chemical content and properties of steels for collars and vacuum chamber (0.2% yield strength $\sigma_{0.2}$; tensile strength σ; elongation δ; Young modulus E; magnetic permeability μ; resistivity ρ).

	Nitronic40	316LN	YUS130S	P506
Cr	19	16	20	19.2
Ni	6	12	6	11
Mn	9	0.8	10	12.1
C	0.03	0.02	0.09	0.01
N	0.34	0.12	0.35	0.3
$\sigma_{0.2}$,kgf/mm^2	46	35	48	41
σ, kgf/mm^2	79	65	80	73
δ, %	44	48	45	-
E, GPa, 300 K,	192	185	192	190
μ , 300 K	1.0019	1.003	1.0018	1.0026
ρ, $\mu\Omega\times$m	79	78	79	79
$\sigma_{0.2}$,kgf/mm^2	142	99	164	162
TS, kgf/mm^2	181	150	191	212
δ, %	20	43	20	-
μ , 4.2 K	1.0021	1.013	1.0018	1.0025
ρ, $\mu\Omega\times$m, 4.2K	-	55	55	50

In the model of SIS300 dipole and quadrupole the Nitronic-40 has been used with thickness 1.6 mm, in the dipole of INFN – steel P506 (3 mm). In the SIS300 quadrupole model Nitronic-40 will be used.

Vacuum chamber

Power of eddy current loss in the vacuum chamber from stainless steel is proportional to tube diameter and tube thickness as well $(dB/dt)^2$. The calculations show that for SIS300 and SIS100 magnets these losses at 4.2 K (ρ=50 $\mu\Omega\times$m, 4.2 K) restrict the tube thickness up 0.3-1 mm. As the tube from Nitronic-40 and P506 are not produced, steels 316L and 316LN are usually used (BNG and BINP for SIS100 dipole models).

Insertion (core) in SC Rutherford cable

The core from stainless steel strip of 25 µm is introduced between layers of Rutherford keystone cable in fast cycling magnets of the SIS 300 for reducing of cable losses. Annealed steel 316L has better mechanical and magnetic properties (μ = 1.02), which do not affect field quality. Moreover the annealing provides oxide film, allowing one to avoid the preliminary cable heat treatment.

CONCLUSION

Industry offers the wide spread of electric isotropic steels with 1.5-3% Si with thickness of 0.5-1 mm and anisotropic with only 3% with thickness of 0.35 - 0.5 mm. The optimal steels are M250-50, M600-100 for the dipoles and M700-100, 2212 for the quadrupoles.

For collars of SIS300 magnets Nitronic-40 or P506 with thickness up to 3 mm can be used.

For the vacuum chamber of SIS300 quadrupoles steels Nitronic 40, YUS130S, P506 or 316L/316LN can be used.

Cable core can be made from annealed stainless steel strip 316L.

REFERENCES

[1] [GSI. (2006, Sept.). Baseline technical report. [Online]. Available: http://www.gsi.de/fair/reports/btr.html

[2] I. Bogdanov et al., "Study of Electrical Steel Magnetic Properties for Fast Cycling Magnets of SIS100 and SIS300 Rings", EPAC-2004, Lucerne, Switzerland, 2004, pp.1741-1743.

[3] Druzhinin V.V., "Magnetic properties of electric steels", Energy, 2 edition, 1974.

[4] "Cold rolled electrical steel", reference book, ed. by B.V. Molotilov, M, Metallurgy", 1989.

[5]http://www.lei.ucl.ac.be/~matagne/ELEC2311/T2007/hinNOFP.pdf

[6] P.Wanderer et al., "Initial tests of a fast ramped SC model dipole for GSI" proposed of SIS 200 accelerator", PAC, 2003, WPAB054.

[7] A.Kovalenko et al., "Design and study of a SF model dipole and quadrupole magnets for GSI fast pulsed synchrotron SIS100", EPAC, 2004.

[8] E. Fischer et al., " Magnetic field characteristics of a SIS100 full size dipole", EPAC, 2008.

[9] S.Kozub et al. , "SIS300 dipole model", MT-21, 2009.

[10] L. Tkachenko, S. Kozub, P. Shcherbakov, V. Sytnik, V. Zubko. "Analysis of the Factors Affecting Field Quality and Heat Releases of the Quadrupole Magnet for the SIS 300", presented at ASC-2010, Washington, USA, August, 2010.

[11] S. Yadav, "Magnetic Permeability of Stainless Steels at Low Temperature", TD-01-065, FNAL, Sept. 27, 2001.

[12] C. Lanza and D. Perini, "Characteristics of the austenitic steels used in the LHC main dipoles", Proceedings of MT-17, September 2001.

[13] K. Couturier and S. Sgobba, "Phase stability of high manganese austenitic steels for cryogenic applications", CERN EST/2000-006 (SM).