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(Sgobba@MT.MSM.cem.ch)

Cryogenic Properties of special Welded Stainless Steels for the Beam Screen of the Large Hadron Collider

S. Sgobba[1] , L-R Bacher[1], M. Couach[2], and S. Marque[1]

Keywords: **High N_2 steels, TIG and EB welding, cryogenic properties, magnetic susceptibility, antiferromagnetic transition, serrated tensile tests.**

Summary

Because of their weldability and excellent austenitic stability, N_2-enriched austenitic stainless steels are candidate materials for different components of the Large Hadron Collider (LHC) to be built at CERN. The LW should operate at cryogenic temperatures (1.9 K) and provide 7 TeV Proton-Proton collisions. The magnet cold bore at 1.9 K will be shielded from the synchrotron radiation emitted by the circulating proton beam and the power dissipated by the beam image currents by a "beam screen" cooled to 10 K. This screen should be totally amagnetic at cryogenic temperatures (the maximum admitted magnetic susceptibility is 5.10^{-3}). Therefore, amagnetic N_2-enriched steels with different Mn contents were selected as candidate materials for the screen. Severe conditions are imposed on the construction material of the beam screen. A quench (sudden loss of superconductivity in the magnet) will induce eddy currents in the screen which result in a risk of plastic deformation. During its life, the screen will be subjected to several thermal cycles between room temperature and cryogenic temperatures. During machine operation the screen will be kept at temperatures higher than 4.2 K, in order to absorb the heat load at a lower cost. However it must be able to withstand, without risk of embrittlement, cooling to the magnet temperature of 1.9 K. Any ductile-fragile transition should therefore be avoided down to 1.9 K. An investigation of the magnetic and mechanical properties of TIG and EB welded candidate steels down to liquid He temperature (4.2 K) is presented.

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1 CERN, MT-SM, CH-1211 Geneva, Switzerland

2 CEA, DRFMC/SPSMS/LCP F-38054 GRENOBLE Cedex 9, France

CRYOGENIC PROPERTIES OF SPECIAL WELDED STAINLESS STEELS FOR THE BEAM SCREEN OF THE LARGE HADRON COLLIDER

S. Sgobba[1], L-R Bacher[1], M. Couach[2] and S. Marque[1]

') CERN, MT-SM, CH-1211 Geneva
2) *CEA, DRFMCISPSMSILCP F-38054 Grenoble Cedex 9*

Because of their weldability and excellent austenitic stability, N_2-enriched austenitic stainless steels are candidate materials for different components of the Large Hadron Collider (LHC) to be built at CERN. The LW should operate at cryogenic temperatures (1.9 K) and provide 7 TeV Proton-Proton collisions. The magnet cold bore at 1.9 K will be shielded from the synchrotron radiation emitted by the circulating proton beam and the power dissipated by the beam image currents by a "beam screen" cooled to 10 K. This screen should be totally amagnetic at cryogenic temperatures (the maximum admitted magnetic susceptibility is 5.10^{-3}). Therefore, amagnetic N_2-enriched steels with different Mn contents were selected as candidate materials for the screen. Severe conditions are imposed on the construction material of the beam screen. A quench (sudden loss of superconductivity in the magnet) will induce eddy currents in the screen which result in a risk of plastic deformation. During its life, the screen will be subjected to several thermal cycles between room temperature and cryogenic temperatures. During machine operation the screen will be kept at temperatures higher than 4.2 K, in order to absorb the heat load at a lower cost. However it must be able to withstand, without risk of embrittlement, cooling to the magnet temperature of 1.9 K. Any ductile-fragile transition should therefore be avoided down to 1.9 K. An investigation of the magnetic and mechanical properties of TIG and EB welded candidate steels down to liquid He temperature (4.2 K) is presented.

KEYWORDS : High N_2 steels, TIG and EB welding, cryogenic properties, magnetic susceptibility, antiferromagnetic transition, serrated tensile tests.

1. INTRODUCTION

High N2 steel grades with different Mn content have been considered for the construction of the beam screen of the Large Hadron Collider planned at CERN. The screen must remain totally amagnetic down to its working temperature of about 10 K, to avoid significant magnetic field distortions in the proximity of the accelerated beam. The maximum admitted magnetic susceptibility (χ') of the screen is 5.10^{-3} [1, 2]. High N_2 steels are suitable materials to replace the traditional austenitic stainless steels of the 300 series for cryogenic applications, which do not generally fulfil the requirements of very low susceptibility at low temperature. Moreover, high N_2 steels have excellent mechanical properties and good weldability, while high Mn steels are known as magnetically stable materials at cryogenic temperatures [3]. Accurate measurements of the magnetic susceptibility as a function of temperature between 4.2 K and room temperature have been performed on three different high N_2 - high Mn steels.

Although the beam screen is not a structural component of the LHC, it must withstand, without risk of embrittlement, repeated cooling at the magnet temperature of 1.9 K and the eventual quench forces losses of superconductivity in the magnets. Tensile test facilities at 4.2 K have therefore been developed at CERN in order to study the mechanical behaviour of steel samples.

In the present design, the screen has a section of 38 x 38 mm^2 and a length of about 15 m. It will be 1 mm thick and welded longitudinally. Since local precipitation of 8-ferrite in the weld metal and/or in the Heat Affected Zones (HAZ) might result in a loss of mechanical properties and a local increase of susceptibility, cryogenic measurements have also been performed on welded joints.

2. STEEL GRADES

The candidate grades for the beam screen are the steels UNS 21904 produced by Ugine, 13 RM 19 by Sandvick and X20MDW by Aubert et Duval. Their composition is given in Table 1.

steel	Cr	Mo	Si	Ni	Mn	N	C	Cr-eq	Ni-eq
13 RM 19	18.5		0.8	7	6	0.25	0.11	18.88	14.64
UNS 21904	20			7	9	0.38	0.03	20	15.02
X20MDW	20.35	2.12	0.4	9.57	3.97	0.366	0.034	23.10	17.43

Tab. 1 : Composition of candidate steels for the beam screen of the LHC. The Cr and Niequivalents are calculated as follows : Cr_{eq} = Cr + 1.21 Mo + 0.48 Si + 2.27 V + 0.72 W + 2.20 Ti+ 0.14 Cb + 0.21 Ta + 2.48 Al; Ni_{eq} = Ni + 0.11 Mn - 0.0086 Mn^2 + 0.11 Co + 0.44 Cu + 18.4 N + 24.5 C.

The three steels are in the fully austenitic region of a Hull diagram. A suitable choice of the welding parameter for the Tungsten Inert Gas (TIG) and Electron Beam (EB) techniques resulted in almost totally austenitic welds [41. Metallographic observations have shown that 3-ferrite precipitates only locally in TIG welded specimens, that is in the first 5 to 100 gm of the HAZ adjacent to the weld bead. Fully austenitic EB welds could be obtained on two of the three grades (13 RM 19 and X20MDW).

3. EXPERIMENTAL TECHNIQUES

Magnetic susceptibility measurements have been performed at CEN - Grenoble on an ac susceptometer by a mutual inductance technique. Details of the measurement principle and apparatus are described in a previous work [5]. The susceptibility has been measured under a field of 35 Oe as a function of temperature between 4.2 K and room temperature. Samples of small size (1 x 1 x 10 mm^3) have been electro-discharge machined from the base metals, the HAZs and the weld beads of the three grades of steels, allowing the local magnetic properties of the HAZs and of the weld beads to be measured. Transverse specimens of the same size have also been cut, perpendicular to the weld bead. As the surface oxides are known to perturb the measurements of magnetic susceptibility [6], the surface of all the measured samples was cleaned and deoxidised by a chemical surface treatment. Effects of the surface oxide layer observed on small size specimens almost disappeared after this surface treatment.

A method for high precision tensile tests at 4.2 K has been developed at CERN. Specimen of 1 mm^2 square section with a calibrated length of 25 mm have been measured in a liquid He cryostat. Two LVDT a carbon potentiometer fixed on the calibrated length of the specimen allow high precision measurements of strain in the early stage of deformation (up to 10%) and in the fully plastic regime respectively. The analogue signals of the sensors and the potentiometer are converted by a 16 bits ADC and treated by Labview on a microcomputer. The high displacement resolution obtained after conversion of the LVDT signals (about 0.5 μm) permits a very precise evaluation of the elastic modulus and the yield stress at 4.2 K. The effects of eventual misalignments of the specimen are corrected for by averaging the two signals of the LVDTs.

4. EXPERIMENTAL RESULTS

4.1 Magnetic susceptibility

A typical curve of magnetic susceptibility measured on the X20~ steel as a function of the temperature between 4.2 K and room temperature is reported in Fig. 1. The curve shows a typical peak of antiferromagnetic transition at the Néel temperature T_{af} [7]. The two other grades also show an antiferromagnetic transition, which is typical of several "nonmagnetic" stainless steels. The transition temperature T_{af}, as well as the height of the maximum, depend on the composition of the alloy. A dependence of the magnetic behaviour on the surface to volume ratio and the machining technique (mechanical or electro-discharge) was also observed. Higher surface to volume ratio result in lower T_{af} and higher values of peak susceptibility. The magnetic susceptibility of X20MDW stays under 5.10^{-3} at the beam screen working temperatures.

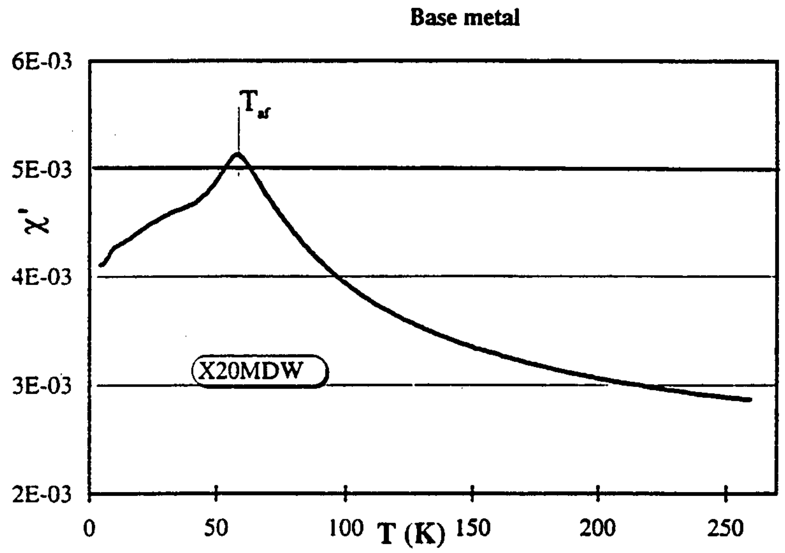

Fig. 1: Magnetic susceptibility measured as a function of temperature for the steel X2OMDW. Base metal.

The susceptibility was measured on the three welded steels (Fig. 2). Although a small ferritic layer is present in the HAZs of the TIG welded samples, TIG welds result in maximum values of X' less than 5.10^{-3} , except for the grade X20MDW where TIG welds enhance X' and decrease T_{af}. The curve measured on a fully austenitic EB welded sample of 13RM19 has a behaviour similar to the same sample welded by TIG. Increasing Mn content corresponds to a general decrease of susceptibility for the whole temperature range. The steel UNS 21904 containing 9% Mn shows two transition peaks.

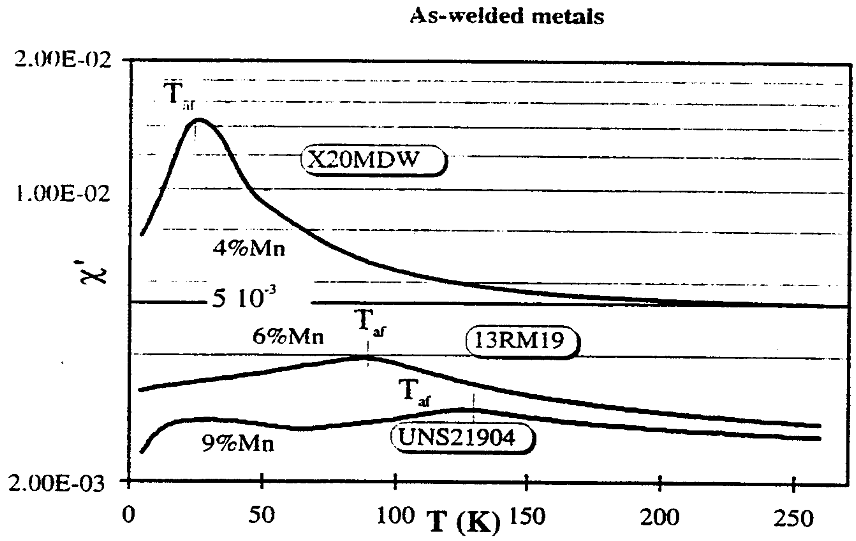

Fig. 2: Magnetic susceptibility measured as a function of temperature for the three steels. TIG welded transversal samples.

4.2 Results of the tensile tests at 4.2 K

Comparison of the tensile tests at 4.2 K for the three base metals are shown in Fig. 3a. The elastic modulus was evaluated by unloading in the early plastic region of the deformation (at about 1% strain). Compared to room temperature measurements we notice at 4.2 K a general increase of the elastic modulus E, the yield stress $R_p0.2$ and the ultimate tensile stress σ_r, and a decrease of the ultimate strain ε_r, (Tab. *2),* as typical for stainless steels at low temperatures [8].

steel grade	$E_{4.2}$ (GPa)	E_{293} (GPa)	$R_p0.2_{4.2}$ (MPa)	$R_p0.2_{293}$ (MPa)	$\sigma_{r4.2}$ (MPa)	σ_{r293} (MPa)	$\varepsilon_{r4.2}$ (%)	ε_{r293} (%)
13 RM 19	**200**	165	**1500**	780	**2050**	815	**16**	17
UNS 21904	**205**	175	**1950**	440	**2000**	515	**6**	39
X20MDW	**220**	185	**1640**	660	**2100**	-	**6**	26

Tab. 2: Compared values of the elastic modulus, the yield stress, the ultimate tensile stress and strain measured at 4.2 K and at room temperature for the three grades of steel. Base metal.

Figure 3a shows the appearance of the so called "serrated yield", which manifests itself as characteristic spikes on the tensile test curve. The onset of serrated yield depends on steel composition (in our strain range, the grade 13 RM19 shows serrated yield, while the UNS 21904 and *X20M/DW* do not).

Figure 3b shows tensile curves on TIG welded specimens cut perpendicularly to the weld bead. Welding was done with the same parameters as for the susceptibility samples. The breakdown occurred in the weld bead *(X20MDW)* or was initiated in the HAZs (UNS 21904, 13RM19). Serrated yield occurred earlier in welded 13 RM 19. Welded *X20MDW* does not show serrated yield. Tensile tests on EB welded specimen give similar results.

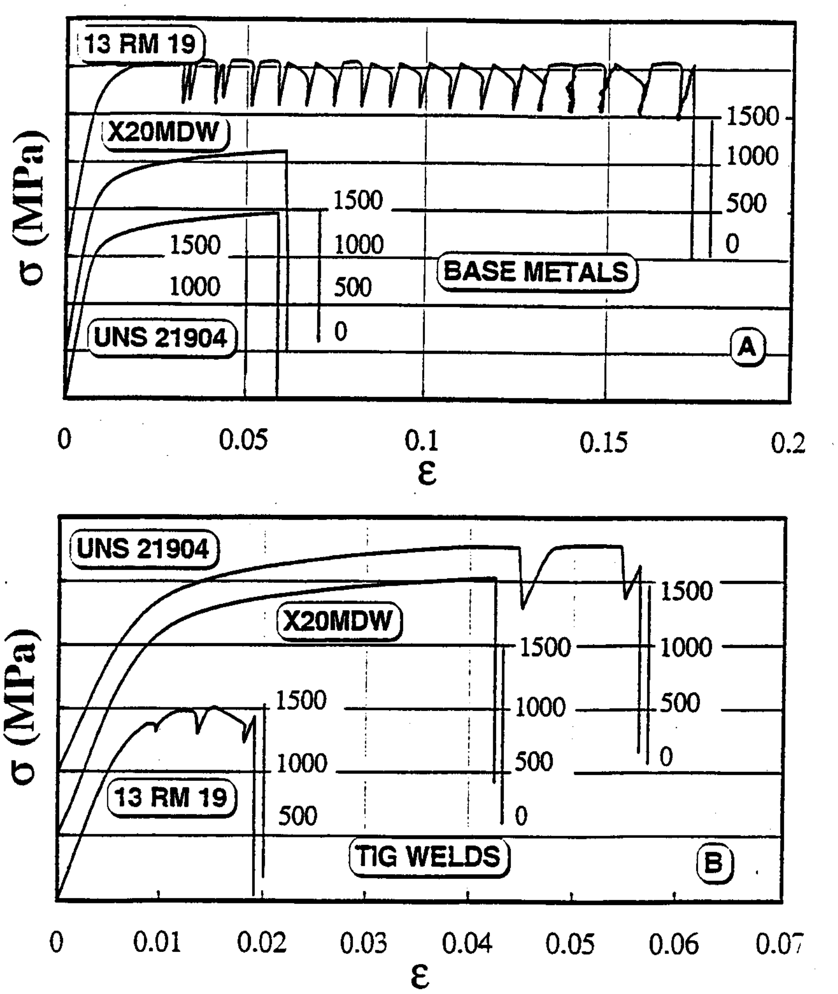

Fig. 3: Tensile tests at 4.2 K for the three steels. a) base metals; b) TIG welded transversal samples.

5. DISCUSSION

The antiferromagnetic transition is a typical signature of magnetic susceptibility versus temperature curves of "nonmagnetic" stainless steels measured at cryogenic temperatures. In particular, Li et al. [9] observed the transition on a Fe-21Cr-6Ni-9Mn-N (comparable to UNS 21904). As established by the equation of Wames et al. [10], the steel composition influences the magnetic behaviour at low temperature. The Néel temperature depends on alloy composition according to the equation:

$$T_{af}(K) = 90 - 1.25Cr - 2.75Ni - 5.5Mo - 14Si + 7.75Mn$$

Since the increase of transition temperature experimentally corresponds to a decrease in the values of X' in the lower branch of the curve (for T ----> 0), the above equation indicates that manganese is the only element reducing X' at very low temperatures. Our experimental results confirm that the lowest values of X' are found for the steel UNS 21904, i.e. the richest in Mn. The effect of nitrogen addition, used to reduce the Ni content and maintain good mechanical properties, is also indirectly beneficial for the amagnetic properties of the studied steels compared to the steels of the 300 series.

Serrated yield is generally attributed to martensitic precipitation occurring in austenitic stainless steels during tensile tests at 4.2 K. However, as serrated tensile curves have also been measured on A-alloys in particular by us on A15083 and A17021 grades) the interpretation that martensite is the cause of serrated yield is highly controversial. Adiabatic heating of the sample due to the heat produced by the deformation is indicated by some authors [11, 12] as the cause for this effect. Nevertheless, martensite may precipitate under stress at low temperature. Martensite is a brittle phase, being possibly magnetic. Further measurements of magnetic susceptibility of deformed specimens are planned to test the risk of stress-induced brittleness and/or magnetism at low temperature.

6. **CONCLUSIONS**

The results of magnetic and tensile tests at 4.2 K confirm that high N_2 - high Mn steels are nonmagnetic materials with excellent cryogenic mechanical properties. Because of their good weldability (with low or zero 3-ferrite content in TIG or EB welds) these steels are suitable for welded assemblies which must stay nonmagnetic at low temperature.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

[1] LHC Study Group, *Large Hadron Collider, The Accelerator Project,* CERN AC-93103 Document (1993)

[2] B. ANGERTH, F. BERTINELLI, J.C. BRUNET, R. CALDER, F. CASPERS, P. CRUIKSHANK, LM. DALIN, O. GROBNER, N. KOS, A. MATHEWSON, A. PONCET, C. REYMERMIER, F. RUGGIERO, T. SCHOLZ, S. SGOBBA and E. WALLEN, *The Large Hadron Collider Vacuum System,* paper presented at the Particle Accelerator and International Conference on High Energy Accelerators, Dallas, 1-5 May 1995

[3] T. HORIUCHI, R. OGAWA and M. SHEVIADA, *Cryogenic Fe-Mn Austenitic Steels,* Adv. Cryog. Eng. Materials 32 (1983) 33

[4] LP. BACHER and S. SGOBBA, *TIG Weldability of Special Stainless Steels for the Beam Screen of the Large Hadron Collider,* Bulletin du Cercle d'Etude des Métaux, 16 (1995) 13-1.

[5] M. COUACH, A.F. KHODER, *Ac Susceptibility Responses of Superconductors : Cryogenic Aspects, Investigation of Inhomogeneous Systems and of the Equilibrium Mixed State,* in : Magnetic Susceptibility of Superconductors and Other Spin systems, R.A. Hein et al eds., Plenum Press, New York (199 1).

[61 F.R. FICKE7IT, *Low Temperature Magnetic Behavior of Nonmagnetic Materials,* Adv. in Cryog. Eng. Materials 38B (1991) 1191

[7] R.P. REED, A.F. CLARK, *Materials at Low Temperatures,* Metals Park, Ohio (1983)

[8] Metals Handbook, 9th ed., vol. 3 (1980), page 759

[9] Y.Y. LI, S. CHAI, Y. XU, B. QUIAN, C. FAN, X. ZHAO, G. LLANG, M. WANG, The *Microstructure and Properties of a Cryogenic Steel Fe-21Cr-6Ni-9Mn-N,* Adv Cryog. Eng. Mat. 30(1983)237

[10] L.A.A. WARNES and H.W. KING, *The Low Temperature Magnetic Properties of Austenitic Fe-CrNi Alloys,* Cryogenics 16 (1976) 659-667

[11] Z.S. BASINSKI, *The Instability of Plastic Flow of Metals at Very Low Temperatures,* Proc. R. Soc. Lon.A,240(1957)229

[12] Z.S. BASINSKI, Aust. J. Phys. 13 (1960) 354