JACKET MATERIAL EVALUATION FOR NET'S

WIND-AND-REACT SUPERCONDUCTOR

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ABSTRACT

The inner poloidal field coils of the Next European Torus (NET) are planned to be built with a Nb₃Sn cable-in-conduit conductor. To meet the severe degradation in the superconductivity of Nb₃Sn due to strain effects the coils will be produced with the wind-and-react technique. High service loads together with the need for good ageability and weldability limit the number of possible jacket material candidates.

Eight Fe and Ni base alloys with promising strength and toughness properties were tested at EMPA within a screening program for their low temperature mechanical behaviour after a heat treatment of 50 h/700°C (base material and flash butt welded specimens). Stainless steels tend to embrittle by intergranular precipitations under these circumstances, whereas the ductility and formability of precipitation strengthening Ni base alloys may cause problems.

INTRODUCTION

The proposed conductor for NET's central solenoid coils, designed for operation with 40 kA at a peak field as high as 12,5 T, is given in Fig. 1. The NET Team has specified from the working stresses and in consideration of the special fabrication procedure of the coils for an ideal jacket material the following requirements:

- a) high yield strength (>1000 MPa) in base and weld at 4 K, tensile elongation >10%
- b) good cold working properties for jacket forming and coil winding
- c) excellent weldability
- d) good fracture toughness (>130 MPa $\sqrt{m}$) and fatigue strength
- e) suitable coefficient of expansion over a temperature range 1000 K - 4 K
- f) compatibility with the reaction schedule of Nb₃Sn, meaning that the properties of a) and d) can be guaranteed after a heat treatment of 50 h/700°C.

Previous works showed that usual stainless steels such as AISI 304, 304 N, 316 LN, can be degraded detrimentally by such a heat treatment; on the other hand an addition of small amounts of V or Nb tends to preserve a tolerable toughness after ageing ^{1,2}. A new developed Ni base alloy ("Incoloy 9XA") has been reported to fulfill the needs for a material with the mentioned specifications in an optimal way³.

To get more fundamental results to answer the question, which commercial alloys could meet the crucial mechanical requirements (points a, d, f) best and what metallurgical parameters influence the ageability most, a screening test program was set up, considering 5 CrNi(MoMn)N stainless steels, 2 Ni base and 1 Fe base alloys (all these three precipitation strengthening). Low temperature tensile and Charpy V-notch tests of base and flash butt welded material should give an idea of the change of the mechanical properties resulting from a treatment of 50 h/700°C; fractography and metallography would reveal the phenomena of possible embrittling and explain its microstructural reasons. The main interest was thereby focused on the base material properties of stainless steels, welding was considered only in secondary priority.

EXPERIMENTAL

Table 1 gives the composition of the 8 investigated alloys (all data by the materials suppliers).

Herein the steel S1 (316 LN + Nb) corresponds to the material described by Shimada/Tone², N1 to "Incoloy 9XA" (commercial designation "Incoloy 908"), N2 to "Inconel 728", whereas P1 is of the type described by Hiraga et al.⁴. S1, S2 and S3 correspond furthermore to the steels JK1, JKA1 and JN1 mentioned in a paper of Nakajima et al.⁵, whereas the ageing behaviour and RT properties of S5 were already described by Heimann⁶.

The content of impurities is in all alloys very low, namely below 0,005% for sulphur and below 0,026% for phosphorus; all alloys were produced with modern metallurgical procedures (ESR, vacuum treating etc.).

Fig. 1. Conductor assembly designed within a feasibility study for NET. The superconducting cable is situated in a jacket of a high performance structural material (stainless steel or Ni base alloy), that will be welded using drawn U-profiles.

Table 1. Chemical compositions of the investigated alloys
(S...stainless steels, N... Ni base alloys, P...
precipitation hardening Fe base alloy)

	C	N	Cr	Ni	Mo	Mn	Nb	V	Ti	Al	Fe
S1	0,010	0,17	17,2	12,3	2,0	1,2	0,05	-	-	-	rest
S2	0,023	0,268	25,0	14,0	0,68	0,49	-	0,30	-	-	rest
S3	0,026	0,34	24,2	14,7	-	4,2	-	-	-	-	rest
S4	0,019	0,17	17,9	13,1	2,6	1,9	-	-	-	-	rest
S5	0,016	0,33	22,3	16,5	3,2	5,9	0,18	-	-	-	rest
N1	<0,005	-	3,9	49,5	-	-	1,5	-	1,5	0,97	rest
N2	0,05	-	19,0	53,0	3,1	-	5,2	-	0,9	0,6	rest
P1	0,003	-	13,9	26,7	2,0	7,2	-	-	2,2	0,13	rest

(wt-%)

For the tensile tests at 4 K a special screw driven testing machine with regulated crosshead displacement and a capacity of 200 kN was used, equipped with a He cryostat and controlled with a IBM AT 03 PC. The strain measurement was done by two capacitance gauges, its rate equaled in the domain of interest $1,6 \cdot 10^{-4} s^{-1}$. The Charpy V-notch tests were done at 77 K only, because the temperature preservation cannot be guaranteed strictly at 4 K during the specimen handling and the testing procedure itself (deformation heat). As experience shows, the toughness data generally do not change very much though between 4 and 77 K; degradation by embrittling phases may eventually not be revealed at RT, but at 77 K the effects are undoubtedly recognizable, a fact that is clearly confirmed by Nohara et al.¹ and Shimada et al.⁷.

MECHANICAL TESTS

The results of the tensile and the Charpy V-notch are summarized in table 2 resp. graphically in Fig. 2.

Table 2. Summary of the cryogenic mechanical properties of the 8 alloys in the aged (50 h/700°C) state.
Averaged values from several measurements in the base (b) resp. flash butt welded (w) material.

	Rp0,2 (MPa), 4 K		Elongation (%), 4 K		Charpy impact value (J), 77 K	
	b	w	b	w	b	w
S1	994	1003	52	27	213	160
S2	1414	1458	7,6	2,7	19	9
S3	1501	1521	2,3	1,3	11	8
S4	1109	1120	48	27	161	63
S5	1714	1611	4,9	2,5	16	11
N1	1152	1076	31	18	57	31
N2	1403	1390	12	14	13	15
P	950	840	30	10,3	64	32

Apparently the toughness of all stainless steels is reduced by the ageing procedure in comparison with the state of delivery (annealed and partially with a low degree of cold work). In the other alloys (N1, N2, P), the heat treatment 700°C/50 h was used directly for precipitation strengthening and toughness in this state is somewhere in between the different stainless steels.

Considering that NET's specified fracture toughness of 130 MPa $\sqrt{m}$ corresponds to a Charpy energy of at least in the order of 50 to 100 J and that the needed elongation at 4 K was not or only hardly reached by S2, S3, S5 and N2 there are finally 3 alloys that can be designated as real jacket material candidates: S1, S4 and N1, whereas the yield strength of P1 drops under the limit, especially after the welding procedure.

DISCUSSION OF THE MECHANICAL RESULTS

A closer look to the chemical compositions in table 1 shows that the N content of the stainless steels lies between 0,17 and 0,34%, whereas C (content between 0,010 and 0,026%) seems to be negligible in comparison. This indeed holds for the yield strength, where in the corresponding Fig. 3 the influence on the N content is visible, thus also confirming the linear dependence in a formula for the mean values

$$R_{p0,2} = 300 + 4000 N$$

($R_{p0,2}$ in MPa, N in wt-%)

The main conclusion is, that with the exception of S3 the heat treatment affects the yield strength only in negligible extent.

Fig. 2. Yield strength at 4 K vs. Charpy impact value at 77 K in a graph, demonstrating with arrows a drastic degradation of toughness starting from the annealed (only stainless steels) to the aged state (first base then flash butt welded material)

Fig. 3. Yield strength at 4 K vs N content. Data from stainless steels S1 to S5, from literature^{1,2} and from unpublished additional investigations by EMPA; comparison between annealed and aged (50 to 75 h/700°C) state.

The situation is quite different for the Charpy toughness; the severe degradation is already visible in Fig. 2. A specific discussion is possible with the graphs of Fig. 4 presenting selected alloys with a limited span in the N content (0,15 to 0,20%), but a variation of the C content by a factor 3.4. It is obvious that the drop is mostly influenced by the carbon content, but can be reduced at least partially by additional alloying of carbide forming elements such as Nb and V, a fact that was already described by Nohara et al.¹ and Shimada/Tone².

PHYSICAL METALLURGY

All 8 alloys of table 1 were examined carefully by metallographical means (including electron microprobe) in all states (annealed, aged

Fig. 4. Drop of the Charpy impact value, measured at 77 K, in dependence of the time of an ageing process at 700°C. On the right side the corresponding the content of C, N and additional alloyed Nb or V is given in wt-%.

and welded), whereas the tensile and Charpy specimens were investigated at their fracture surface with the scanning electron microscope and partially (intergranular fractures) also with Auger spectroscopy. It was found, that with the exception of the precipitation hardening alloys P and N2 no intermetallic precipitations were detectable in the light microscope, but in the aged steels S2 to S5 a formation of intergranular precipitations was revealed, hardly visible and often only localized in the case of S2 and most pronounced at S3. Qualitative investigations of isolated precipitations (selective etching of the austenitic steel matrix) supports the theory that these consist mainly of $M_{23}C_6$ carbides⁸. Thus it can be concluded that an addition of the elements Nb and V in the case of S2 and S5 could not completely avoid its intergranular precipitations during the ageing, or at least a stabilizing procedure before, as it is described by Shimada et al.⁷ for example in similar steels, was not carried out in an optimal way and didn't render C innocuous.

Cold worked material showed not only precipitations at grain, but also at incoherent twins boundaries⁸. The fractographical investigation revealed that the steels S1 and S4 were the only ones that didn't break intergranularly. Thus the above mentioned poor toughness properties of the steels S2, S3 and S5 can also be correlated with the mode of fracture. Fig. 5 finally gives a three-dimensional graphical view, confirming that the weight of the C content is about ten times higher in its influence on the Charpy impact value than the N content.

The physical metallurgy of the precipitation hardening alloys will not be treated here any longer, for fundamental microstructural information on the alloy "Incoloy 9XA/908" the publication of Morra⁹ is recommended.

Fig. 5. Visualization of the dependence of the Charpy impact value, measured on aged (50 h/700°C) stainless steels at 77 K, on the content of the elements C and N. Some steels are stabilized with Nb or V. The high energies in this selected series of literature and EMPA data go along with transgranular fracture.

CONCLUSIONS

The low temperature toughness of CrNi(MoMn)N stainless steels aged for 50 h/700°C is strongly influenced by C content. Similar to the sensitization for the intergranular corrosion of austenitic steels after such a heat treatment the failure mechanism is correlated with the carbide precipitation at the grain boundaries. On the other hand the low temperature yield strength of these alloys is governed by the nitrogen content confirming the corresponding linear dependence in the annealed state as well as in the aged. Flash butt welding reduces especially the Charpy impact values, but not in dramatic manner. The influence of inclusions and their spacings, as described by Simon and Reed¹⁰, was not investigated within this study.

To fulfill the requirements of NET the N content should be adjusted at about 0,17% and that of C reduced below at least 0,020%; small amounts of Nb or V together with an optimized stabilizing procedure and an appropriate degree of cold work improving so the distribution characteristic of precipitations may lead to better results in the ageing behaviour.

The Ni base alloy "Incoloy 908" is to a certain extent limited in its ductility, but has a considerable potential because of its suitable expansion coefficient compared with the Nb₃Sn superconductors.

Detailed investigations planned for the near future on these two types of alloys will allow further conclusions.

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