Cryogenic Tensile and Fracture Properties of Structural Materials for Superconducting Magnets in Fusion Technology

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INTRODUCTION

The cryogenic materials needs for large high field superconducting magnets are severe due to the huge forces associated with the size. Todays design goals for the next generation on superconducting magnets, which will be needed in machines like NET (Next European Torus) or ITER (International Tokamak Experimental Reactor), have targets of ~16 meters coil outer diameter at a field of ≥ 12 Tesla (Toschi, R., 1988). So far, industrial available conventional austenitic chromium nickel stainless steels have been used as structural materials for magnet cases. A well known material from the AISI series 300 is the nitrogen strengthened 316 LN stainless steel. The dissolved nitrogen plays here a twofold role, firstly it increases the materials strength, especially in the cryogenic regime, and secondly it enhances the stability of the austenitic phase for 4 K applications. Several hundred tonnes of this steel have been used worldwide in the past for cryogenic machineries. The key structural characteristics are the materials toughness and the strength. The combination of these two parameters in form of toughness-strength data plots are well verified for conventional austenitic stainless steels, as given in Fig. 1. This Figure also shows the design specifications developed by the JAERI (Japan Atomic Energy Research Institute) for future tokamak machines. This specification aims for a toughness-strength combination, which is beyond todays capability of the existing industrial available stainless steels. However, if even one would be able to offer plate materials, meeting these future design goals, still questions concerning the materials weldability, weld metal toughness-strength relation, proper weld diagnostics and economics have to be answered. The present paper has the objectives to discuss the still existing gaps for the determination of materials strengths and toughness levels, to evaluate the state-of -the-art of particular cryogenic materials application for large superconducting magnets and to give indications towards new material designs.

INVESTIGATED MATERIALS

Many mechanical investigations carried out at 4 K were already part of the efforts undertaken during the manufacturing period of the Euratom coil of the IEA-LCT-project (Beard et al, 1988) and are now continued within the NET structural materials program. Table 1 gives the investigated materials and their specifications. The stainless steel of primary interest throughout these investigations was the nitrogen strengthened 316 LN type steel, which is designated with the German Werkstoff No. 1.4429 (Alloys A, B, C, D, G, H and I). Beside this material, the 4 K stress vs. strain behaviour of the alloys type 304 L (J), type 316 L (K), and a high nitrogen, commercial stainless steel (L) were subject of investigations.

The stainless steel 321 type (F) was used to determine the influence of a magnetic field on 4 K fracture toughness. In addition, a high manganese chromium stainless steel, provided as small quantity laboratory heat, was measured at 4 K with respect to its tensile properties. Alloy E is an optimized particular high manganese chromium austenitic steel selected with respect to the high strength cryogenic alloy development program.

For structural performance reasons the weld metals of several commercial heats were a key investigation issue, to establish a solid engineering 4 K data base. The alloys H and I are the different type of weldments of the plate material 316 LN (TIG and SMA welding). The TIG welding of the alloys 304 L and 316 L were also fabricated with the same TIG wire material as given by alloy I. This welding wire with 1.2 mm dia. was selected by a weld wire qualification program, where ten different wires of five vendors were subject of investigations. The test program for this check was the 77 K Charpy V-notch impact tests and the hot cracking susceptibility of the weld metal. Only weldments with a low hot cracking susceptibility and impact values above 150 Joules were selected. The chemistry of these investigated materials are given in Table 2.

METHODS OF TESTS

All cryogenic tensile and fracture toughness tests were carried out with a spindel driven commercial tensile testing machine of 200 kN load capacity. For the 4 K tests the cryogenic rig was immersed in a liquid helium cryostat of 400 mm diameter.

Tensile Tests

The 4 K tensile tests were carried out with cylindrical 60 mm long specimens. The reduced length was 30 mm with a diameter of 5 mm. The used cryogenic rig allowed to test four specimens individually after cool down in one run. The 4 K resolution of the used extensometers (each calibrated at 4 K) for displacement measurement is below 1 µm and fulfills the class B1 specifications according to the ASTM E-83 procedure. The high linearity ($< \pm 0,2\%$) coupled with the high resolution gave the possibility to determine the material's tensile Young's modulus. The tensile specimens were machined in T-L and L-T orientations. The specimens machined from welded samples covered in case of L-T orientation the fusion boundary of bulk metal and weld zone as well as the heat affected zone (HAZ). Therefore by placing the extensometers in the mid of the specimens reduced section (16 mm gage length) one could detect the weld/bulk properties including right and left HAZ positions. The T-L orientated weld specimens ensured the information of pure weld metal.

Fracture Toughness Tests

These 4 K tests were carried out with standard compact tension specimens of 63x60x15 mm^3 size. For the fracture tests a similar multispecimen testing unit were used as in the case of tensile tests. The fracture toughness determination was obtained by elasto-plastic J-Integral method using the multispecimen technique. For the determination of the influence of magnetic field on the fracture toughness at 4 K, a special cryogenic rig was designed, which could be placed in a 15 T split coil type Nb_3Sn superconducting magnet. The specimens were modified compact tension type with 48 x 47 x 10 mm^3 size, because of the small useable area given by the bore of the magnet.

RESULTS

The tensile properties of the tested materials (B, C, J, K, E and L) are given in Table 3. The data comprise wherever possible the result of two independent tests to give information about the materials homogeneity and the statistical scatter of the measurements. For the alloys of the series A, D, G and H the data are given in the papers (Nyilas et al, 1982 and Nagai et al, 1988). An analysis of the recorded stress vs. strain plots of the tested alloys at 4 K revealed that the serrations occuring during the tensile loading could be used to gain further information about the structural performance of the materials under test. The extensometers with the 16 mm gage length placed in the middle of the 30 mm long reduced section gave the possibility to classify the rapid unloadings as events which happens outside or inside the gage length. The Figures 2 and 3 show the original records of the welded materials (B) 4 K stress vs. strain behaviour. The serrations occured inside the gage lengths were coupled with registered discrete displacements with step lengths of up to 100 µm. The serration events of the weld metal (Fig. 2) show an uniform statistical unloading distribution along the reduced section, whereas the HAZ/weld-zone test (L - T) given in Fig. 3 show very clearly that the majority of the unloadings occur within the gage length. Here the fusion boundary seems to be the key controlling element for the serrations. On the other hand we see also that the onset of the serrations for the transverse L-T orientation are shifted towards smaller strain values ($\sim$1.7% compared to $\sim$6.5% strain in the case of T-L orientation). Responsible for this phenomena is the stiffness difference between the weldment and the bulk phase. The higher yield strength and the somewhat lower Young's modulus of the weldment determines the lower onset of the serrations and their accumulation at the vicinity of the fusion boundary. Table 4 shows the recorded onset position of the serrations at 4 K. Only the alloys with high nitrogen have higher onsets. The alloy K ($\sim$316 L) with its relatively high nickel content

(~14%) shows an intermediate onset range of ~4% strain. However, joining of the high nickel and high nitrogen containing materials with similar type weldments doesn't help much due to the dissimilar mechanical properties of the individual phases. The weld transverse orientation (L-T) is the weakest structural link and design should be concentrated to remove this regime from high stress fields. For structural applications the candidate material seems to be the material 316 LN (B,C). Materials with superiour yield strengths (E and L) have on the other hand lower elongations which may limit their structural use.

The above given tensile results coupled with the recently gained 4 K toughness data of the work (Nyilas et al., 1989) can be represented in the performance diagram (Fig. 1). As shown in Fig. 1 the nitrogen strengthened alloy 316 LN has a significant higher structural performance compared to conventional Cr-Ni austenitic stainless steels. In addition, with metallurgical refinement, which improves the microstructural properties a further increase of the toughness-strength behaviour can be expected as given in the case of the investigated forgings. The relatively high toughness variation of the alloy D is due to the high anisotropic behaviour of these forgings.

The 4 K toughness measurements carried out with the 321 type material (F) at high magnetic fields revealed a significant toughness drop of ~10% at 10 Tesla. This toughness reduction has been assumed to be related to the strain induced martensite, a ferromagnetic phase at the crack tip. This phenomena should be encountered in future structural applications. The degree of the ferromagnetism may control the decreasing level of the fracture toughness value.

CONCLUSIONS

For the cryogenic use of structural materials the following conclusions are applicable: 1. The candidate material for structural use is the stainless steel 316 LN. 2. The weld transverse orientation is the most critical structural part. 3. The rapid unloadings (serrations) during tensile loading at 4 K give information about the structural materials performance. 4. The onset of the observed serrations shifts to lower strain values with materials of lower performance. 5. High nitrogen, high manganese stainless steels with high yield strength values can be used for special cryogenic applications, but their elongation at fracture is low compared to the 316 LN material. 6. High magnetic fields affects inversly the fracture toughness behaviour of stainless steels probably due the ferromagnetic phase transformation.

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TABLE 1. Type and specifications of the investigated materials at 4 K

Alloy	Designated according to German Werkstoff No.	Materials specification
A	1.4429	50 mm thick plate material provided from LCT case fabrication. Heat No. 255139 (~316 LN)
B	1.4429	30 mm thick plate material. Heat No. 669560 NET structural mat. program
C	1.4429	Forging 4560 x 355 x 220 mm^3, Electro slag remelted/solution treated/Water quenched (LCT-coil-case)
D	1.4429	Forging ring, 358 mm thick, 825 mm o. dia./741 mm i. dia. Electro slag remelted, forged and cold expanded (~22%)
E	-	Cr-Mn-Ni-N stainless steel. Heat No. 764, high manganese austenitic program
F	1.6903	30 mm thick plate mat. (~321)
G	-	316 LN Japanese plate material, VAMAS* structural materials test program
H	1.4455	SMA weldment, 50 mm thick provided from LCT coil case fabrication
I	1.4465	TIG-weldment double half V-type joint, NET structural mat. program. Heat No. 760633
J	1.4306	Heat No. 61410, 30 mm plate mat., NET structural mat. program (~304 L)
K	1.4435	Heat No. 610240, 30 mm plate mat., NET structural mat. program (~316 L)
L	1.3964	High nitrogen austenitic commercial stainless steel 30 mm thick plate mat.

* VAMAS = Versailles Project on Advanced Materials and Standards

TABLE 2. Chemistry of the investigated stainless steel materials in weight %

Alloy	C	Si	Mn	P	S	Cr	Ni	Mo	N
A	0.032	0.41	1.26	0.016	0.016	16.7	13.7	2.68	0.16
B	0.023	0.34	1.50	0.028	0.003	16.8	12.6	2.60	0.17
C	0.020	0.24	1.60	0.026	0.017	17.6	12.6	3.03	0.17
D	0.021	0.54	0.97	0.019	0.006	17.6	13.9	2.70	0.17
E	0.040	0.06	27.8	0.004	0.006	13.9	4.80	-	0.30
F*	0.070	0.69	1.29	0.031	0.015	17.3	10.9	0.31	-
G	0.019	0.50	0.84	0.025	0.001	17.9	11.1	2.62	0.18
H	0.039	0.31	5.36	0.020	0.005	19.3	15.4	2.99	0.17
I	0.020	0.17	4.50	0.010	0.014	23.7	21.2	2.04	0.13
J	0.014	0.50	1.69	0.023	0.003	18.9	9.3	0.39	0.07
K	0.018	0.16	1.52	0.021	0.004	17.7	14.2	2.45	0.06
L**	0.03	1.00	4.50	0.025	0.010	20.0	16.0	3.30	0.30

* 0.43% Ti
** 0.20% Nb

TABLE 3. 4 K weld and bulk metal tensile properties of selected stainless steels for cryogenic use

Alloy	Mechanical Properties	Bulk material		Weld metal welded with alloy I	
		T-L	L-T	Weld centerline T-L	Weld transverse L-T
	σ_y MPa	932 , 926	988 , 988	1085 , 1095	1069 , 1079
B	UTS MPa	1507 , 1527	1527 , 1538	1416 , 1426	1360 , 1370
	EL %	42 , 41	40 , 36	33 , 26	23 , 29
1.4429	RA %	54 , 54	50 , 41	30 , 29	28 , 24
	E GPa	204 , 205	203 , 206	170 , 190	205 , 205
	σ_y MPa	906 , 948	1038 , 1040	-	-
C	UTS MPa	1426 , 1497	1446 , 1441		
	EL %	38 , 41	33 , 31		
1.4429	RA %	50 , 54	42 , 42		
	E GPa	203 , 204	205 , 204		
	σ_y MPa	410 , 428	468 , 460	1049 , 1049	621 , 800
J	UTS MPa	1578 , 1619	1589 , 1537	1355 , 1395	1344 , 1324
	EL %	43 , 47	46 , 44	28 , 41	32 , 31
1.4306	RA %	54 , 51	51 , 51	23 , 29	45 , 29
	E GPa	204 , 205	196 , 208	202 , 206	206 , 193
	σ_y MPa	626 , 646	652 -	1049 , 1049	825 , 855
K	UTS MPa	1334 , 1314	1314 -	1355 , 1344	1324 , 1242
	EL %	50 , 47	47 -	28 , 26	33 , 25
1.4435	RA %	59 , 62	51 -	18 , 22	26 , 19
	E GPa	197 , 207	206 -	183 , 197	200 , 194
	σ_y MPa	1463 , 1557			
E	UTS MPa	1758 , 1831			
	EL %	25 , 19			
C-764	RA %	44 , 40			
	E GPa	198 , 195			
	σ_y MPa	1345 , 1339 , 1385			
L	UTS MPa	1731 , 1711 , 1742			
	EL %	25 , 25 , 24			
1.3964	RA %	42 , 37 , 39			
	E GPa	204 , 205 , 206			

TABLE 4. Onset of serrations given in % strain

Alloy	Bulk material		Weld metal welded with alloy I	
	T-L	L-T	Weld centerline T-L	Weld transverse L-T
B	8.1 ; 8.1	9.1 ; 7.9	6.6 ; 6.5	1.7 ; 1.6
C	6.5 ; 6.3	9.4 ; 10	-	-
J	2.2 ; 2.4	1.3 ; 1.5	3.4 ; 5.2	0.4 ; 0.6
K	3.9 ; 4.1	4.0 ; -	6.9 ; 6.6	0.7 ; 0.7
L	9.5 ; 9.6 ; 7.8	-	-	-
E	8.9 ; 7.5	-	-	-

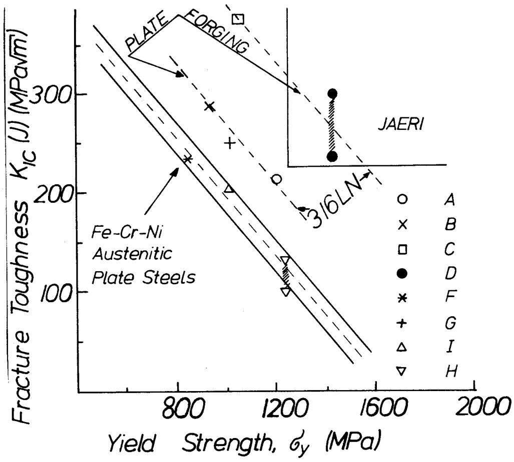

Fig. 1. 4 K toughness-strength relation of nitrogen strengthened stainless steels.

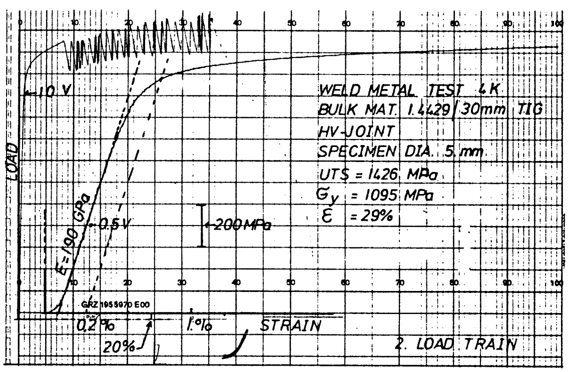

Fig. 2. 4 K stress vs. strain record of weld metal (~316 LN). Specimen consists of purely weldment and is machined in weld longitudinal direction (T-L). Strain rate $\sim 3{\cdot}10^{-4} s^{-1}$.

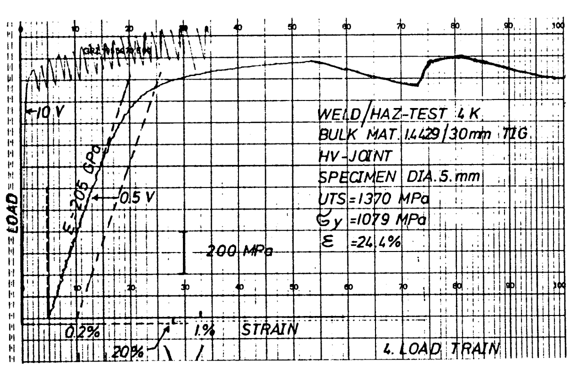

Fig. 3. 4 K stress vs. strain record of weld/HAZ test. Specimen consists of weldment, HAZ and bulk material and is machined in weld transverse direction (L - T). Strain rate $\sim 3{\cdot}10^{-4} s^{-1}$.