

The 4 K Tensile and Fracture Toughness Properties of a Modified 316LN Conduit Alloy

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The 45-T Hybrid magnet will employ Cable-In-Conduit Conductor (CICC) technology for the windings of the Nb₃Sn and NbTi coils. The conduit steel must retain high strength and fracture toughness at 4 K, following the Nb₃Sn reaction heat treatment. The design requirements call for a 4 K yield strength exceeding 1000 MPa and a 4 K fracture toughness (K_{Ic}) greater than 110 MPa m^{-0.5}. We report the mechanical properties of a commercial 316L alloy and modified version of 316 LN with extremely low carbon content, before and after a simulated Nb₃Sn reaction heat treatment. The related effects of prior cold work are also reported.

INTRODUCTION

Large superconducting magnets often employ Cable-In-Conduit Conductors (CICC). In the CICC conductor geometry a superconducting cable is enclosed in a steel conduit which serves the dual purposes of distributed structural support and containment vessel for force-flowing liquid helium. The CICC concept can be employed for both NbTi and Nb₃Sn superconductors, but in the case of Nb₃Sn, the brittleness of the A-15 superconducting phase requires that the wire be inserted into the conduit prior to the reaction heat treatment. Typically this heat treatment involves exposure to temperature up to 750°C for tens of hours. The 300 series alloys are favored by some magnet designers due to their extensive 4 K mechanical and physical properties data base and predictable fabrication and processing characteristics. They, however, are susceptible to a loss of fracture toughness when subjected to Nb₃Sn reaction heat treatments. This loss of toughness is associated with precipitation of grain boundary carbides, a process referred to as sensitization.

The loss of low temperature toughness following sensitization has been well documented. Low temperature Charpy impact values for heat treated stainless steels have been reported by Nohara, et al. and Reed, et al. [1, 2] Both Shimada and Tone, and Muster and Elster have reported 4 K fracture toughness values for several heat treated alloys including 304 LN and 316 LN steels with standard and modified compositions. [3, 4] Kübler, et al. have reported 77 K Charpy impact data for several alloys over a large heat treatment matrix as well as 4 K fracture toughness for a limited number of heat treatments. [5]

The superconducting wire selected for the 45-T Hybrid Magnet will be given an abbreviated heat treatment as short as 21h/ 210°C + 5h/ 340°C + 40h/ 625°C. Previous investigations austenitic steel sensitization have concentrated on the higher temperatures and longer times. Kübler did cover the times and temperatures of interest to Hybrid, however, the

fracture toughness was estimated from 77 K Charpy impact tests [5].

Table 1. Composition of the stainless steels in weight percent, the balance is iron.

Steel	C	N	Mn	Si	P	S	Cr	Ni	Mo	Nb+Ta
316L	0.012	0.05	1.2	0.43	0.021	0.004	16.44	10.29	2.1	--
316LN	0.010	0.21	1.53	0.26	0.011	0.005	16.91	13.75	2.32	0.11

Table 2. Test material metallurgical conditions.

ALLOY	Material Condition	
316L	1	Annealed (as rec'd)(@295 K,gs=150 μm YS =296 MPa, TS=589 MPa)
	2	Ann. + H.T. 1 (Aged at 340 C for 48h + 625 C for 70 h in Argon)
	3	20% Cold Worked
	4	20 % C.W. + H.T. 1 (Aged at 340 C for 48 h + 625 C for 70 h in Argon)
316LN Mod.	1	20%CW(as rec'd),(@295 K,gs=17 μm , YS =438 MPa, TS=754 MPa)
	2	20 % C.W. + H.T. 1 (Aged at 340 C for 48 h + 625 C for 70 h in Argon)
	3	20%CW + H.T. 2 (Aged 700 C for 100h)

EXPERIMENTAL PROCEDURE

The first of two alloys reported here, a commercial heat of AISI 316L is investigated to address preproduction process variables of the 45-T Hybrid conduit. The second is the modified AISI 316LN conduit alloy for the Nb₃Sn conductor for the Hybrid Magnet. The alloy compositions are shown in Table 1. The 316L alloy is received in a hot rolled and annealed plate form (25 mm thick) and is tested in the four metallurgical states that are shown in Table 2. The 316L plate is machined to about 14 mm thickness before cold rolling to a uniform reduction in thickness of 20 %. The modified 316 LN is received in a cold worked (around 20 % C.W.) plate form, approximately 3 mm thick and is investigated in three metallurgical states also shown in Table 2. The as received condition of the both alloys are verified with 295 K tensile measurements shown in Table 2 along with estimated average grain size. Heat treatment 1 is selected as it is the upper range of times and temperatures expected for reacting the Nb₃Sn Hybrid magnet coils. Age heat treatment 2 (H.T. 2) is selected to verify the 316LN performance after a more severe heat treatment.

Tensile specimen's axes are transverse to the rolling direction (T orientation). The (CT) specimens are oriented with the crack direction parallel to the rolling direction (TL orientation). Following heat treating, the (CT) specimens are fatigue precracked at 77 K.

Samples are tested at 4 K in liquid helium using a 100-kN capacity test system. Tension test were conducted according to ASTM Standard Test Method E 1450-92. For the tensile test a strain rate of $2 \times 10^{-4} \text{ s}^{-1}$ is employed. Strain was measured using clip-on style extensometers. Fracture toughness tests were performed using J-integral methods according to ASTM Standard Test Method E 813-81.

RESULTS

The results of mechanical properties measurements are shown in Table 3. The 4 K results are the average of at least 2 tests. The high 4 K yield strength of the 316LN alloy is the result of its high nitrogen content. For the 316L alloy, the effect of cold work is nicely shown with a twofold change in both tensile and fracture properties. The 4 K yield and tensile strengths

increase, with the introduction of 20 % C.W., while the fracture toughness decreases by about the same factor. The results are plotted in Figure 1 as Yield Strength vs. Toughness along with the NIST trend line for comparison [6]. The 316 L alloy falls slightly below the trend line and the effect of C.W. is shown as a shift of the data

Table 3. The 4 K mechanical properties tests results

ALLOY	Material Condition	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Fracture Toughness (MPa*m ^{0.5})
316L	Annealed	485	860	37	260
	Ann + aged H.T. 1	460	845	35	232
	20% CW	1006	1734	35	117
	20%CW + H.T. 1	843	1722	35	111
316LN	20% CW	1284	1648	28	159
Mod.	20%CW + H.T. 1	1326	1677	31	133
	20%CW + H.T. 2	1202	1586	26	90

H.T. 1 = 340° C for 48 h + 625° C for 70 h in Argon

H.T. 2 = 700° C for 100 h in Argon

parallel to the trend line. The effect of aging is to shift data away from the trend line indicating degradation of the quality of the alloy.

The aging H.T. 1 has little effect on the tensile and fracture properties of these alloys. The greatest exceptions to this are a 16 % decrease in the yield strength of the 316L C.W. condition and a 16 % decrease in the toughness of the 316LN. Aging H.T. 2 adversely affects the fracture toughness of the 316LN with a more than 40 % decrease in toughness while having little effect on tensile strengths (less than 10 % decrease).

DISCUSSION

The results obtained from these alloys indicate that short term low temperature heat treatment to be used for the Hybrid Nb₃Sn coils, does not cause a dramatic decrease in the fracture toughness. There is a relatively large decrease in the toughness (43 %) after the higher temperature H.T. 2 of the 316LN. This trend is similar to that observed by Kübler, et al. who showed that 77 K Charpy impact values do not fall appreciably until heat treatment temperatures and times reach 675°C and more than 100 hours [5].

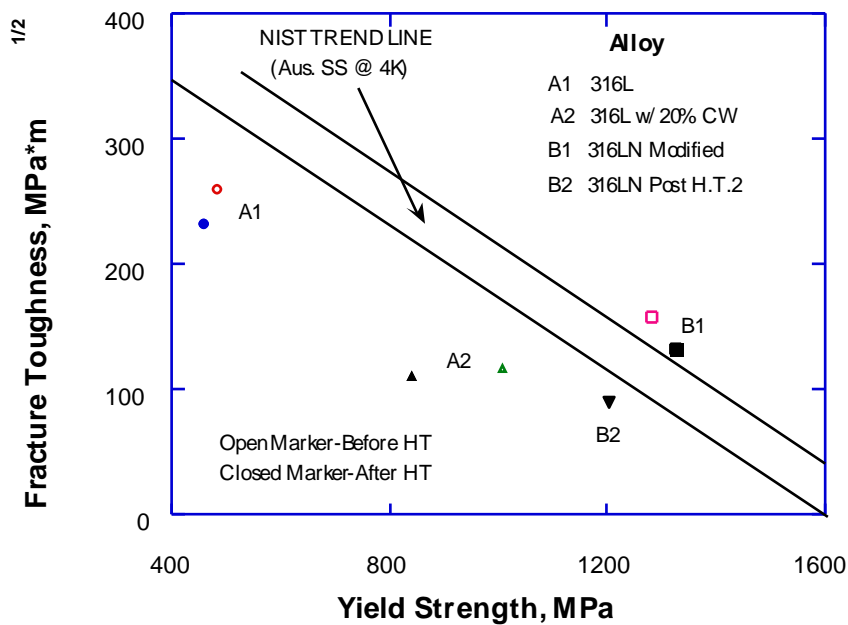


Figure 2. The 4 K yield strength vs. fracture toughness of the alloys studied plotted along with the NIST trend line for austenitic steels.

The aging heat treatment (H.T. 1) appears to have distinct effects on the two alloys which we attribute to the higher nitrogen content of the 316LN. There is a decrease in yield strength, and relatively unchanged toughness, of the 316L after H.T. 1 which is likely attributable to an annealing/ recovery effect. There is a slight increase in yield strength of the 316LN and an associated decrease in toughness after H.T. 1, which may be the result of precipitation of carbonitrides which provide strengthening.

CONCLUSIONS

The proposed Nb₃Sn reaction heat treatments, for the NHMFL 45-T Hybrid magnet that use temperatures near 600°C and times of less than 100, hours do not have a marked influence on the cryogenic fracture toughness these 316 alloys. The introduction of 20 % C.W. in the 316L alloy causes a predictable decrease in toughness from work hardening. The influence of C.W. with respect to embrittlement, after aging at the low temperature heat treatment is not detrimental. The higher temperature, longer time heat treatment, of 700°C for 100 hours, significantly degrades the fracture toughness of the modified 316LN alloy. The mechanism for the toughness reduction has not been fully studied but is at least partially attributed to increased intergranular brittle fracture, caused by precipitate formation at the grain boundaries.

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