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MECHANICAL PROPERTIES OF MODIFIED JK2LB for Nb3Sn CICC APPLICATIONS

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ABSTRACT

Since the introduction of the cable-in-conduit conductor (CICC) concept, a variety of alloys have been proposed for fabricating the conduit in high field magnets. The conduit provides containment of the liquid helium coolant and is typically also the primary structural component for the magnet coils. These functions create requirements for strength, toughness, fatigue crack resistance, and fabricability. When the CICC uses Nb3Sn superconductor, the conduit alloy must retain good mechanical properties after exposure to the superconductor's reaction heat treatment. Here we present data from cryogenic tensile, fracture toughness, fatigue crack growth rate, and axial fatigue tests for a modified heat of JK2LB, before and after the exposure to the reaction heat treatment. The alloy is presently being considered as a candidate for use in ITER Central Solenoid (CS) Coils. The direct comparison of the data from the comprehensive test program with earlier versions of JK2LB and another CICC candidate alloy (modified 316LN) is intended to assist design engineers with material selection for CICC applications.

KEYWORDS: Cryogenic**,** Fatigue Crack Growth, Fracture Toughness, Axial Fatigue, Yield Strength, Conduit, CICC

INTRODUCTION

JK2LB is a high-manganese austenitic steel, developed by the Japan Atomic Energy Agency (JAEA) and Kobe Steel, which is proposed for use as the conduit alloy in the ITER Central Solenoid. The steel is low thermal expansion alloy developed for Nb_3Sn CICC applications [1]. Chemistry optimization designed to improve mechanical properties [2,3] has resulted an optimized grade with lower nitrogen content that meets the CS mechanical property specifications. Prototype CS conduit made with JK2LB, produced by JAEA, was used here for in-situ materials characterization program. The objective is to confirm

Table 1: JK2LB chemistry in wt.%

Alloy	C	Si	Mn	P	S	Cr	Ni	Mo	N	B	Fe
Specification	<0.03	<0.5	20.5-22.5	<0.015	<0.015	12.0-14.0	8.0-10.0	0.5-1.5	0.09-0.15	0.001-0.004	Bal
Present Conduit	0.025	0.41	21.42	n/a	0.002	11.93	8.43	0.78	0.119	0.0013	Bal
Billet A [3,6]	0.023	0.28	21.0	0.005	0.002	12.8	9.3	1.0	0.24	0.0017	Bal
Billet B [3]	0.032	0.35	20.9	0.008	0.003	12.68	9.25	0.98	0.20	0.0038	Bal
Hamada et al.[5]	0.013	0.26	21.8	0.007	0.002	12.8	9.25	0.98	0.12	0.0036	Bal

production grade properties in, the as near-to in-service conditions as probable. The conduit is required to have 4K yield strength >1000 MPa, a fracture toughness > 130 MPa*m^0.5 and a fatigue life of 60,000 cycles, in a process state that consist of prior cold work and post–aged thermal treatment.

In order for the chemistry modified version to be used in the CS coils there must be a supporting mechanical properties database and the material tests performed here significantly increase the available database [3] for the low nitrogen content version of JK2LB. The elastic properties such as thermal expansion, modulus, and magnetic properties for the prototype conduit material tested here have been reported previously [4].

MATERIAL INFORMATION

The seamless CS conduit developed by Japan Atomic Energy Agency (JAEA) in collaboration with Kobe Steel Co. is hot extruded to slightly oversized dimensions to facilitate cable insertion during actual coil manufacturing. Final compaction is performed cold, to reduce the conduit's nominal dimensions about 2 to 2.5 mm, which adds residual stress, which could influence the final aged conduit properties. Two 1m long sections of the round-hole in square-tube, conduit (shown schematically in figure 1) were received at NHMFL in the compacted state (As-Received (AR) state), which is the production state of the conduit prior to exposure to the Nb_3Sn reaction heat treatment. The aged condition (AG) is accomplished by aging the conduit at 650C/200h in an Argon atmosphere. This represents the final step of the Nb_3Sn reaction heat treatment that the conduit alloy must endure. The post-aged condition has nominal grain size of approximately 100 µm. Note; the conduit sections tested here do not contain additional stress that is introduced during the coil winding process.

The material chemistry is shown in Table 1 along with the target chemistry and three other chemical compositions of prior versions of JK2LB that have been tested [3,5,6]. The composition of material tested here is similar to the version tested previously in [5] but with higher carbon and lower boron. The earlier versions of JK2LB [3,6] that have higher nitrogen content (> 0.2%) experience a loss of ductility in the CW + Aged condition. The reduction in nitrogen levels to < 0.13% appears to be effective in helping the CW+Aged condition of the alloy retain ductility and toughness.

TEST PROCEDURES

The material's AR and AG conditions are evaluated with specimens removed from the conduit, as shown in Figure 1, using electro-discharge machining (EDM) fabrication. Residual stress and material property variability are addressed with axial and transverse oriented specimens positioned throughout the wall thickness. AG specimens are removed from conduit sections after the aging heat treatment. All the tests are conducted on a 100 kN capacity MTS machine equipped with a cryostat to enable testing at 4 K with the test

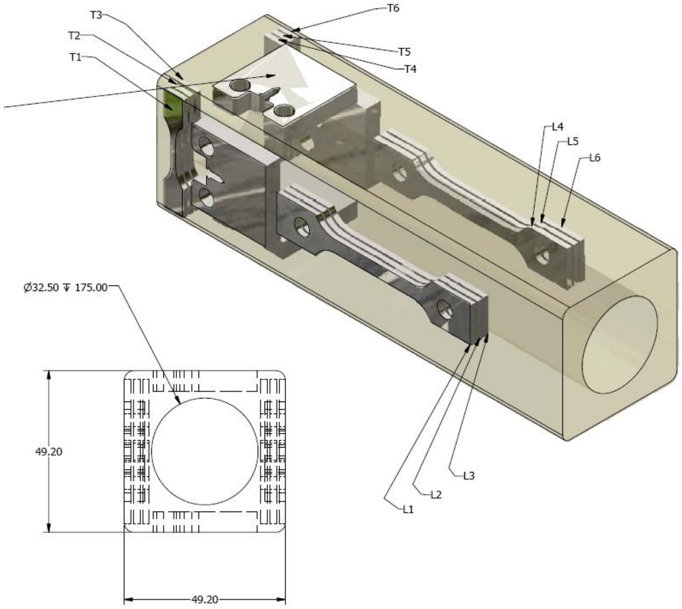

Figure 1. Schematic showing location of specimen removal from the conduit section.

specimen and fixturing immersed in liquid helium. The properties of the two conduit sections are evaluated at three locations along conduit lengths in order to randomly sample the available material more effectively.

Tensile tests are conducted in displacement control at a rate = 0.5 mm/min according to procedures prescribed in ASTM E8 and E1450. The longitudinal tensile specimens (axis parallel conduit axis) have a 33 mm gage length while the transverse samples are shorter with a 16 mm gage length. Strain is measured with a 10% strain range clip-on extensometer.

For fatigue crack growth rate (FCGR) tests and J-integral (J_{IC}) fracture toughness tests, dual-purpose specimens (Figure 1) were used. The 0.5 CT specimens are machined with a short notch (7 mm), after 2mm crack initiation at 77 K, FCGR tests are conducted at 4 K for approximately 6 mm of crack extension (from 9 to 15 mm) or a/W ratio = 0.6. Specimen orientation is defined by two letters, TL or LT, the 1st designates direction of applied force and the 2nd defines the crack direction. FCGR tests are conducted according to the guidelines in ASTM E647 using either the constant ΔP method or decreasing ΔK method. The J_{IC} tests are conducted according to the guidelines provided in ASTM E1820.

Force-control axial-fatigue tests are used to generate cyclic stress vs. cycles to failure data (S-n curves). The 4 K tests are performed according to the guidelines in ASTM E466 for 295 K tests. Figure 1 shows the constant-radius fatigue test specimen geometry used. The tests parameters are sinusoidal tension-tension fatigue cycle, frequency f = 20 Hz, R-ratio (P_{min}/P_{max}) = 0.1. The subscale specimens tested here are ASTM proportional with a couple of exceptions. The exceptions, probably negligible, are; the test section area is smaller than recommended, and ratio of width to thickness is 1.5, (recommended minimum is 2).

RESULTS and DISCUSSION

Residual Stress Evaluation

The 295 K tensile results shown in Table 2 for the AR material show a yield strength gradient through the wall thickness which is attributed to strain hardening from the

Table 2: 295 K Tensile Results.

Specimen No.	Yield Strength (MPa)	Tensile Strength (MPa)	Elong. in 25 mm (%)	Red. Area (%)
AR-L1	438	627	51.4	74.2
AR-L2	420	601	62.2	73.9
AR-L3	432	595	65.1	76.8
AR-L4	416	599	59.3	75.7
AR-L5	430	608	54.0	77.7
AR-L6	562	642	36.8	69.8
AR Average	450	612	55	75
AR Stdev	55.6	18.6	10.2	2.8
AG1-L1	404	599	55.2	74.1
AG1-L2	388	605	52.4	72.1
AG1-L3	388	609	53.4	73.1
AG Average	393	604	54	73
AG Stdev	9.24	5.25	1.43	0.99

prior forming operations. The shaping and compaction tends to work harden the outer surface more than the inside. One would expect symmetry of the strength measurements as the thickness is traversed, but there is a significant difference in the measured yield strength for the opposing outside-surface specimens AR-L1 and AR-L6, which is not fully understood. A possible explanation is that post-compaction straightening of the conduit may have occurred before receipt of the material at NHMFL. Nevertheless, this variation in yield strength isn't present in tests of the aged material, indicating stress relief from the heat treatment. Although tensile tests of the AG material do not exhibit the through thickness yield strength gradient, they do indicate a 13% decrease in yield strength compared to AR material (AR avg. YS = 450 MPa, AG avg. YS =393 MPa). The reduction in yield strength is further indication that the aging heat-treatment has the effect of relieving the residual stress caused by conduit forming operations.

4 K Tensile Properties

The 4 K tensile results are summarized in Table 2. The alloy performance with respect to CS coil design is the highlighted row of 4K data for the L orientation in the Aged condition. Here we can see the material has acceptable yield and tensile strengths and retains good ductility after aging. There is little data scatter in the results from the nine tests of specimens from three different locations within the 2 meters of conduit length. The strength and ductility of the aged material is very consistent and in good agreement with those reported by Hamada et. al. [5] on modified JK2LB with similar chemistry and processing, (YS = 1005 MPa, TS = 1375 MPa and elong. = 47%).

Table 2: Summary of Tensile Results.

Temp	Spec. Orientat'n	Condit'n	Yield Strength (MPa)	Yield Std Dev (MPa)	Tensile Strength (MPa)	TS Std Dev (MPa)	Elong. in 25 mm (%)	Reduct'n of Area (%)	No of Tests
295	L	AR	450	56	612	19	55.0	75.0	6
295	L	AG	393	9	604	5	54.0	73.0	3
4	L	AG	1006	20	1414	22	46.0	39.0	9
4	T	AR	1015	77	1391	13	40.3*	44.9	3
4	T	AG	1063	3	1397	19	37.9*	37.5	3

* T sample elongation is for 16 mm gage length

Table 3: 4K Fracture Toughness Test Results

Condition	Spec No. Orientation	Kic(J) MPa*m^0.5	Kic(J) Avg. MPa*m^0.5
As Received	LT-1 LT-2	290 >270	280
As Received	TL-1 TL-2	157 152	154
Aged	TL-1 TL-2	161 174	167

4K Fracture Toughness Results

The fracture toughness results (Table 3) indicate that the aged material has good toughness (TL Average =167 MPa*m^$^{0.5}$) and that the toughness improves after the aging heat treatment compared to the AR material (154 MPa*m^$^{0.5}$). The small improvement in fracture toughness may be related to the aging heat treatment residual stress relief, mentioned above in the 295 K tensile results. The toughness recorded here is lower than the > 200 MPa*m^$^{0.5}$ reported for compacted and aged condition by Hamada et. al. [5]. In both cases the specimen is oriented with the crack plane parallel to the conduit axis which yields more conservative design data. The ~15 % lower toughness measured here is not considered significant due to the difficulty in performing valid 4 K fracture toughness tests and the limited number of tests to be compared (2 for each case). In addition, the alloy tested here is different and has slightly different chemistry with a higher carbon content and lower boron content. Importantly, these tests confirm that the low nitrogen content version does not become brittle after exposure to the reaction heat treatment. The fracture surface in the J-test tearing region for the AR and the AG conditions are shown in Figure 2. At the magnifications observed, there is no obvious distinction between the two, supporting the idea that fracture properties are insensitive to the aging heat treatment. The fracture surfaces on both exhibit very similar transgranular fracture appearance with ductile dimple features. There are small inclusions present in the bottom of some dimples, which probably act as fracture initiation sites. The inclusions are present, before and after aging, and their size does not appear affected by the heat treatment.

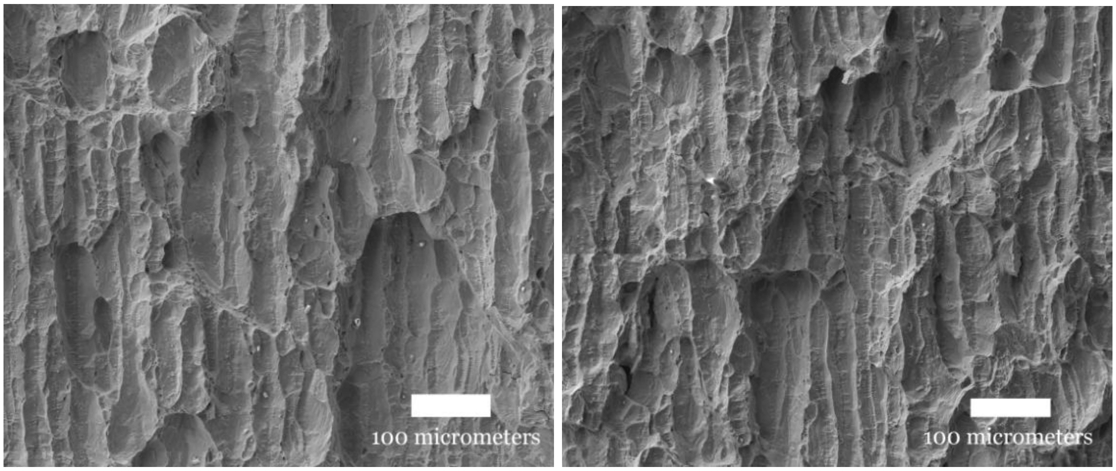

Figure 2. J test fracture surfaces, crack growth direction is vertical, AR condition is on the left and AG condition is on the right side.

Table 4: 4 K FCGR Test Results

Specimen No.	Paris Eqn Parameter*	
	C	n
AR-LT-1	1.19E-09	3.27
AR-LT-2	2.12E-10	3.76
Avg AR-LT	5.24E-10	3.50
AR-TL-1	4.84E-11	4.16
AR-TL-2	9.24E-10	3.42
Avg AR-TL	6.08E-10	3.50
AG-TL-1	6.42E-10	3.52
AG-TL-2	6.80E-10	3.50
Avg AG -TL	6.44E-10	3.52

* FCGR units (mm/cycle, MPa*m^0.5)

Fatigue Crack Growth Rate

The FCGR results are shown in Table 4 and Figure 3. The measured crack growth rates are very consistent for the AR and AG conditions and there is little effect of crack orientation. For clarity, the results shown in the graph are calculated data based on the experimentally determined Paris parameters. The average parameters of two tests for each are calculated by combining the data and performing linear regression analysis.

Research on the 4 K fatigue crack growth rates of alloys used in superconducting magnets has focused mainly on 316 austenitic steels and there is a range of properties published in the literature. The upper and lower bounds for the range of crack growth rates found in the literature [7,8] for aged 316LN intended for CICC applications are plotted in Figure 3 for reference. Previously published FCGR measurements for the higher nitrogen content (0.24 and 0.2 %) JK2LB published in [2,6] are also shown on the same plot are in good agreement with each other but quite different from the current measurements. More recent measurements on the 0.12% nitrogen version [5] of JK2LB, are in better agreement

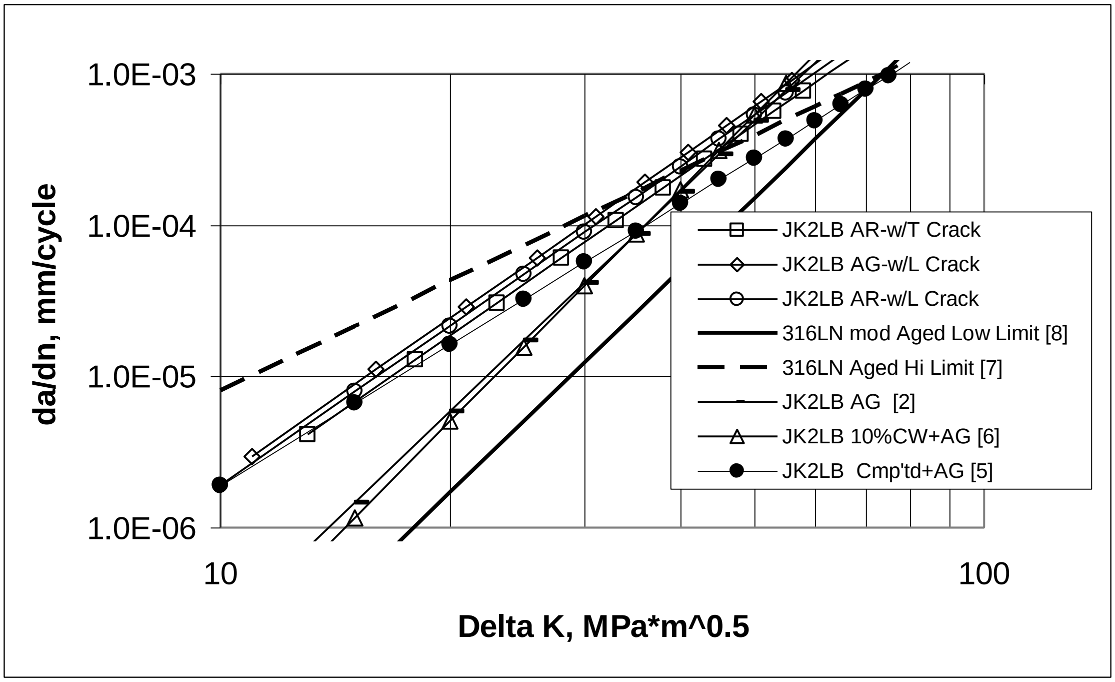

Figure 3. Graph of FCGR data and reference data for comparison.

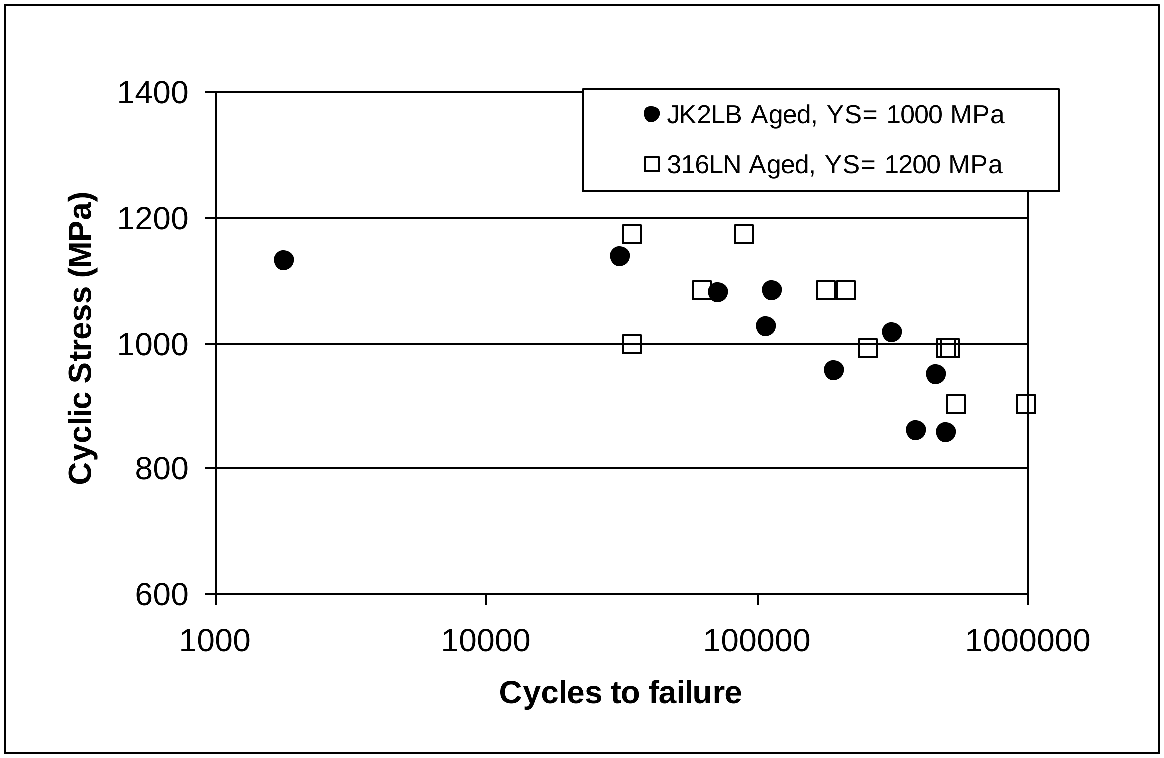

Figure 4. Graph of axial fatigue data for JK2LB and 316LN modified [9] reference data for comparison.

with the data here, but still exhibits a different slope. Obviously, the FCGR is dependant on metallurgical and materials processing parameters and more work should be done to understand the importance of the parameters that affect the crack growth mechanics.

Axial Fatigue (S-n) Results

The fatigue test results are shown in Figure 4 along with fatigue data from CW + Aged 316LN modified [9] for comparison. There is limited 4 K fatigue data available in the literature for comparison and the data generated here and in [9] represent a significant addition. The data presented here are for the R-ratio of 0.1 and test frequency of 20 Hz. The fatigue test elastic strain rate is about 2E-1 strain*sec^{-1} which is considerably faster than the strain rate used to determine the 4 K yield strength 2e-4 strain*sec^{-1}. Conceivably, high stress fatigue tests where plastic flow is present may not yield conservative design data since flow stress is strain dependant. The specimen behavior is regular during testing and no obvious discontinuous yielding is observed that would signify a temperature rise in the specimen. The good agreement of the two data sets (JK2LB compared to 316LN modified) is interesting since they have significantly different yield strengths.

CONCLUSIONS

An optimized grade of JK2LB, with nitrogen content ~ 0.12 %, has undergone a comprehensive 4 K mechanical properties characterization to generate data for the ITER Central Solenoid design. The 4 K yield strength and fracture toughness exceed the ITER-CS coil requirements of yield strength >1000 MPa, and fracture toughness > 130 MPa*m^$^{0.5}$. Concerns about post-aged, low ductility and low fracture toughness, noticed in the prior higher nitrogen versions of the alloy, appear to be resolved in the optimized version as there was no post-aged degradation of fracture toughness or tensile elongation. The FCGR measured here is higher than previously published for JK2LB but in relatively good agreement with the similar chemistry version tested in [5]. The axial fatigue properties of the alloy and are plotted as an S-n curve that provides a limited database that should be bolstered before using for design.

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