Tensile and fatigue qualification testing of ITER-CS conduit alloy JK2LB

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Abstract. The ITER Central Solenoid (CS) coils utilize cable-in-conduit conductor (CICC) and the conduit alloy is JK2LB. The production grade conduit alloy (and it’s welds) must meet strict requirements for strength, toughness, fatigue crack resistance, and fabricability. The conduit alloy must retain good mechanical properties after additional fabrication steps such as welding, coil winding strain and exposure to the Nb3Sn superconductor’s reaction heat treatment. Here we present data from cryogenic tensile, fracture toughness, fatigue crack growth rate, and axial fatigue tests of JK2LB alloy and conduit butt welds, before and after the exposure to the reaction heat treatment. The tests of specimens removed directly from the conduit provide confirmation of the materials properties and the effect of the cold work and aging. The 4 K fatigue performance is extremely important to the reliability of the CS and is covered both by axial cyclic fatigue tests and the fatigue crack growth rate measurements.

1. Introduction
JK2LB is a high-manganese austenitic steel, developed by the Japan Atomic Energy Agency (JAEA) and Kobe Steel, which has been selected for use as the conduit alloy in the ITER Central Solenoid. The steel is a low thermal expansion alloy developed for Nb₃Sn CICC applications [1]. The alloy has a carefully controlled chemistry and microstructure in order to obtain the desired mechanical properties.

The goal of this characterization program is to bolster the existing database for JK2LB and increase the understanding of the material’s structure and performance in addition to qualification testing to satisfy the basic minimum requirements.

2. Summary
Production grade conduit material was supplied by ITER to NHMFL in the compacted state for qualification testing reported here. Additional processing (cold work and heat treatment) of about (10) 1 m lengths of conduit are performed at NHMFL for characterization tests the production grade of JK2LB in the as-near-to in-service condition as possible.
At 295 K, the base and weld metals must have minimum yield strength (YS), tensile strength (TS) and elongation of 300 MPa, 550 MPa and 30% respectively. The conduit undergoes fabrication steps during magnet construction (welding and deformation processes) that affect the mechanical properties and are included for the qualification testing. The properties of the annealed conduit prior to the magnet processing steps are supplied by the manufacturer - KOBE Steel, (YS = 332 MPa, TS = 569 MPa and Elong. = 45%). Here we investigate how the addition of cold work, welding and an aging heat treatment influence the strength, ductility, and fatigue performance of the conduit. The 295 K tests of the conduit- base and weld metal, in the as-near-to in-service condition, confirm a change in 295 K properties with the NHMFL measurements of (base, weld); (YS = 435 MPa, 466 MPa), (TS = 618 MPa, 619 MPa) and (Elongation = 44%, 34%).

At 4 K mechanical properties specification includes a fracture toughness requirement in addition to the tensile specification. The 4 K requirements are for the conduit to have minimum YS > 850 MPa, TS > 1150 MPa, Elongation > 25%, and $K_{IC} > 130$ MPa*m$^{0.5}$. Tests of the conduit base metal and welds, in the as-near-to in-service condition, results in average 4 K properties of (base, weld); (YS =1076 MPa, 1031 MPa), (TS = 1456 MPa, 1432 MPa), (Elongation = 42%, 34%) and ($K_{IC} =175$ MPa*m$^{0.5}$, $K_{IC} =244$ MPa*m$^{0.5}$), which easily satisfy the ITER requirements.

Additionally, the 4 K fatigue properties of the conduit base and weld metal, have been characterized in axial fatigue test to generate cyclic stress vs cycles to failure (S-n) curves. The results from these tests plus 4 K fatigue crack growth rate tests provide the data that allows designers to estimate the conduit’s service lifetime and reliability.

In summary, the production grade JK2LB conduit base metal and welds, before and after the final processing steps, are found to have excellent mechanical properties that easily satisfy the ITER 295 K and 4 K requirements.

### 3. Material Information

The JK2LB’s target chemistry and the production grade heat analyses are shown in Table 1. Piece lengths of the seamless square tube with a round hole are butt welded together at mid-length to provide the approximately 1 m lengths for qualification testing. The conduit was initially fabricated to slightly oversized dimensions (51.3 mm across flats, 35 mm inside dia.) for ease of cable insertion (not applicable for this exercise). For this program the manufacturer provides the conduit after performing next fabrication step; compaction, on the hollow tubes that would normally be done after cable insertion. Prior to the compaction step which adds 4 to 5% cold work strain, the conduit was solution annealed (1100C, 5 min., WQ) and has an average ASTM grain size = 5.

The material preparation procedures for the addition of CW and the heat treatment are briefly described. The 1 m conduit test sections are subjected to bending strains with a 3 pt. bending jig. The bending is done in four steps shown in Figure 1. At Step 3, two different bending sequences can be identified as DB for Double Bend and RB for Reverse Bend. The material preparation and conditions are described below;

#### 3.1 Compaction - the process step used to achieve final conduit cross-section dimensions after cable insertion. Compaction reduces the conduit’s nominal outside dimensions approximately 2 to 2.5 mm, and is performed prior to receipt at NHMFL, the material condition is; As-Compacted (AC).

#### 3.2 Welding - the procedure is a combination of automated and manual TIG process and is documented elsewhere [1]. The filler metal is high Mn steel JK2LB and the material referred to as the Weld. Welding is done prior to compaction and the welds are ground on the outside surface to the nominal conduit dimensions. The inside weld surface is not treated (ground) and is left in the as-welded condition.
3.3 Cold Work (CW) - Pre-coiling and coil winding introduce cold work. To simulate the cold work (prior to heat treatment), the (AC) conduit sections were formed in a 3 pt bend method over 2 different radii mandrels as shown in Figure 1. Step 1 bending simulates pre-coiling at 1.66 m radius. Step 3 bending simulates the minimum winding radius of 1.3 m of the CS coils. One of the two CW conditions is achieved with a Double Bend and the other CW condition is achieved with a Reverse Bend. The difference is a 180 degree flip of the conduit with respect to the bending direction. Since the final step is straightening the conduit for the removal of test specimens, it is thought that the difference in the state of the CW Reverse Bend and the CW Double Bend is negligible.

3.4 Aged condition (AG) - is accomplished by aging the (AC + CW) conduit at 650C/200h in an Argon atmosphere. This represents the final step of the Nb3Sn reaction heat treatment that the conduit alloy must endure.

FIGURE 1. Schematic showing the material preparation steps done to simulate subsequent magnet winding operations after compaction and prior to the aging heat treatment.

FIGURE 2. Schematic flat and round tensile specimens removed from the conduit section.
4. Test Procedures

The mechanical properties of the base and weld metal are evaluated with tests on specimens that are electro-discharge machined (EDM) from the conduit as shown in Figures 3 and 4. All the tests are conducted on a 100 kN capacity MTS machine equipped with a cryostat to enable testing at 4 K with the specimen and fixture immersed in liquid helium. Tensile tests are conducted in displacement control at a rate = 0.5 mm/min according to procedures prescribed in ASTM E8 and E1450. Round tensile specimens were removed from conduit corners and the 2 mm thick flat tensile specimens were removed from the flat of the conduit as shown in Figures 2 and 5. Strain is measured with a 10% strain range clip-on extensometer.

For fatigue crack growth rate (FCGR) tests and J-integral (Jc) fracture toughness tests, dual-purpose compact tension (CT) specimens (Figure 3) were used. The 7 mm thick, 0.5 CT specimens are machined with a short notch (7 mm), after 2 mm 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 an 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.

The fracture toughness tests are conducted according to the guidelines provided in ASTM E1820-13. Fracture toughness CT specimens are usually oriented (TL) to generate conservative design data, with the crack direction parallel to the rolling direction. The ITER CS coil in-service stress is well defined, and a potential fatigue crack would run transverse to the conduit axis and the primary rolling (or extrusion) direction, thus one could argue that J tests should be performed on specimens with the LT orientation. Here we performed tests of the base metal with CT specimens from both orientations (4 each, TL and LT). For the butt weld material there is only one specimen orientation possible (LT). One half of the specimens (2 for each condition) were side grooved after pre-cracking as identified the results table.

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TABLE 2.

| Material       | Condition | Temp K | Yield Strength (MPa) | YS Std Dev (MPa) | Tensile Strength (MPa) | TS Std Dev (MPa) | Elong. in 25 mm (%) | Reduction of Area (%) | No of Tests |
|----------------|-----------|--------|----------------------|------------------|------------------------|------------------|----------------------|------------------------|-------------|
| ITER Req. Minimum | AC+CW+AG  | 295    | 300                  | 550              | 30                     | 2                | 4                    | 2                      | 2           |
| Base in Flats   | AC+CW+AG  | 295    | 435                  | 12               | 818                    | 8                | 44                   | 47                     | 2           |
| Weld in Corners | AC+CW+AG  | 295    | 465                  | 2                | 619                    | 4                | 34                   | 54                     | 2           |
| ITER Req. Minimum | AC+CW+AG  | 4      | 850                  | 1150             | 25                     | 2                | 25                   | 32                     | 12          |
| Base in Flats   | AC+CW+AG  | 4      | 1085                 | 40               | 1458                   | 44               | 41                   | 47                     | 12          |
| Weld in Corners | AC+CW+AG  | 4      | 1076                 | 5                | 1456                   | 5                | 42                   | 47                     | 4           |

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, parameters are sinusoidal tension-tension fatigue cycling, frequency $f = 20$ Hz, R-ratio ($P_{\text{min}}/P_{\text{max}}$) = 0.1. The test specimens are removed directly from the conduit as shown in the in Figure 4. The fatigue sample retains the original inside and outside surface finish of the as-manufactured conduit. Typically S-n fatigue tests are performed on polished samples but here we want to simulate the in-service conditions to get a better estimate of the in-service fatigue life.

5. Results and Discussion

5.1 Tensile Properties

Table 2 shows that the material has excellent 4 K tensile properties that easily satisfy the ITER requirements. Material variability is not very large as seen by the standard deviation of around 40 to 45 MPa for the 4 K average yield (1085 MPa) and tensile strength (1458 MPa) of the 12 base metal tests on flat specimens. The flat tensile specimens were tested to evaluate possible residual stress that may occur during processing of the conduit (Figure 5) and the test results showed negligible through thickness material variability.

The tensile properties of the welds are also excellent and only slightly lower strength than the base metal. The average 4 K tensile elongation of 34% is well above the required minimum of 25% and slightly reduced compared to the base metal’s 42% elongation.

![FIGURE 5. Stress-strain curves for evaluation of residual stress in conduit wall.](image-url)
TABLE 3.

5.2 FCGR and Fracture Toughness
The fatigue crack growth rate (FCGR) test results are shown on Table 3 and the graph in Figure 6. The graph shows the analyzed data for four test each for the comparison of the average FCGR behavior of the fully processed (AC+CW+AG) base and weld metal as well as comparison with previously published comparable data for conduit alloys. The upper and lower bounds for the range of crack growth rates found in the literature [5,6] for aged 316LN intended for CICC applications are plotted in Figure 6 along with previously published FCGR measurements for JK2LB published in [2-4]. Previously published data for JK2LB nicely brackets current measurements.

The goal of fracture toughness testing is to determine the J integral at the point of fracture instability (JQ) that satisfies the criteria to become the critical J integral (JC), which can then be converted to the more commonly used critical stress intensity factor (KC). The strict validity

![4K Fatigue Crack Growth Rate data graph along with reference data for comparison.](image)

FIGURE 6. 4K Fatigue Crack Growth Rate data graph along with reference data for comparison.
TABLE 4. 4K Fracture Toughness Test Results

| Specimen No. | Material | Orientation | $K_{IC}$ (MPa m$^{0.5}$) | $K_{IC AVG}$ (MPa m$^{0.5}$) | STD DEV, (MPa m$^{0.5}$) | Validity Notes |
|--------------|----------|-------------|---------------------------|-----------------------------|--------------------------|----------------|
| CT-9         | Base     | LT          | 360                       | 357                         | 14                       | Invalid due to J test crack tunneling |
| CT-10        | Base     | LT          | 376                       | 376                         | 14                       | Invalid due to J test crack tunneling |
| CT-11, side grooved | Base     | LT          | 346                       | 346                         | 14                       | Invalid due to J test crack tunneling |
| CT-12, side grooved | Base     | LT          | 348                       | 348                         | 14                       | Invalid due to J test crack tunneling |
| CT-17        | Base     | TL          | 174                       | 174                         | 7                        | Invalid due to J test crack tunneling |
| CT-18        | Base     | TL          | 188                       | 188                         | 7                        | Invalid due to J test crack tunneling |
| CT-19, side grooved | Base     | TL          | 173                       | 173                         | 7                        | Invalid due to J test crack tunneling |
| CT-20, side grooved | Base     | TL          | 176                       | 176                         | 7                        | Invalid due to J test crack tunneling |
| CT-13        | Weld     | LT          | 243                       | 237                         | 26                       | Invalid due to J test crack tunneling |
| CT-14        | Weld     | LT          | 267                       | 235                         | 26                       | Invalid due to J test crack tunneling |
| CT-15, side grooved | Weld     | LT          | 235                       | 235                         | 26                       | Invalid due to J test crack tunneling |
| CT-16, side grooved | Weld     | LT          | 204                       | 204                         | 26                       | Invalid due to J test crack tunneling |

requirements of the ASTM E1820 test standard are designed to ensure the resulting measurements are specimen size independent. Satisfying all the requirements is difficult, especially in cryogenic tests. The most basic qualification criteria are the geometric requirements in Equation 1;

$$B, b \geq 10 \times \frac{J_Q}{\sigma_y} \quad (1)$$

Where: $B =$ sample thickness, mm

$b =$ uncracked ligament length

$J_Q = J$ integral at the onset of significant tearing

$\sigma_y = \frac{(\text{Yield Strength} + \text{Tensile Strength})}{2}$

Although this size criteria was met by all the specimens, with thickness ($B$) of 7 mm and remaining ligaments ($b$) of around 10 mm, almost all of these tests failed to meet other more discreet requirements related to crack front straightness as noted on the results table. Even though most of the test results are invalid, according to the strict ASTM requirements, they are considered to be good estimates of the fracture toughness and confirm the JK2LB material and welds have very good toughness at 4 K.

The fracture toughness test results are shown in Table 4. The base metal shows a high degree of anisotropy with almost a factor of 2 difference in the values measured for the two orientations (the LT toughness is greater). A similar degree of anisotropy has been seen previously in tests of JK2LB conduit material [2] with 40% higher toughness for the LT orientation compared to the TL orientation. The base metal exhibits extremely high toughness (357 MPa m$^{0.5}$) with the crack direction transverse to the conduit’s longitudinal axis (LT orientation). The toughness of the TL orientation (177 MPa m$^{0.5}$) is also excellent and compares well with previously reported toughness (167 MPa m$^{0.5}$) [2] of aged JK2LB conduit for the TL orientation. The weld falls in between with exemplary toughness of 237 MPa m$^{0.5}$ as the measured average.

5.3 Axial cyclic fatigue (S-n)

The cyclic fatigue results are shown graphically in Figure 7 along with a table of the individual data pts. Previous S-n fatigue data for JK2LB [2] with slightly better fatigue performance is also plotted on the graph for comparison. The reason for the better fatigue performance of the prior data [2] from JK2LB conduit may be that the samples had a polished surface finish and the ones tested here were left with the as manufactured finish.
6. Conclusions
In summary, the production grade JK2LB conduit base metal and welds, before and after the final processing steps, are found to have excellent mechanical properties that easily satisfy the ITER 295 K and 4 K requirements. The 4 K fatigue properties of the conduit base and weld metal, have been characterized in axial fatigue test and fatigue crack growth rate tests generating data that allows designers to estimate the conduit’s service lifetime and reliability.

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