Mechanical properties of high manganese austenitic stainless steel JK2LB for ITER central solenoid jacket material

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Abstract

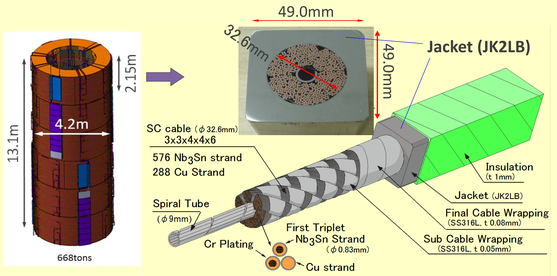
The ITER central solenoid (CS) has to support powerful electromagnetic force because it is operated in a high current and high magnetic field. Additionally, the main load on the CS modules is a cyclic tension generated by the electro-magnetic hoop force during operation.

- The high manganese austenitic stainless steel JK2LB, which has high tensile strength, high ductility and high resistance to fatigue at 4 K has been chosen for the CS conductor.
- The CS jacket is required to have Yield strength (YS) ≥ 1000 MPa, Ultimate Tensile Strength (UTS) ≥ 1150 MPa, Elongation (EL) ≥ 25 %, fracture toughness $K_{IC}(J)$ ≥ 130 MPavm and fatigue life of 60,000 cycles at 4 K following prior cold work and heat treatment (650 °C - 200 h).
- The cryogenic temperature mechanical property data of JK2LB are very important for ITER magnet design but there is scant data.

Objectives

- In order to increase the available database for the JK2LB, following test were carried out: tensile tests, fracture toughness tests ($K_{IC}(J)$), fatigue crack growth tests and fatigue tests (*S-N*) at 4.2 K (liquid helium).
- In the *S-N* testing of welded joint, specimens were machined as-welded to evaluate real fatigue characteristic including stress concentration at weld joint.

CS coil and conductor

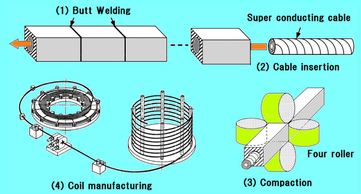


Operation condition: 40 kA at 13.0 T, 45 kA at 12.6T

The requirements of ITER CS conductor jacket at 4.2 K

Tensile test	0.2% YS : ≥ 850MPa UTS : ≥ 1150MPa EL : ≥ 25%
J_{IC} test	$K_{IC}(J)$: ≥ 130 MPa√m

Jacketing process

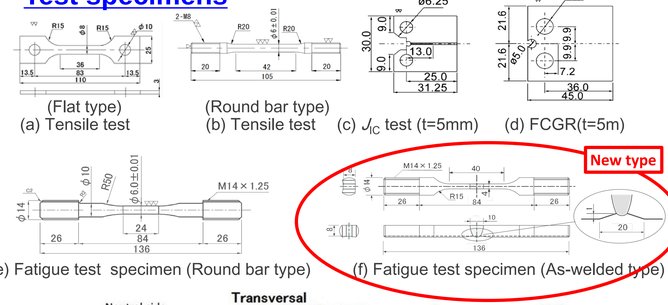


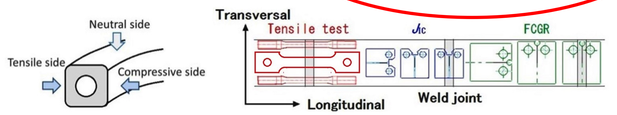
The sample jacket underwent "Pre-Test Cycle".

Pre-Test Cycle :

(i) Compaction (Outer dimension is reduced from 51.3mm x 51.3 mm to 49 mm x 49 mm)
(ii) Bending to a radius of 2000 mm, which corresponds to radius of transport spool
(iii) Straightening
(iv) Bending to a radius (1300 mm) which corresponds to the radius of the inner side of CS coil
(v) Straightening
(vi) Nb_3Sn superconductor reaction aging heat treatment

Test specimens

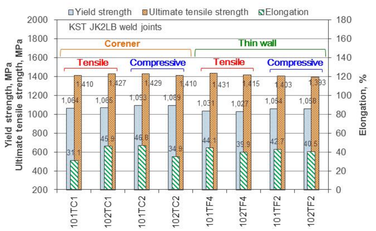




Major examples of the specimen location

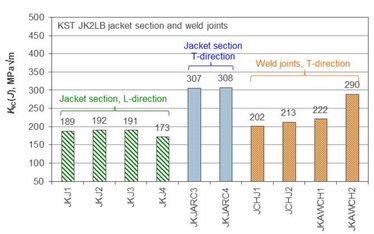
Mechanical Test Results at 4K

● Tensile test for weld joint at 4K



Results of tensile tests satisfied the requirements of the ITER CS conductor jacket, which are more than 850 MPa of YS, more than 1150 MPa of UTS, and more than 25 % of EL. And, it doesn't make much difference whether it is corner section or twin wall part , and tensile or compressive side.

● Fracture toughness for jacket section and weld joints at 4K

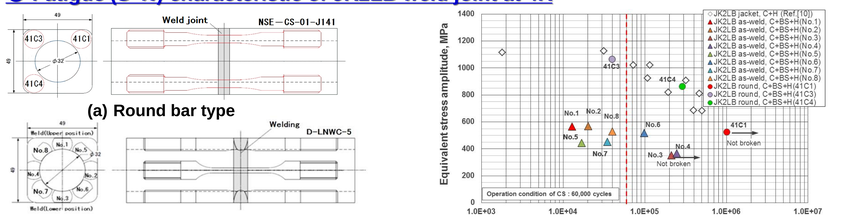


For the jacket section, results of the longitudinal direction are markedly lower than the transversal direction. As for the transversal direction of jacket sections and weld joints, the notch direction of these samples is same direction. However, these results showed different trends, which means that the weld joints were lower than jacket sections. Even so, $K_{IC}(J)$ values of jacket section and weld joint satisfied the ITER CS jacket requirements, which is more than 130MPa$\sqrt{m}$.

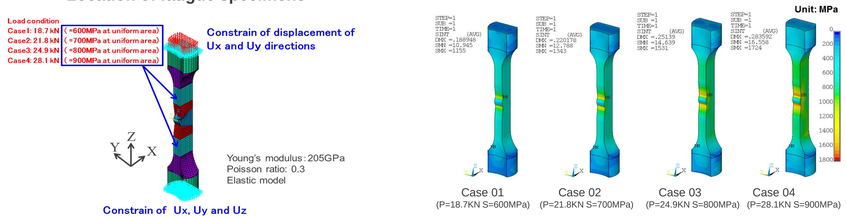
● Fatigue Crack Growth Rate test for jacket section and weld joints at 4K

As for the jacket sections, the results indicated very comparable regardless of the cutting position and the notch direction of specimen. As for the weld joints, specimen from tensile side, J131CPD1, exhibits a different slope. This means that tensile side of bending process is faster than that of compressive side and neutral side insensibly. However, the measured fatigue crack growth rates are low enough to achieve the operation cycle of the CS coil.

● Fatigue (*S–N*) characteristic of JK2LB weld joint at 4K

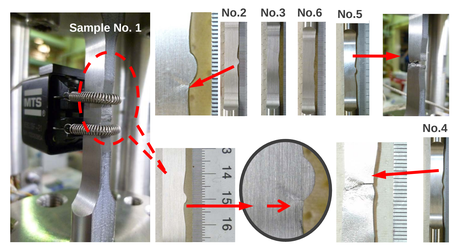


Result of S-N data for JK2LB weld joint.



Analysis condition of Finite Element Method

Analysis results of FEM：Stress intensity (Tresca) Sint



photos of as-weld type specimen after test

For the as-weld type specimen, the cycles-to-failure decreased because of the stress concentration.
From the case 01 (specimen No. 3 and No. 4) of the FEM result, the weld toe have the near 0.2% YS because of the stress concentration. Furthermore, it has more UTS in the case 03 (No. 6 and No. 8).
The fatigue life of JK2LB as weld joint satisfies the ITER lifetime requirement of 60,000 cycles.

Summary

In order to increase the available database for the JK2LB, the mechanical tests at 4 K (liquid helium) were carried out. The results of tensile test satisfied the requirements of the ITER CS conductor jacket, which are more than 850 MPa of 0.2%YS, more than 1150 MPa of UTS, more than 25 % of EL. And the fracture toughness $K_{IC}(J)$ is more than requirement 130MPa√m . For the FCGR test of weld joints, tensile side of bending process is faster than that of compressive side and neutral side insensibly. They are low enough to achieve the operation cycle of the CS coil. In the fatigue testing of welded joint, specimens were machined as-welded to evaluate real fatigue characteristic including stress concentration at weld joint, and tests were carried out. In addition, the specimens which don't have the stress concentration were compared with them. For the as-weld type specimen, the number of cycles-to-failure decreased because of the stress concentration. However, it is expected that the fatigue life of JK2LB as weld joint satisfies the ITER lifetime requirement of 60,000 cycles.