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Mechanical tests on the welding part of SS316LN after heat treatment for Nb_3Sn superconducting conductor

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Abstract

Japan Atomic Energy Research Institute (JAERI) plans to construct a tokamak fusion device called JT-60SC in which superconducting magnet systems will be used. The purpose in this paper is to qualify type 316LN stainless steel (SS316LN) for use as the conduit material of the Nb_3Sn cable-in-conduit conductor for the central solenoid (CS) of JT-60SC. Tensile properties, fracture toughness and fatigue crack growth rates of the as-welded metal and the aged (923 K × 240 h) one of SS316LN were evaluated at 4 K. The tensile properties and fatigue crack growth rates were adequate to ensure the design requirements for JT-60SC. However, fracture toughness of the aged weld metal could not be validated due to unstable crack growth. It was concluded that improvement of fracture toughness after aging was required to ensure the structural integrity of the CS conduit.

1. Introduction

Modification of JT-60 as a full superconducting coil tokamak (JT-60SC) is planned [1,2]. The objectives of the JT-60SC programme are to establish scientific and technological bases for steady-state of high performance plasmas and utilization of reduced-activation materials in an economically and environmentally attractive DEMO reactor [3]. Advanced fusion technologies relevant to the DEMO reactor have been developed for the superconducting magnet technology and plasma facing components of the JT-60SC design [4].

The central solenoid (CS) of JT-60SC is designed to use cable-in-conduit conductors (CICC) with Nb_3Sn strands as shown in Fig. 1. The conductors are fabricated by the pull-through process [5] and the type 316LN stainless steel (SS316LN) conduit has many welded joints. Since the conduits for the Nb_3Sn superconductor have to undergo reaction heat treatment (923 K × 240 h), which corresponds to aging for austenite stainless steels, degradation of mechanical properties due to sensitization is concerned [6,7]. It is also necessary to evaluate the mechanical properties of conduit material at cryogenic temperature because the CICC is cooled to about 4.5 K by supercritical helium during the operation. Although 4 K mechanical properties of SS316LN base metal in some aged conditions are reported before [6,8], there are not sufficient data on mechanical properties of welds.

Tensile properties, fracture toughness and fatigue crack growth rates of the as-welded metal and the aged one were evaluated at 4 K to confirm whether the above mentioned mechanical properties satisfy the CS conduit material requirements.

(1) yield strength at 4 K > 600 MPa
(2) fracture toughness at 4 K > 80 MPa $m^{1/2}$
(3) fatigue crack growth rate: life greater than 9.0×10^4 cycles (safety factor 5) without unstable failure.

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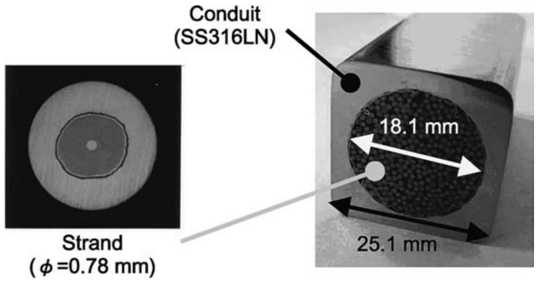

Fig. 1. Cable-in-conduit conductor for central solenoid of JT-60SC.

Table 1
Chemical compositions of tested sample (wt%)

	SS316LN	Filler wire	Weldment
C	0.014	0.013	0.011
Si	0.66	0.41	0.49
Mn	0.63	7.42	5.58
P	0.023	0.012	0.015
S	0.001	0.008	0.006
Cr	18.21	20.13	19.69
Ni	11.06	16.34	14.95
Mo	2.81	2.71	2.73
N	0.170	0.148	0.117

2. Experimental procedure

The material used in this study was SS316LN commercial grade after solution treatment at 1373 K. Filler wire specified in Germany Standard DIN 1.4455 (0.01C–7Mn–20Cr–15Ni–3Mo–0.15N, diameter 12 mm) was selected to produce a full austenitic structure in the weld metal. The SS316LN plate ($250L \times 200W \times 30T$, in mm) was divided in four pieces and two pairs were welded by a gas tungsten arc welding technique in the configuration shown in Fig. 2(a). The welding conditions were welding current of 250–300 A, welding speed of 80–100 mm/min with center shield gas (75%He–25%Ar) of 15 l/min and outer shield gas (Pure Ar) of 30 l/min. Fig. 2(b) shows the weld zone of single V-butt welding. One of the welded plates was aged at 923 K for 240 h. Chemical compositions of the materials used in this study are listed in Table 1.

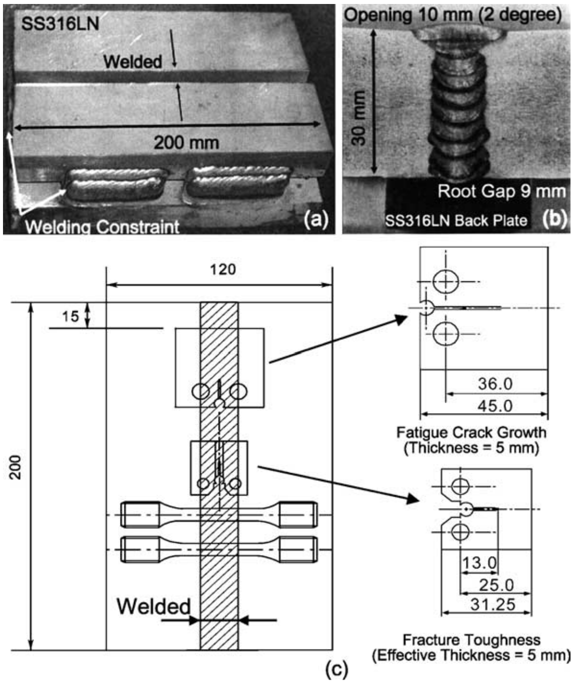

Fig. 2. (a) The configuration before welding, (b) weld zone, (c) sampling map on welded plate and the dimension of test pieces (right upper: fatigue crack growth specimen, bottom: fracture toughness specimen).

Two specimens for tensile, fracture toughness ($K_{IC}(J)$) and fatigue crack growth rate (FCGR) tests were machined from each as-welded metal and aged one. Round bar specimens with a diameter of 7 mm and length (gage portion 42 mm) of 105 mm were used for the tensile test [9]. Two size of proportional small compact tension (CT) specimens, $W = 25$ mm, effective thickness $t = 9$ mm with side grooves for the $K_{IC}(J)$ test and $W = 36$ mm, $t = 5$ mm for the FCGR test, were prepared. The orientation of each specimen and dimension of the proportional small CT specimens are shown in Fig. 2(c).

The evaluation of fracture toughness was performed using the elastic–plastic fracture toughness test with the unloading compliance technique and the measured elastic–plastic fracture toughness (J_{IC}) was converted to fracture toughness ($K_{IC}(J)$) [10].

The FCGR results were evaluated by the material constants C and m used in the Paris law. Paris law is expressed as follows;

$$\frac{da}{dN} = C(\Delta K)^m$$

where da/dN is fatigue crack growth rate, and ΔK is range of stress intensity factor.

3. Results

Tensile test results at 4 K are shown in Fig. 3. The fracture occurred at the welded zone. The 0.2% yield strength (YS) did not change after aging. However, the ultimate tensile strength (UTS) and reduction of area (RA) decreased.

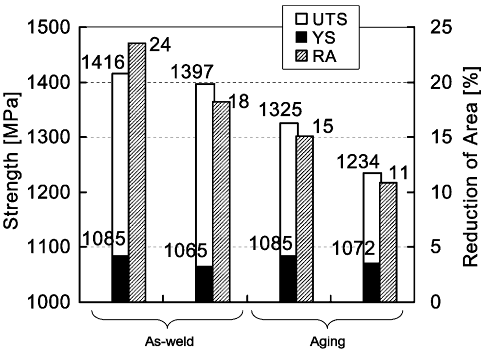

Fig. 3. 4 K Tensile properties of as-welded and aged specimens. UTS: Ultimate Tensile Strength, YS: 0.2% Yield Strength, RA: Reduction of Area.

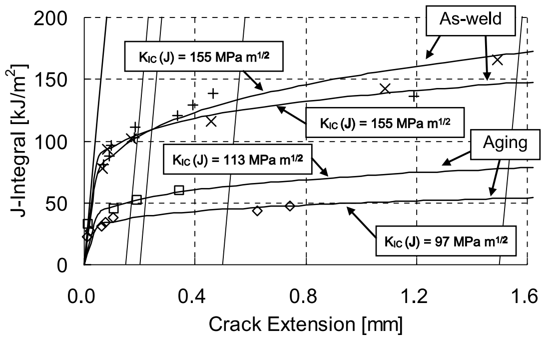

Fig. 4. 4 K *R*-curve of as-welded and aged specimens.

Fracture toughness test results at 4 K are shown in Fig. 4. The as-welded specimens showed higher $K_{IC}(J)$ over 150 $MPa\,m^{1/2}$ and stable crack growth was observed. The aged specimens showed $K_{IC}(J)$ of 113 $MPa\,m^{1/2}$ and 97 $MPa\,m^{1/2}$ but the aged specimens did not meet the criteria for $K_{IC}(J)$ [10] due to unstable crack growth.

Fig. 5 shows typical fracture surfaces of the tensile and the fracture toughness. The dimples, which represent ductile failure, were observed in the as-welded specimens of the tensile and the fracture toughness. In contrast, the fracture surface of the aged tensile specimens showed quasi-cleavage and intergranular, but the surfaces of the aged fracture toughness showed cleavage. Fractography suggested that the weld metal was not brittle at 4 K in the as-welded condition but became brittle after aging.

Fig. 6 shows the relations between stress intensity factor range and FCGR at 4 K. The FCGR of the aged specimens were faster than the as-welded specimens. The coefficients of the fastest FCGR were obtained by liner regression as $C = 7.63 \times 10^{-15}$ and $m = 4.33$.

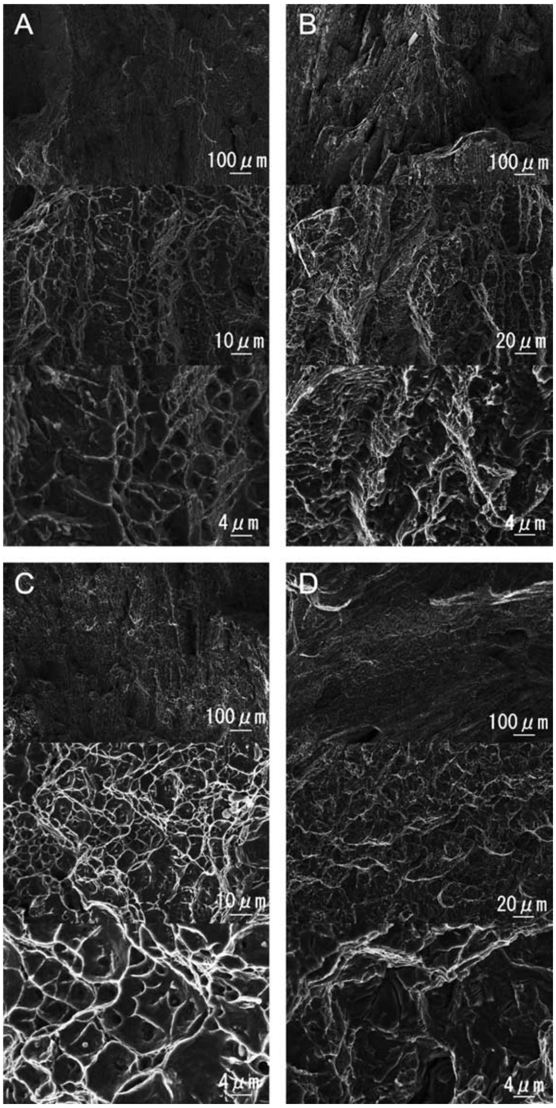

Fig. 5. Fractography of ruptured surface: (A) as-welded tensile specimen, (B) aged tensile specimen, (C) as-welded J_{IC} specimen, and (D) aged J_{IC} specimen.

4. Discussion

4.1. Acceptability as a conduit from the static mechanical properties

The required YS of the CS conduit material was determined to be 600 MPa, which allows the safety margin, because the Tresca stress calculated by the finite element method [2] was less than 400 MPa. The required UTS was automatically defined as 900 MPa because the allowable stress was defined as either lower value of 2/3 YS or 1/3 UTS [11]. All measured YS and UTS after

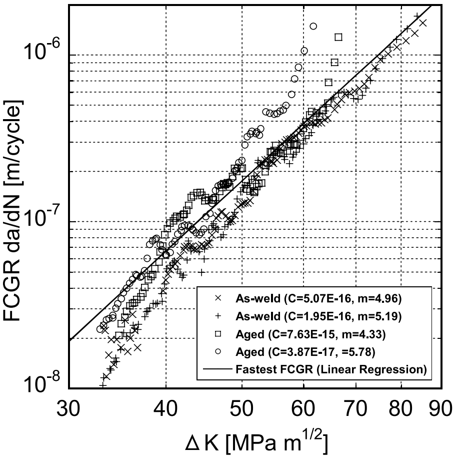

Fig. 6. 4 K fatigue crack growth rate (FCGR) of as-welded and aged specimens.

aging satisfied these requirements and the aged weld metal can be acceptable to the CS conduit.

The concept of leak before break (LBB) is adopted for the CS conductor design of JT-60SC. A stress intensity factor of 40 MPa m$^{1/2}$ is calculated [12] as a critical value, at which the CS conduit will show unstable fracture under the condition that a through-thickness crack 4.65-mm wide exists and stress of 400 MPa is applied. To ensure LBB, the required K_{IC} of 80 MPa m$^{1/2}$ was also determined for the same consideration as YS requirement. The welded metal after aging did not satisfy this requirement due to unstable crack growth during $K_{IC}(J)$ test. From the fractography, the intergranular fracture of the aged weld metal suggests that the depletion and/or the segregation of some elements would occur on the grain boundaries as reported for the base materials [7,13–15]. It is concluded that further microscopic study will be required to improve the fracture toughness of the aged weld metal.

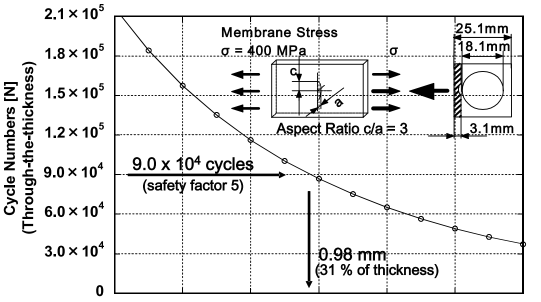

Fig. 7. Relation between initial crack size (aspect ratio of 3) and life cycle numbers. Numerical model of the thinnest part at welding.

4.2. Acceptability as a conduit for the cyclic operation

Crack growth analysis using a simple model as shown in Fig. 7 was performed to confirm the acceptability of the aged weld metal in the CS conduit. To ensure the structural integrity against fatigue crack growth, a safety factor of 5 is taken and then, the required number of test cycles is 9.0×10^4. A semi-elliptic crack with an aspect ratio 3, which existed at a surface of the 3.1-mm thick plate, was postulated [16] and fatigue life was defined by the number of cycles at which the crack depth equaled the thickness of the conduit. Applied stress of 400 MPa was determined from the result of the stress analysis [2], taking account of a safety margin. Stress intensity factor was calculated with the Newman–Raju equation [17] and the fastest measured FCGR was used, as shown in Fig. 6.

The calculation result is shown in Fig. 7. The maximum allowable crack depth which gave fatigue life of 9.0×10^4 was estimated by about 0.98 mm. This crack size corresponded to 31% of the thickness of the conduit and it was expected that it could be detected by non-destructive testing during fabrication [5,18].

5. Conclusion

SS316LN welded metal aged at 923 K for 240 h has adequate tensile strength and fatigue crack growth rate at 4 K for the conduit of the CS for JT-60SC. However, fracture toughness of aged weld metal at 4 K cannot be evaluated as a valid value due to unstable crack growth. Improvement of fracture toughness after aging is required to qualify SS316LN as the structural material of the CS for JT-60SC.

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