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Tensile test of SS 316LN jacket with different conditions

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ABSTRACT

316LN stainless steel is selected as a material for Toroidal-field (TF) conductor jacket of International Thermonuclear Experimental Reactor (ITER). When energized, the ITER TF coils experience large pulsed electromagnetic forces that the conductor jacket itself must withstand. The conductor will be compacted, spooled and aged at approximately 650 °C during manufacture. Therefore, the sample jackets were prepared under compaction, stretching and annealing to simulate the manufacturing process and operation of TF coils. The present Chinese TF jacket has good performance under standard conditions. In order to investigate more mechanical properties of 316LN jacket, the different cold working and annealing were applied to the raw materials. The samples were measured at 4.2 K, 77 K and 300 K. Youngs modulus, yield strength (0.2% offset), elongation at failure and SEM images are reported. There is no big deviation among different conditions. The test results show that Chinese TF jacket has good performance.

1. Introduction

ITER is a joint international research and development project [1,2] that aims to demonstrate the scientific and technical feasibility of fusion power. To confine the plasma superconducting magnets are used. The ITER magnet system is made up of four main sub-systems: The 18 Toroidal Field coils, referred to as TF coils; the Central Solenoid, referred to as CS; the 6 Poloidal Field coils, referred to as PF coils; and the Correction Coils, referred to as CCs. All coils having different dimensions are designed as Cable-In-Conduit Conductors (referred to as CICC). Here the conduit is a stainless jacket.

316LN stainless steel is used as jacket material in the ITER TF conductor [3]. Since the conductor has to undergo compaction, bending and annealing after inserting the superconducting cable into the jacket, the effect of cold working and annealing on the mechanical properties of jacket needs to be investigated. It is also necessary to evaluate the mechanical strength at low temperature because the CICC is operated at about 4.5 K. Some research on the TF jacket with cold working and annealing are made [4–8]. Two different heat treatment schedules and the variation of cold working condition were applied in order to study their effect on materials properties in [8]. The results show that heat treatment and cold working could reduce the properties of TF jacket, especially for the elongation at failure. The results also show that cold working is more dominant to the degradation of tensile properties than aging treatment to this material.

China needs provide TF conductor for ITER. At present, Chinese 316LN jacket has good performance under standard conditions, which contains compaction, 2.5% stretching and 200 h annealing at 650 °C. In order to investigate the properties of 316LN jacket fully, the different cold working and annealing are performed to the jacket. The samples tested at 4.2 K, 77 K and 300 K. The elongation at failure are compared in particular. The results show that the present Chinese 316LN jacket has good properties.

2. Sample preparation

The test specimens are from one electro-slag re-melting heat (ESR). The chemical composition is shown in Table 1. The dimension of the test jackets is 47.0 × 1.9 mm before compaction (Fig. 1) and 43.7 × 2.0 mm after compaction.

Different cold workings, including compaction and stretching, were applied to the raw materials, and three kinds of different heat treatment were used. The samples with different conditions are shown in Table 2. The maximum cold working applied to raw materials is about 10%. After cold working, the jacket was aged at high temperature in order to simulate the process route of the Nb_3Sn strand. Three kinds of heat treatment are shown in Fig. 2.

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Table 1
Chemical composition of 316LN jacket

Element wt.%	Heat analysis	Product analysis	ITER requirement
C	0.014	0.017	<0.02
Si	0.400	0.376	<0.75
Mn	1.390	1.380	<2.0
P	0.011	0.006	<0.04
S	0.004	0.004	<0.03
Cr	16.55	16.42	16.0–18.0
Ni	12.96	13.64	11.0–14.0
Mo	2.350	2.340	2.0–3.0
Co	0.029	0.021	<0.1
N	0.145	0.151	0.14–0.18

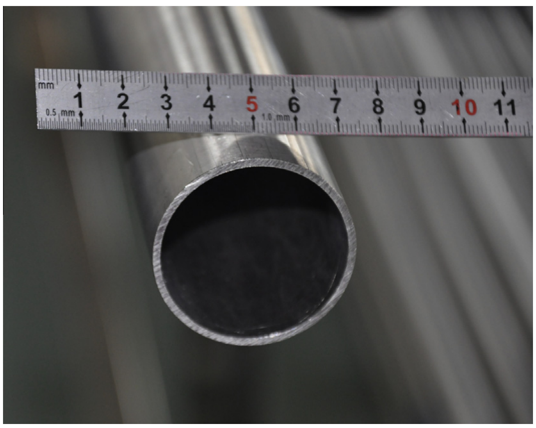

Fig. 1. 316LN jacket used in Chinese TF conductor.

Table 2
Sample information.

Type	Compaction	Stretching	Total cold working	Aging
Type 1	No	No	0	HT1
Type 2	No	No	0	HT2
Type 3	No	No	0	HT3
Type 4	Yes	2.5%	6.3%	No
Type 5	Yes	2.5%	6.3%	HT1
Type 6	Yes	2.5%	6.3%	HT2
Type 7	Yes	2.5%	6.3%	HT3
Type 8	Yes	3.5%	7.3%	HT1
Type 9	Yes	4.5%	8.3%	HT1
Type 10	Yes	7.0%	10.8%	HT1

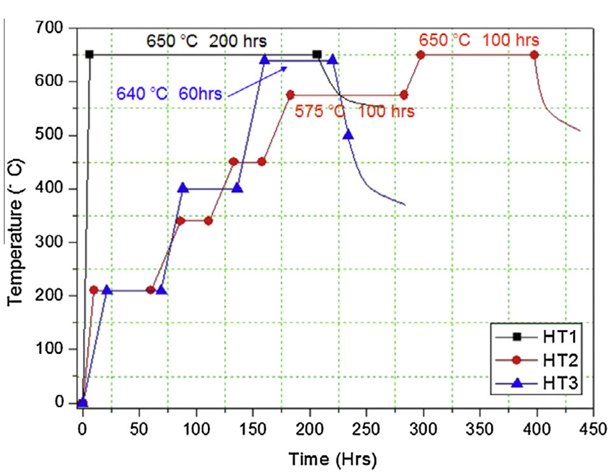

Fig. 2. Different heat treatments for 316LN jacket.

Table 3
Required dimensions of tensile testing samples

Parameter	Dimension
G-Gage length	50 ± 0.1 mm
W-Reduced section length	12.5 ± 0.2 mm
T-Specimen wall thickness	Tube wall thickness
R-Radius of fillet	⩾12.5 mm
A-Length of reduced section	⩾60 mm
B-Length of grip section	⩾75 mm
C-Width of grip section (approximate)	20 mm

Heat 1 is from standardization of TF conductor jacket mechanical testing procedure provided by ITER. Heat 2 is one kind of real heat condition of TF coil, and Heat 3 is the real heat condition of one kind of Nb_3Sn conductor used for high field. The tensile test samples (Table 3, Figs. 3 and 4) were machined by Electro Discharge Machining (EDM). The samples were cut axially symmetric with the gage length of the stretched tube, and from various locations around the circumference of the tube. The sample dimensions were compliant with ASTM E8M. The samples were tested at room and cryogenic (77 K and 4.2 K) temperature, immersed in liquid nitrogen and helium respectively.

3. Results and discussions

In this section, the test results are given. The tensile tests were carried out according to ASTM E1450. All tensile tests were conducted in displacement control with the strain rate below $5 \times 10^{-4}\ s^{-1}$. 30 samples were tested at 4.2 K, 77 K and room temperature. The results, including elongation at failure (EL), 0.2% yield strength (YS), ultimate tensile strength (UTS), and Young's modulus (YM) are given. The typical tensile curve is shown in Fig. 4. The yield and ultimate tensile strength are shown in Fig. 5.

From the results, it can be seen that there is distinct change for the properties of 316LN jacket at different temperature. As expected, the yield strength and ultimate tensile strength increased strongly by reducing the temperature. Theoretically, the cold working could increase the yield strength of metal. But the heat treatment could remove the effect. The maximum yield strength at 4.2 K is from the sample with cold working, but no heat treatment. The Young's modulus are shown in Fig. 6. It is easily to be found that the Young's modulus changed little for most types.

The standard deviation was used to collect statistics. The tested results with same temperature is assumed a one-sample. The matrix of sample and standard deviation are as following,

$$T_{YS} = \begin{pmatrix} 495 & 540 & 465 & 520 & 525 & 530 & 560 & 540 & 635 \\ 975 & 1080 & 870 & 990 & 970 & 995 & 1060 & 1030 & 895 \\ 1070 & 1190 & 1020 & 1430 & 1220 & 1070 & 1180 & 1190 & 1210 \end{pmatrix},$$

$$T_{UTS} = \begin{pmatrix} 755 & 740 & 690 & 745 & 750 & 710 & 765 & 730 & \\ 1390 & 1360 & 1220 & 1370 & 1430 & 1390 & 1430 & 1420 & 1220 \\ 1540 & 1550 & 1510 & 1650 & 1630 & 1500 & 1460 & 1620 & 1590 \end{pmatrix},$$

$$T_{YM} = \begin{pmatrix} 193 & 204 & 205 & 200 & 193 & 196 & 198 & 195 & 202 \\ 210 & 197 & 203 & 203 & 210 & 210 & 203 & 205 & 214 \\ 203 & 194 & 201 & 208 & 212 & 209 & 208 & 210 & 212 \end{pmatrix},$$

$$SD(T_{YS}) = \begin{pmatrix} 46.8004 \\ 69.3271 \\ 119.803 \end{pmatrix},\quad SD(T_{UTS}) = \begin{pmatrix} 27.5505 \\ 82.5295 \\ 65.2772 \end{pmatrix},\quad SD(T_{YM}) = \begin{pmatrix} 4.55826 \\ 5.28463 \\ 5.93717 \end{pmatrix}.$$

In the sample matrix, the columns represent the results of 300 K, 77 K, 4.2 K from top to bottom, respectively. From the results, we can find that the test results at 300 K has the smallest standard deviation for yield strength (YS), ultimate tensile strength (UTS) and Young's modulus (YM). The variation of yield strength of material at 4.2 K is much bigger than those at 300 K and 77 K. The biggest