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Mechanical test on the ITER CC and Feeder jacket

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HIGHLIGHTS

- ▶ Make tensile tests on the ITER MB jacket.
- ▶ Make tensile tests on full and sub-size samples for ITER CC and CB jacket.
- ▶ The tested CC and Feeder jacket has high performance on tensile property.

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ABSTRACT

This paper focuses on mechanical tests on the ITER correction coils (CC) and Feeder jacket 316L stainless steel material. During manufacture, the conductor will be compacted and spooled after cable insertion. Therefore, sample jackets were prepared under compaction in order to simulate the status of conductor during manufacturing. Yield strength (0.2% offset), ultimate tensile strength, Young's modulus and elongation at failure shall be reported. The mechanical properties of materials were measured at 300 K and low temperature (<7 K). The cryogenic test results show that the present jackets have very high properties. It is concluded that the results meet the ITER requirement.

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. 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; the main busbar for the TF, CS and PF feeders, referred to as MB; the corrector busbar for the CC feeders, referred to as CB. All coils with different dimensions used cable-in-conduit conductors (referred to as CICC). The cross sections of CC, MB and CB conductor are shown in Fig. 1. The CICCs are made of superconducting strand. The TF and CS conductors are made of Nb_3Sn strand, and PF, CC and Feeder conductors are made of NbTi strand. One of the key-point in CICC fabrication is the stainless steel jacket.

The 316L stainless steel materials will be used as the CC and Feeder (MB, CB) jackets. Since the conductor has to undergo compaction after inserting the superconducting cable into the jacket, the effect of cold work on the mechanical properties of jacket shall be investigated. It is also necessary to evaluate the mechanical test at low temperature because the CICC is operated at about 4.5 K. The normal stainless jacket without compaction is much different from compacted one, having different yield strength and elongation at failure. The properties of the PF and TF jacket have been investigated [3,4]. In order to evaluate the mechanical performance of the CC and Feeder jackets, tensile tests are performed. According to standardization, the full size samples need to be made for CC and CB jacket. But it is difficult to make the full size test because of absence of testing facility in China now. The sub-size samples are proposed to compare with full size samples. In China, the Institute of Plasma Physics of Chinese Academy of Sciences (ASIPP) is in charge of the research on CC and Feeder jacket, and all jackets from Jiuli Company. The cryogenic testing was made in Technical Institute of Physics and Chemistry of Chinese Academy of Sciences (TIPC) and CryoMak (Cryogenic-Material testing – Karlsruhe) laboratory at the Karlsruhe Institute of Technology (KIT) lab. The results

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Table 1
Chemical composition of CC, MB and CB jacket.

Element (wt.%)	Heat analysis			Jacket analysis			ITER requirement
	CC	MB	CB	CC	MB	CB	
C	0.013	0.012	0.020	0.015	0.008	0.021	<0.03
Si	0.288	0.330	0.470	0.261	0.362	0.442	<0.75
Mn	1.350	1.370	1.480	1.440	1.390	1.500	<2.0
P	0.022	0.007	0.027	0.018	0.008	0.022	<0.03
S	0.004	0.001	0.003	0.002	0.004	0.004	<0.01
Cr	16.25	16.50	16.29	16.29	16.50	16.39	16.0–18.5
Ni	13.66	12.53	13.91	13.70	13.64	13.77	11.0–14.0
Mo	2.130	2.300	2.170	2.280	2.100	2.120	2.0–2.5
Co	0.053	0.010	0.052	0.055	0.031	0.052	<0.1

Fig. 1. Cross section of conductor (left: CC, middle: MB, right: CB).

Table 2
Dimension of CC, MB and CB jacket (before compaction).

	CC	MB	CB
Outer diameter (mm)	23.2	47.8	23.9
Wall thickness (mm)	2.2	1.9	1.9

Table 3
Dimension of CC, MB and CB jacket (after compaction).

	CC	MB	CB
Outer dimension (mm)	19.2 × 19.2	44.5	22.0
Wall thickness (mm)	2.2	2.0	2.0
Dimension	Square	Circle	Circle

show that the CC and Feeder jackets have very good properties, which meet the ITER requirements.

2. Sample preparation and experimental procedure

The chemical compositions are shown in Table 1. The dimensions of the testing jacket are shown in Tables 2 and 3, Fig. 2.

Fig. 2. ITER CC, MB and CB jacket.

The tested jacket needs compaction in order to simulate the exact processing conditions of conductor manufacture. The CC and CB jacket need full size testing according to standard, but the sub-size samples are also proposed due to the lack of testing capability in China. The dimension of samples is shown in Fig. 3. 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 [5]. The samples were tested at room and cryogenic (<7 K) temperature, immersed in liquid helium.

3. Results and discussion

In this section, the tested results are given. Analysis of MB is shown in Fig. 4, including grain size and grain boundary sensitization. Pictures revealed no presence of ditches at grain boundaries and no visible ferrite content. Grain size measurement was performed, and the size number according to ASTM E112-96 (2004) e1 [6] is $G = 6.0$. The metallographic phase analysis of CC and CB jacket are also made, which are similar to MB jacket. All metallographic phases meet the ITER requirements of $G > 5$.

The tensile tests of all jackets were carried out according to ASTM E8M [5] and E1450 [7]. CC and CB jacket need full size test according to standardization [8]. But sub-size samples for CC and CB jacket were also used to compare with full size samples. All tensile tests were conducted in displacement control with the strain rate below $5 \times 10^{-4}\,\mathrm{s}^{-1}$. The samples were tested at cryogenic 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 summarized in Tables 4 and 5, Figs. 5 and 6.

2 samples at room temperature and 2 samples at 4.2 K of MB jacket were tested. The results are shown in Table 4, it can be seen that the jacket has similar elongation at failure at different temperatures (300 K and 4.2 K). The elongation decreased only about 10% when the temperature was reduced from 300 K to 4.2 K.

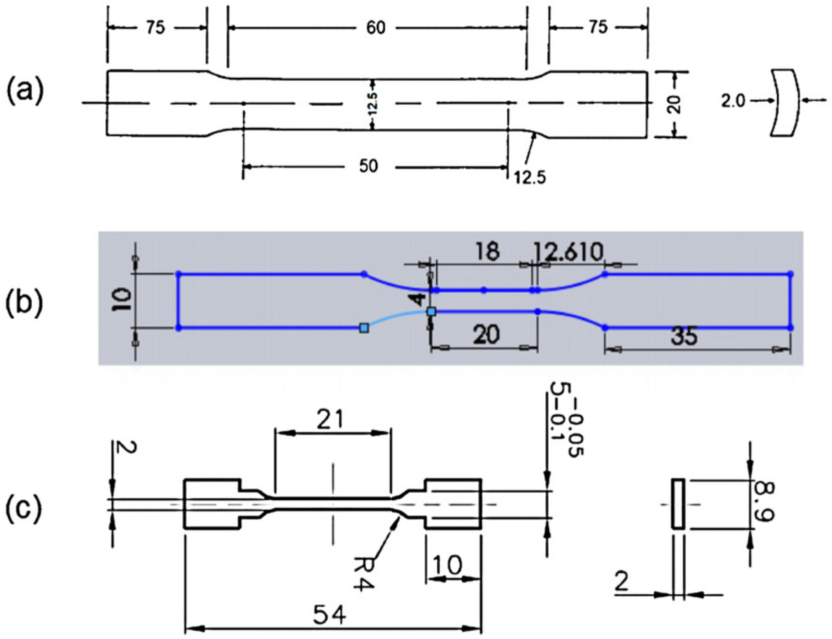

Fig. 3. Schematic of jacket mechanical testing sample (a: MB sample, b: CC and CB sample tested in TIPC, c: CC and CB sample tested in KIT).

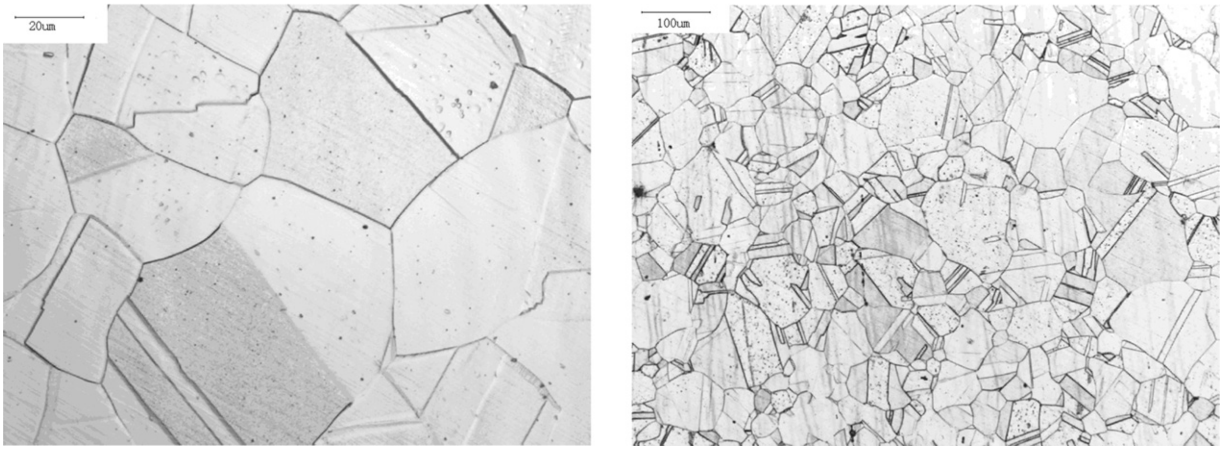

Fig. 4. Metallographic phase (MB jacket).

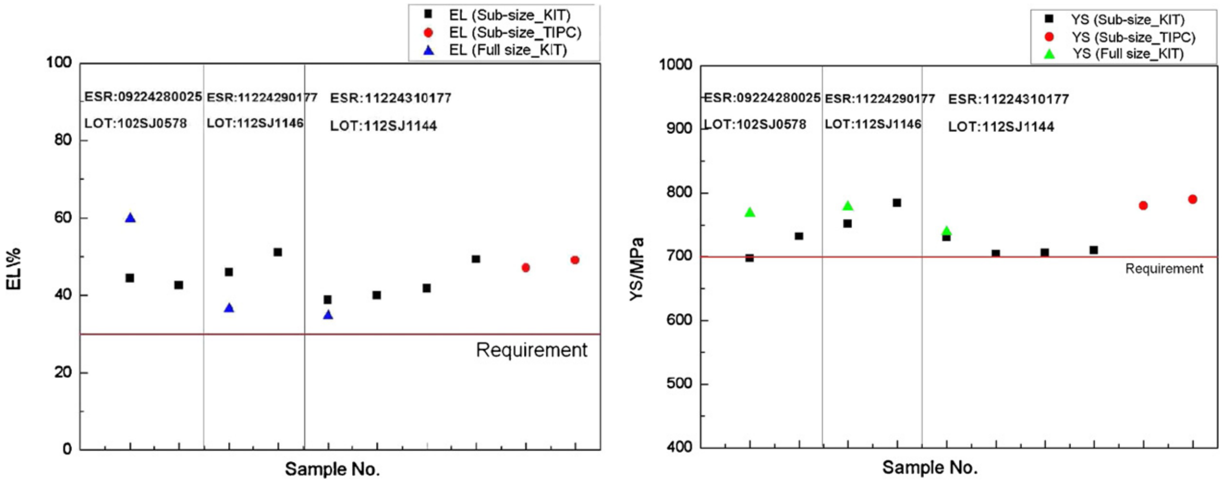

Fig. 5. CC tensile test results at low temperature (<7 K).

Table 4
Tensile test results of MB jacket.

Temperature	Sample	EL (%)	YS (MPa)	UTS (MPa)	YM (GPa)
300 K	Requirements	>35	>173	>483	>190
	1	40.3	488	650	192
	2	40.3	483	635	190
4.2 K	Requirements	>30	>700	>1000	>205
	1	37.2	773	1500	205
	2	36.0	710	1520	207

Table 5
Full size tensile test results of CC and CB jacket at room temperature.

Jacket	Sample	EL (%)	YS (MPa)	UTS (MPa)	YM (GPa)
	Requirements	>35	>173	>483	>190
CC	1	47.0	470	568	198
	2	46.0	483	583	198
CB	1	36.5	530	625	191
	2	36.5	525	625	192

For CC jacket, two full size samples at room temperature were tested, and the results were shown in Table 5. Three full size and ten sub-size samples from three different ESRs were tested at low temperature (<7 K), shown in Fig. 5. From the results, it can be easily found that the sub-size and full size samples have similar properties, except for the yield strength. For CB jacket, two full size samples at room temperature, one full size and two sub-size samples at low temperature (<7 K) from one ESR were tested. From Fig. 6, the elongation of full size sample is less than one of sub-size samples, but both are more than requirement. The yield strength of sub-size samples shows less value, which maybe caused by different dimension and error of computational value.

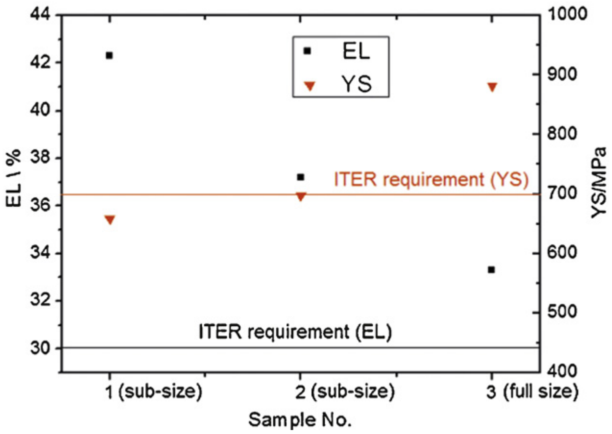

Fig. 6. CB tensile test results at low temperature (<7 K).

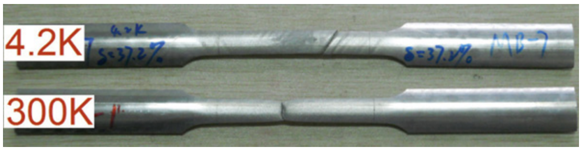

Fig. 7. Fracture surface of MB tensile samples tested in TICP.

As expected, the yield strength and ultimate tensile strength increased greatly by decreasing the temperature. The Young's modulus changed little from room to cryogenics temperature. Examples of the fractured tensile samples are shown in Figs. 5–9, and stress–strain curve is shown in Fig. 10. For the samples tested at cryogenics temperature, the angle of fracture surface is about 45°,

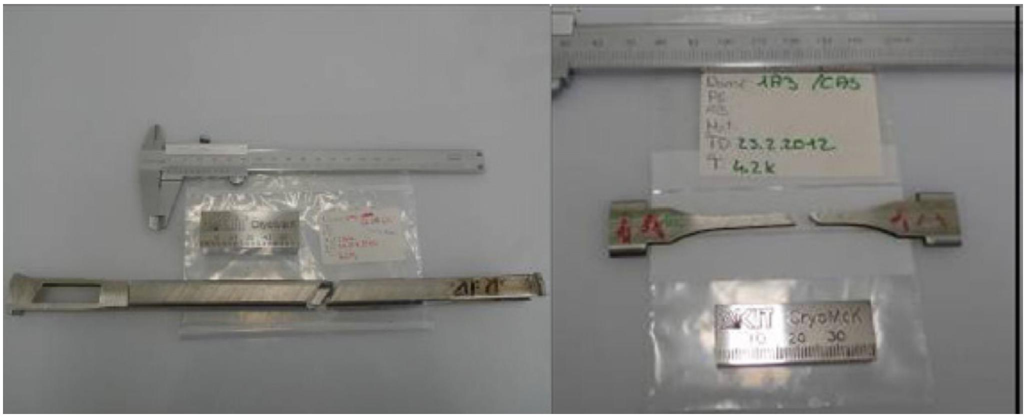

Fig. 8. Fracture surface of CC tensile samples tested at low temperature (<7 K) in KIT.

Fig. 9. Fracture surface of CB tensile samples tested at low temperature (<7 K) in KIT.

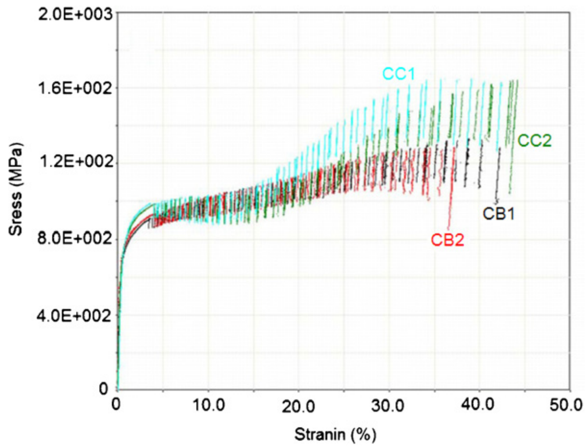

Fig. 10. The stress–strain curve for CC and CB full size samples at 4.2 K.

which is different from those of samples tested at room temperature. The angle of the fracture surface shows a distinct behavior of ductile fracture.

4. Conclusions

The ITER CC and Feeder conductor jacket needs compaction. The mechanical samples were prepared under compaction according to the ITER requirements. The tensile samples were tested at cryogenic temperature ($T < 7$ K), including sub-size and full size samples. The test results were discussed, and showed that requirements were fulfilled.

Acknowledgements

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References

[1] ITER Structural Design Criteria for Magnet Components (SDC-MC), N11 FDR 5001-07-05 R 0.1, NAKA, Japan, 2001.
[2] ITER Final Design Report, IAEA Vienna and ITER IT Team Design Description Document 1.1 Update, January 2004.
[3] H. Liu, Y. Wu, Q. Han, Z. Wu, L. Li, Mechanical tests on the ITER PF 316L jacket after compaction, Cryogenics 51 (2011) 234–236.
[4] J. Qin, Y. Wu, K. Weiss, Z. Wu, and L. Li, Mechanical test on the ITER TF jacket, Crogenics 52 (2012) 336–339.
[5] Standard test method for tension testing of metallic materials, ASTM E8M, 2004.
[6] Standard test methods for determining average grain size, ASTM E112-96 (2004) e1, 2004.
[7] Standard test method for tension testing of structural alloys in liquid helium, ASTM E1450, 2003.