STUDY ON JACKET PERFORMANCE AND CRAFT TF COIL HEAT TREATMENT

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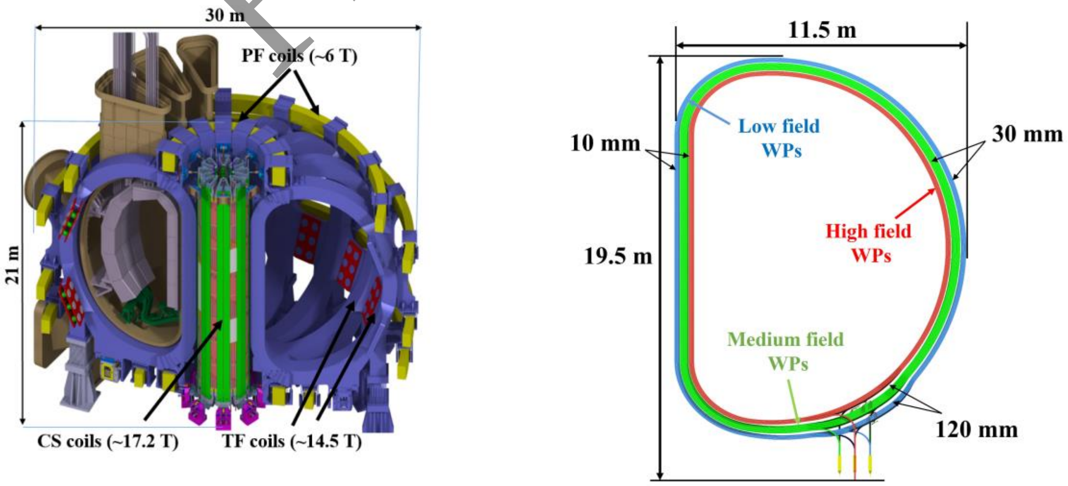
Abstract

Modified 316LN and JK2LB stainless steel were selected as candidate jacket materials for superconducting cable in conduit conductors (CICC) of the China Fusion Engineering Test Reactor (CFEDR). Different superconducting conductors need to undergo different cold working deformations and different heat treatment processes during the manufacturing process. Therefore, a systematic investigation was done to examine the influence of different cold working deformations and different heat treatment processes on the mechanical properties of the two materials. The mechanical properties of materials were measured at 4.2 K, 77 K and 300 K, and Young's modulus, yield strength (0.2% offset), ultimate tensile strength and elongation at failure were reported. In addition, the fracture morphology of all tensile samples was observed by backscattered-electron imaging (BSEI). In addition, to evaluate the final mechanical properties of CICC conductors wound into coils under actual service conditions, heat treatment was performed on CRAFT TF coils. The experimental measurement results were excellent.

1. INTRODUCTION

Magnetic confinement Tokamak is one of the most promising devices which can realize controlled thermonuclear fusion and solve the problem of the human energy crisis. The magnet system is the core component of Tokamak, mainly including central solenoid (CS) coils, toroidal field (TF) coils and poloidal field (PF) coils. The magnets are usually considered to be semi-permanent and should not require much maintenance. CS and PF coils excite poloidal magnetic fields, which are used to heat plasma, counteract plasma's expansion, balance and control plasma. TF coils excite strong toroidal magnetic fields, which are mainly used to confine plasma [1-2]. The CS and TF coils are located in the strong magnetic field region of the device. In 2018, the Comprehensive Research Facility for Fusion Technology (CRAFT) project was officially initiated to conduct pre-studies of the China Fusion Engineering Demo Reactor (CTEDR) prototype components and systems. The CRAFT TF coil incorporates a hybrid superconducting magnet structure, integrating high-field, medium-field, and low-field winding packs (WPs). The high-field, medium-field and low-field coils are made of high-performance Nb_3Sn material, ITER-grade Nb_3Sn material and NbTi material respectively. Fig. 1 shows the main components of the CTEDR magnet system and the dimensions of the CRAFT TF coil winding.



(a) (b)

Fig. 1. (a) Main components of the CFEDR magnet system; (b) The dimensions of the CRAFT TF coil winding.

Based on the current development process of Tokamak device upgrading, there is a tendency towards larger systems with higher magnetic field strengths. It is inevitable for the magnet system to adopt superconducting magnets or even high-temperature superconducting magnets, such as International Thermonuclear Experimental Reactor (ITER) and CFEDR, etc [3-4]. All coils of the superconducting Tokamak are designed with different sizes of Cable-In-Conduit Conductors (CICC) and will be cooled by forced flow of supercritical helium. Here the conduit is a stainless jacket that acts not only as the helium pressure vessel but also as a bearing structure for the huge electromagnetic force.

Nb_3Sn, MgB_2, REBCO and Bi-2212 are typical examples of practical superconducting materials. The former has been applied successfully, and the latter three are the candidate materials for future superconducting coils of fusion magnets. Nb_3Sn is the material of choice for the current design of CFEDR superconducting magnets. Compared with NbTi, MgB_2 has the advantages of higher superconducting transition temperature and lower raw material cost. It is considered to have the potential to replace NbTi superconducting coils and be applied to PF coils [5]. From the current design point of view, the MgB_2 material has been listed as a spare material for the manufacture of CFEDR PF coils. The design value of the maximum magnetic field of the CFEDR CS coil is 17.2 T, which is a great challenge for Nb_3Sn material. REBCO and Bi-2212 magnets can be used as the insert solenoid coil of CS coils to develop CFEDR high-field magnets [6-8]. In the future, it may also replace Nb_3Sn materials and develop high-temperature superconducting fusion magnets [9]. Except for REBCO, all of these superconducting materials require heat treatment to form the superconducting phase, and they are all brittle materials. Thus superconducting coils produced with wind and react techniques are preferred [10-11].

As stainless-steel jacket material in CICC structure, the importance of the properties of low-temperature steel was underestimated previously [12]. Conductor jacket must be subjected to tremendous forces during the manufacturing and energizing of the coils. Therefore, it is required that the jacket not only has great strength but also good toughness at low temperature. At present, the yield strength of the commonly used stainless steel jacket materials 316LN and high manganese steel JK2LB can reach around 1050 MPa at 4.2 K, which have been successfully applied in superconducting magnets, especially in ITER [13-14]. Several studies have estimated the mechanical behavior of conduits after compaction and aging treatments [15-18]. However, there is still insufficient research data about the effect of different cold working deformations and different aging treatments on the mechanical properties of different materials. The current CFEDR central solenoid model coil (CSMC) requirements for the CS conduit are yield strength >850MPa and elongation >25% at 4.2 K, in a process state that consists of prior cold work and post-aged thermal treatment [19]. The modified 316LN and high Mn-bearing austenitic stainless steels JK2LB have become the preferred jacket materials for the CFEDR, and the coefficient of thermal expansion between room temperature and 4.2 K of JK2LB is lower than that of modified 316LN [20-23].

The Nb_3Sn conductor jacket of the CRAFT TF consists of circle-in-square extruded and drawn austenitic stainless-steel pipes. The conductor material used for the CRAFT TF coil is modified 316LN, with a cross-sectional dimension of 64 mm × 64 mm. 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 the jacket needs to be investigated.

This paper studies the mechanical properties of modified 316LN and JK2LB materials under the variation of cold working conditions, four different annealing conditions and three different test temperatures. The dependence on mechanical properties and microstructure of fracture has been assessed for the different samples. Scanning electron microscope analysis indicates that the fracture mechanism combines ductile and brittle fractures. Additionally, the heat treatment results and contour deformation of the CRAFT TF coil were demonstrated.

2. EXPERIMENTAL SECTION

2.1. Experimental material

Two kinds of materials are used in this experiment, namely modified 316LN jacket and JK2LB jacket, which are provided by Jiuli company. The process for base material production underwent an electro-slag re-melting (ESR) step to ensure refined and clean steel microstructures featuring a limited amount of nonmetallic inclusions and an absence of exogenous macro-inclusions.

Sample preparation will follow the sequence of cold working (CW), heat treatment (HT) and wire-cut sampling to simulate the CICC manufacturing process. The jackets were compacted into two dimensions in a single step using a cold-rolling machine. Through cold working, the total deformation of one jacket reaches 5.1% (actual deformation of CSMC conductor manufacturing) and the other reaches 9.2% (study the mechanical properties of jacket after large deformation). The amount of cold work was estimated by measuring the elongation of the jackets in the longitudinal direction. The jacket dimensions before and after cold working are listed in Table 1.

Table 1. The jacket dimensions before cold working and deformation after cold working.

Identification	Cold working deformation
CW0	0%
CW5	5.1%
CW9	9.2%

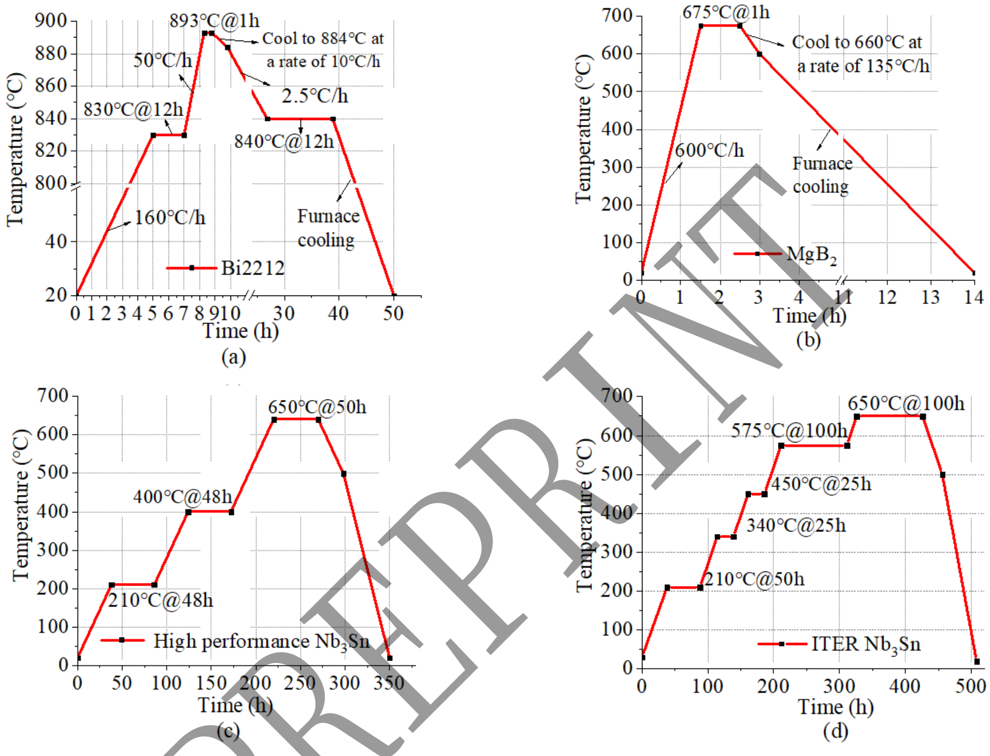


Fig. 2. Four kinds of heat treatment regimes (a: Bi-2212 heat treatment regime, b: MgB_2 heat treatment regime, c: high-performance Nb_3Sn heat treatment regime, d: ITER Nb_3Sn heat treatment regime).

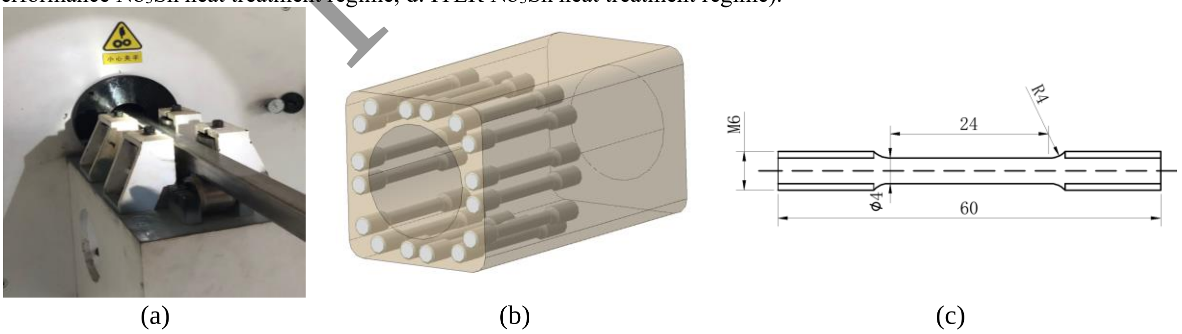


Fig. 3. The schematics and dimensions of the sample preparation (a: Jacket cold working, b: The cut position of samples from the jacket, c: Sample dimensions).

After cold working, the jackets will be annealed in a vacuum furnace. During the heat treatment process, the vacuum is kept at about 5×10^{-3} Pa, and the temperature uniformity in the furnace is less than ±3°C. Four kinds of heat treatment regimes were used in this experiment, which are Bi-2212 heat treatment regime (provided by Northwest Institute for Non-Ferrous Metal Research), MgB_2 heat treatment regime (provided by University of Twente), high-performance Nb_3Sn heat treatment regime (provided by Western Superconducting Technology) and ITER Nb_3Sn heat treatment regime (provided by ITER). Four kinds of heat treatment are shown in Fig. 2. REBCO does not require heat treatment. We have designed a set of samples that have not undergone annealing for mechanical performance evaluation to explore the possibility of REBCO CICC conductors.

The tensile specimens are taken from various locations around the jacket's circumference along the jacket's longitudinal direction by wire cutting. Round bar specimens with a diameter of 4 mm and a length of 60 mm were used for the tensile test in accordance with relevant ASTM standards. A total of 240 specimens were prepared for testing in this experiment. All tensile samples were tested at the Technical Institute of Physics and Chemistry, Chinese Academy of Sciences. The schematics and dimensions of the sample preparation are shown in Fig. 3.

2.2. Experimental method

The samples were measured at room temperature (RT), liquid nitrogen (LN_2) and liquid helium (LHe) respectively. When tested at cryogenic temperature, the samples were put in a thermal-insulator sleeve and immersed in liquid nitrogen or liquid helium. Tensile tests are conducted in displacement control with the strain rate below 5×10^{-4} s^{-1}, according to procedures prescribed in ASTM E1450. Strain is measured with a 10% strain range clip-on extensometer in the test. Obtain the mechanical properties parameters of the sample through testing, including elongation at failure (EL), 0.2% yield strength ($YS_{p0.2}$), ultimate tensile strength (UTS) and Young's modulus (YM). The sample coding format is composed of four parts: test temperature (RT: 300 K, LN_2: 77 K, LHe: 4.2 K), material type (N: modified 316LN, M: JK2LB), cold working deformation (CW0: 0% cold working deformation, CW5: 5.1% cold working deformation, CW9: 9.2% cold working deformation) and heat treatment process (HT0: No annealing, HTB: Bi-2212 HT, HTM: MgB_2 HT, HTN: high-performance Nb_3Sn HT, HTI: ITER Nb_3Sn HT). Sample coding format specification is shown in Fig. 4. For example, RT-N-CW0-HT0 represents that modified 316LN specimens are tested at room temperature without cold working and heat treatment.

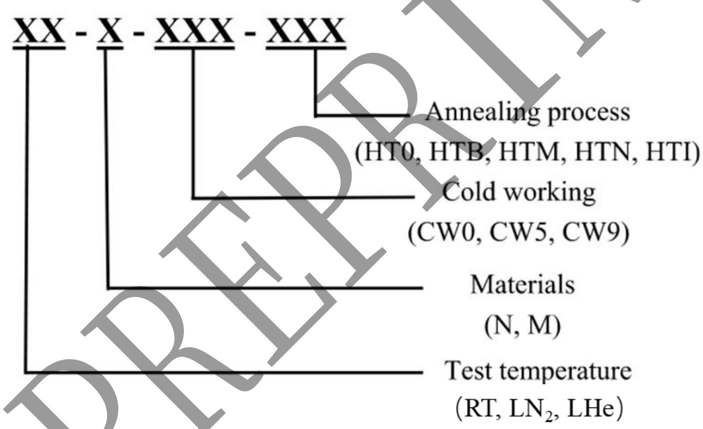


Fig. 4. Sample coding format specification.

2.3. CRAFT TF Heat treatment system

Following the winding process, Nb_3Sn coils require heat treatment to achieve superconducting properties. Since Nb_3Sn superconductors are extremely sensitive to stress and strain, the manufacture of TF coils will still adopt the "wind and react" process. Fig. 2(c) and (d) present the two optimized heat treatment profiles for the CRAFT TF Nb_3Sn coil. The Institute of Plasma Physics of the Chinese Academy of Sciences (ASIPP) and Shenyang Vacuum Technology Institute Co., Ltd. cooperate to design and build a full argon atmosphere oven heat treatment system. This comprehensive system for CRAFT TF coil heat treatment integrates multiple functional subsystems: power distribution, thermal reaction chamber, transportation/loading carriage, hot air circulation, water cooling, controlled argon gas protection, and data acquisition/monitoring systems. The system features a total power capacity below 4 MW, with a maximum operating temperature of 750 ℃ and a loading capacity of 150000 kg. The effective temperature uniformity zone measures 20.1 m (length) × 11.5 m (width) × 1.5 m (height). The system incorporates 18 variable-frequency fans and a specially designed D-shaped flow guide device, which enhances forced convection and improves heat exchange efficiency within the furnace chamber. Fig. 5 is a picture of the heat treatment system.

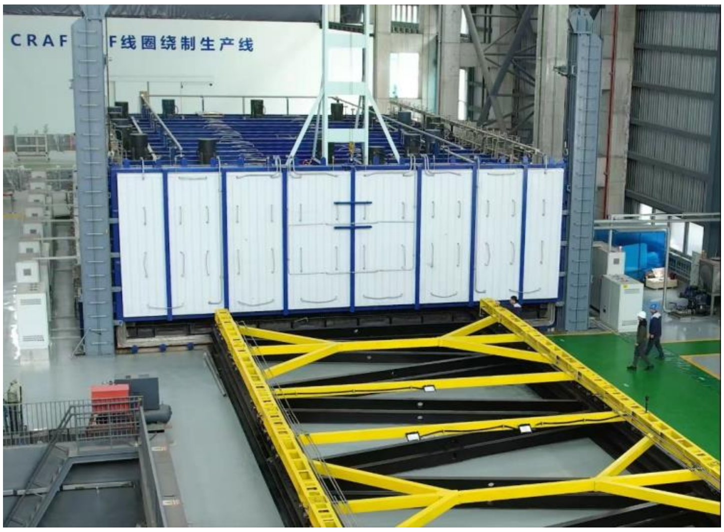


Fig. 5. The picture of the heat treatment system.

3. RESULTS AND DISCUSSION

3.1. Mechanical Properties of Modified 316LN and JK2LB

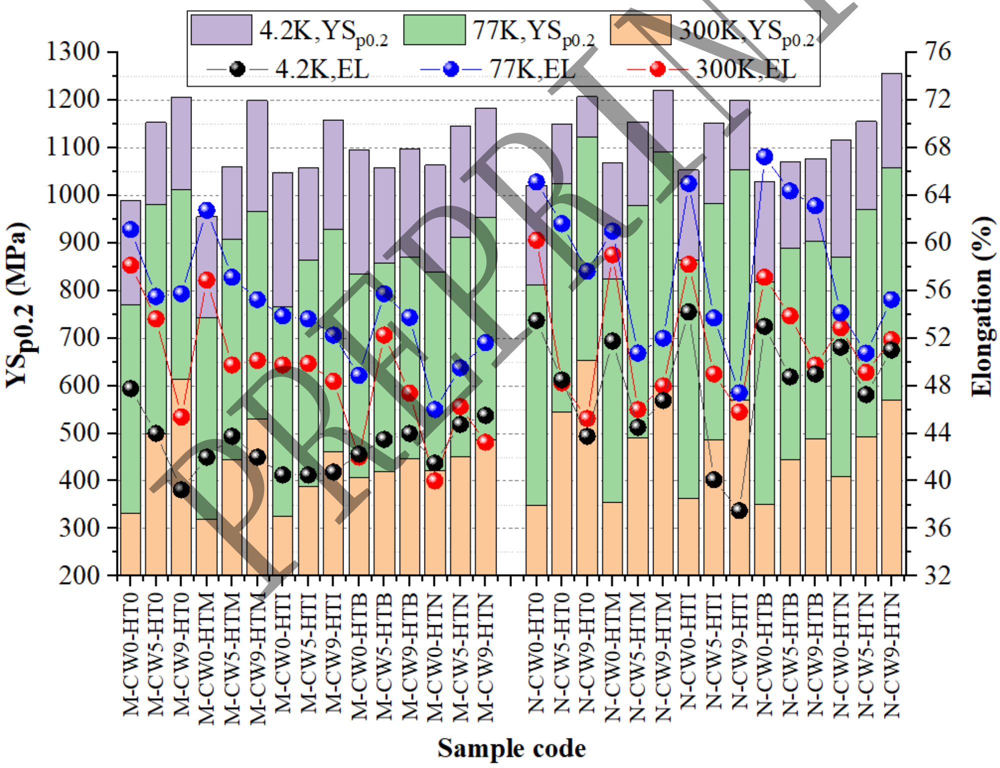


Fig. 6. The yield strength and elongation of samples.

Two to four tensile tests were performed on each type of sample. The yield strength and elongation of the two materials are shown in Fig. 6. (The data in Fig. 6 is averaged values for two to four tensile test samples.) All JK2LB and modified 316LN samples with a cold working deformation of 5.1% (actual deformation of CSMC conductor manufacturing) have a yield strength >1050 MPa and elongation >40% under 4.2 K test conditions. The mechanical performance test results of the experimental samples all meet the technical requirements of CFETR CSMC. In addition, the slight effects of different heat treatment processes on the mechanical properties of the samples are also within the specified technical requirements. Therefore, both modified 316 LN and JK2LB made in China can be used as jacket materials for Nb_3Sn, MgB_2 and Bi-2212. Bi-2212 needs to be heat treated in an oxygen environment. Thus, these two jacket materials cannot be used directly, but they can be combined with high-temperature alloy steel to form a composite tuber.

3.2. BSEI analysis

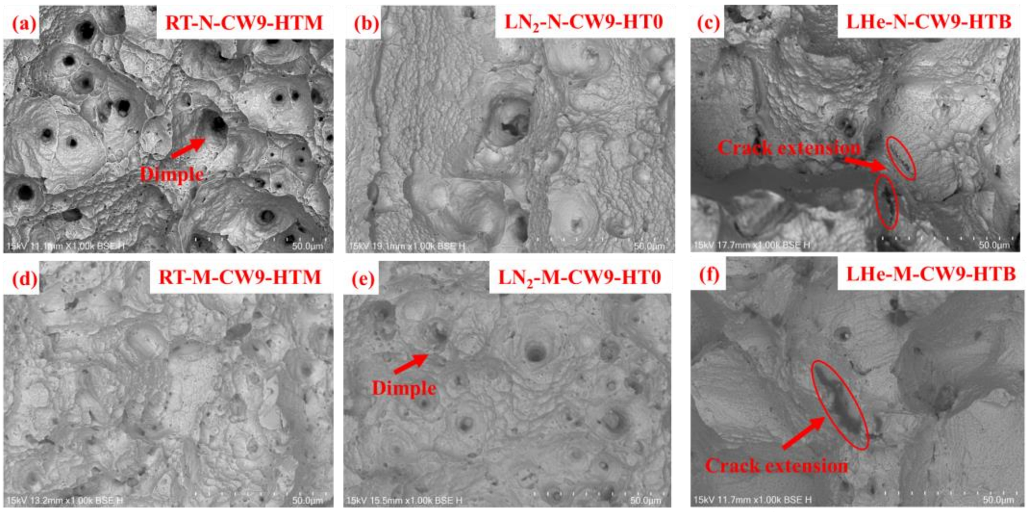
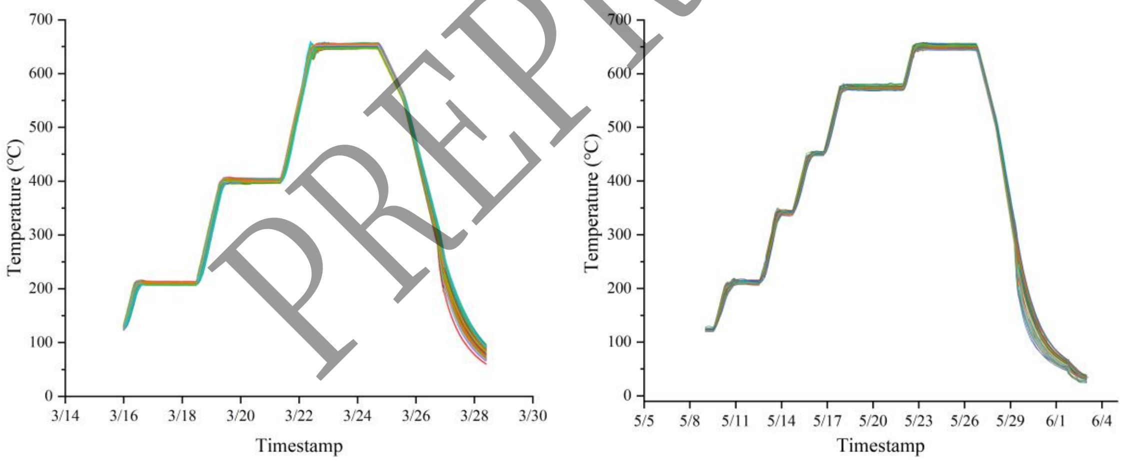


Fig. 7. The BSEH image of the fracture surface of some types.

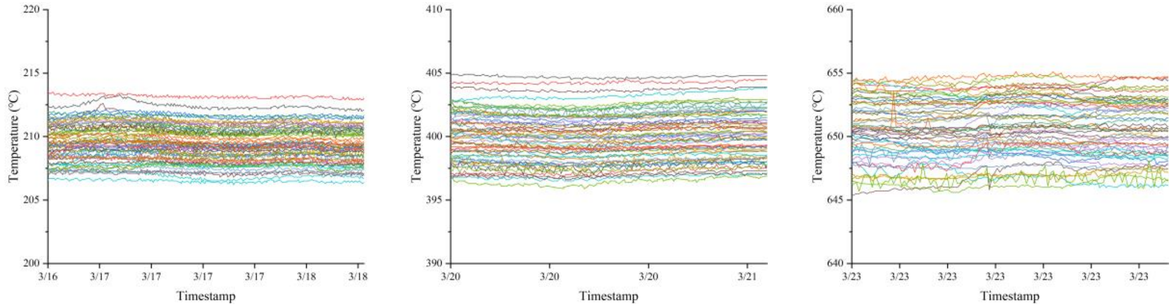
To fully understand the fracture mechanism of the material, we used backscattered electron imaging (BSEI) technology to scan all the sample fracture positions. From the scanning results, it can be seen that each sample has the characteristics of ductile failure mode dimple structure. The fracture of all samples contained a large number of dimples and micropores. It is observed that the fracture mode of the samples with different heat treatment regimes at the area across the slip band is similar to the samples without heat treatment. However, cracks were observed at the fracture of the samples after Bi-2212 heat treatment. The microstructure morphology of some samples is shown in Fig. 7.

3.3. TF Coil Heat Treatment



(a) (b)

Fig. 8. (a) TF high-field coil. (b) TF medium-field coil. (In the X-axis, “yyyy/mm/dd” indicates year/month/date.)

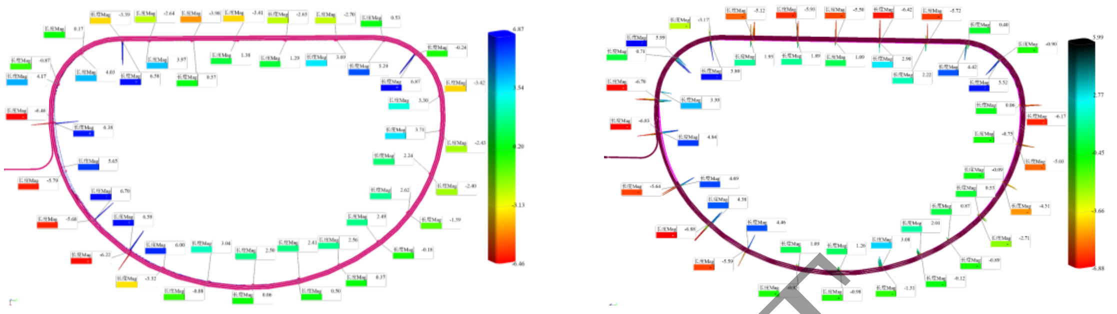


(a) (b) (c)

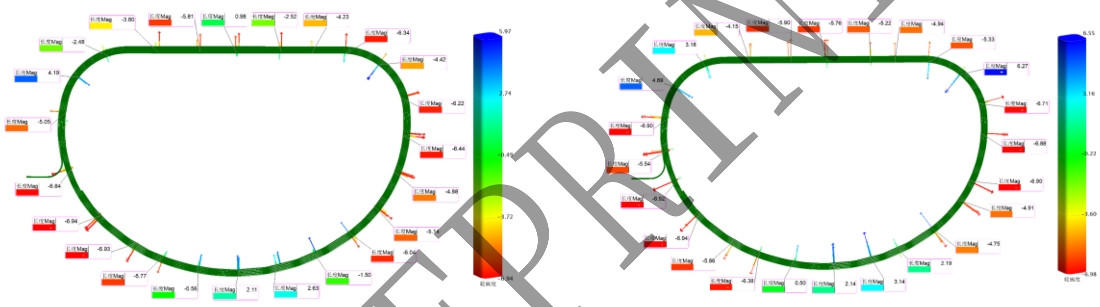
Fig. 9. The temperature uniformity across all key insulation platforms.

The TF coil successfully completed its heat treatment process. The temperature evolution throughout the heat treatment process is recorded in Fig. 8. The temperature uniformity across all key insulation platforms, as shown in Fig. 9. Notably, during the critical plateau at 650 °C on the heat preservation platform, the temperature uniformity remained within ± 5 °C, meeting the specified requirements.

Before and after heat treatment, the TF coil contour is measured by the laser tracker and compared with the standard design model to obtain the TF winding deformation. The deformation of the high-field and medium-field coils before and after heat treatment is less than ± 1 mm. It can be confirmed that the coil size satisfies the requirements. The coil geometry measurement after heat treatment is shown in Fig. 10.



(a) High-field coil (Left: Before heat treatment; Right: After heat treatment).



(b) Medium-field coil (Left: Before heat treatment; Right: After heat treatment).

Fig. 10 The geometry measurement of the TF coil.

4. CONCLUSION

CICC type coils need to undergo cold working and heat treatment during manufacture. To systematically evaluate the mechanical performance of the modified 316LN and JK2LB jacket material under different conditions, different cold working and aging were applied to the materials. The mechanical tensile tests were performed at 4.2 K, 77 K and 300 K. The test results show that the JK2LB and modified 316LN jackets after cold working and aging have a yield strength >1050 MPa and elongation >30% at 4.2 K. Scanning electron microscope analysis indicates that the fracture mechanism was the combination of ductile fracture and brittle fracture at 4.2 K for modified 316LN. This study has accumulated a large amount of data on the mechanical properties of the jacket and laid the foundation for the subsequent jacket development. Modified 316LN and JK2LB produced in China have been successfully applied in Nb_3Sn CICC conductors. Currently, the winding technology for large-scale TF coils has been successfully validated at ASIPP, and the heat treatment experimental outcomes of the TF coils have shown promising results.

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