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Axial strain characterization of the Nb_3Sn strand used for China's TF conductor☆

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ABSTRACT

Oxford Superconducting Technology (OST) has developed a type of Nb_3Sn strand which can be used in the ITER TF coils. The strand (billet number is OST 10424FE) is made by an internal tin process. The critical current (I_c) has been measured subjected to uniaxial strain in the Twente University. The strand is destined for the cable-in-conduit conductors (CICC) of the China first short conductor sample for ITER toroidal field coil. For the uniaxial strain characterization, the voltage–current characteristics were measured with an applied axial strain from −0.8% to +0.5%.

The strand appears to be fully reversible in the compressive regime during the axial strain testing, while in the tensile regime, the behavior is already irreversibly degraded when reaching the maximum in the critical current versus strain characteristic. The parameters for the improved deviatoric strain description are derived from the I_c data, giving the accuracy of the scaling with a standard deviation of 1.5 A, which is by far within the expected deviation for the large scale strand production of such a high I_c strand. Analysis of the relation between I_c, n index and the axial strain is reported.

1. Introduction

The magnet system for international thermonuclear experimental reactor (ITER) consists of 18 toroidal field (TF) coils, a central solenoid (CS), six poloidal field (PF) coils and 18 correction coils (CCs) (Fig. 1). All coils are superconducting. The TF coils generate the field to confine charged particles in the plasma, the CS coils provide the inductive flux to ramp up plasma current and contribute to plasma shaping, the PF coils provide the position equilibrium of plasma current (i.e. the fields to confine the plasma pressure) and the plasma vertical stability. The CCs allow correction of error field harmonics (up to 3 harmonics in toroidal and poloidal directions) due to position errors as well as from busbars and feeders [1,2].

The ITER TF coils require a higher-performance Nb_3Sn strand than that developed during the ITER model coil project, in order to recover the loss in conductor critical current caused by transverse electromagnetic forces acting inside the conductor. The minimum acceptable value for the critical current is 190 A made by a bronze process and 230 A internal tin process strand under a strain of 0.25%, a temperature of 4.2 K and a magnetic field of 12 T [3]. During operation the Nb_3Sn strands in the ITER TF coils will undergo strain, so they have to be characterized under relevant strain conditions to be able to predict their performances in the TF coils [4]. This paper presents the results of strand characterization by using Pacman apparatus carried out at Twente University [5].

2. Specification of the strand

The high current density strand manufactured by Oxford Superconducting Technology (OST) follows the internal tin method and the billet number is OST 10424FE. The specification is given in Table 1.

A cross-section of the strand before heat treatment (HT) and the filament bundle is shown in Fig. 2.

Before the heat treatment, the chrome layer on the wire surface of all samples, except for some of the axial stress–strain samples, was removed by etching with a 37% solution of hydrochloric acid.

The samples for all I_c measurements were heat treated in vacuum following the HT schedule used: 38 h at 210 °C; 25 h at 340 °C; 25 h at 450 °C; 100 h at 575 °C; 100 h at 650 °C; with a ramp rate of 10 °C/h The temperature was within 2 °C deviation from the specified value.

3. Uniaxial strain

3.1. Experimental arrangement for I_c versus uniaxial strain testing in Twente University

After the HT the sample was transferred carefully to the Pacman spring and was fixed with Sn–5 wt% Ag solder at about 500 K. Fig. 3 shows a view of the Pacman [5] spring with a wire sample soldered.

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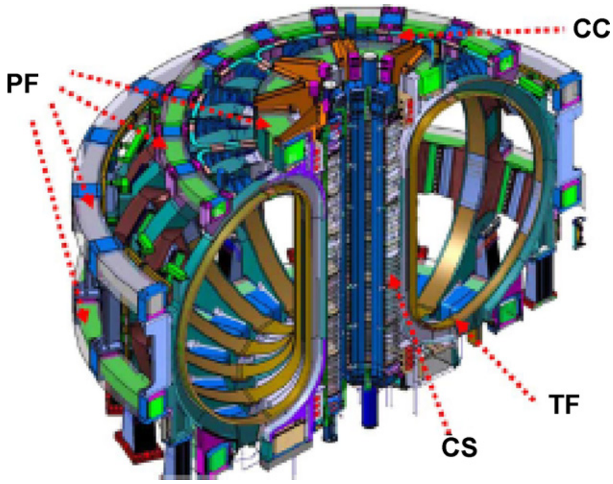

Fig. 1. The ITER coils.

Table 1
The structure parameter of Nb_3Sn strand.

Parameter	Numeric values
Diameter	0.82 mm ± 3 μm
Cr plating	1.0 μm
Twist pitch	17 mm
Cu/non-Cu ratio	0.933
Twist direction	Right
I_c (4.2 K, 12 T, 10 μV/m, A)	271.9
n (4.2 K, 12 T)	27.6

The Pacman spring is a circular bending beam made of Ti alloy with a T-shaped cross-section. The strain on the outer surface of the beam is controlled by the torque applied to the spring and it is measured by the strain gauges attached to the spring. The rotation induced by the motor–worm gear combination at room temperature is transferred to the low-temperature region through a set of concentric tubes, coupled mechanically with the two revolving halves of the Pacman spring support.

The temperature variations are applied by placing a polyimide insulator cup over the Pacman, thus creating a helium gas volume. Cooling and heating paths on the spring are symmetrical. Two thermometers are used so that the temperature gradient over the measured sample length can be minimized. The temperature can be balanced well within ±20 mK. The set-up is inserted into the bore of a superconducting solenoid, with the magnetic field perpendicular to the sample.

Fig. 2. The cross-sectional area of Nb_3Sn strand before heat treatment.

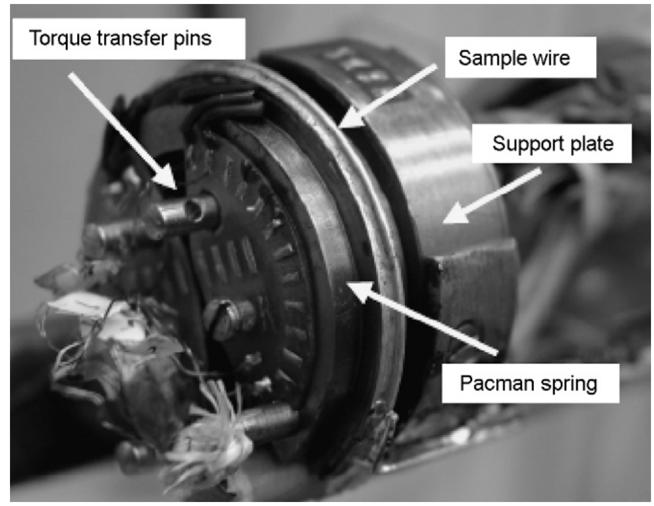

Fig. 3. Overall view of the Pacman spring with the sample soldered.

3.2. Experimental results I_c versus uniaxial strain testing

In total about 60 VI curves as a function of strain (−0.8% to +0.5% applied), temperature (4.2, 6, 8, 10, and 12 K) and magnetic field (6, 8, 10, 12 and 14 T) were measured per sample during the experimental phase. The maximum critical current in the experiment exceeds 500 A. The critical current criteria is $E_c = 10\,\mu V/m$ [6].

The results of the critical current measurements as a function of strain, temperature and magnetic field are summarized in Figs. 4–6.

3.3. n-value

The n-value is commonly used to characterize the sharpness of field-current transition in superconductors, which is related to the performance degradation and the filaments uniformity. Like I_c of strands, the n-value varies with field, temperature and strain for superconducting wires. Fig. 7 shows the n-value plotted as a function of applied strain for the strands of OST.

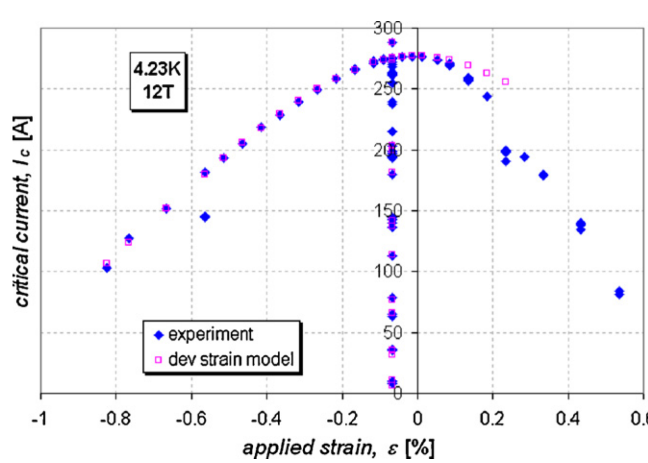

Fig. 4. Critical current as a function of applied strain.