Compressive Pre-Strain in Nb₃Sn Strand by Steel Tube and Effect on the Critical Current Measured on Standard ITER Barrel

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Abstract—The large Cable-In-Conduit Conductors (CICC) designed for the magnet coils in the International Thermonuclear Experimental Reactor (ITER), are composed of Nb₃Sn strand bundles in a Stainless Steel (SS) or Incoloy conduit. Both, the thermal contraction of the strand composite and the conduit material, define the final pre-strain after cooling down and thus affect the strand critical current (I_c). The transverse forces, introduced when charging a coil, in addition affect the overall strain state due to bending and pinching of strands. Recently, periodic bending tests were applied on strand samples without additional axial compressive pre-strain. Here we explore the method of swaging a SS-tube around a strand to imitate the cool-down strain effect of the conduit. The experimental results of the I_c measurements at 12 T and 4.2 K are presented for a Nb₃Sn PIT strand with and without swaged SS tube on both Ti-6Al-4V and SS standard ITER sample holder (barrels). The effect of gluing the sample to the barrel is also investigated. The intrinsic strain state of the samples is verified by measurement of the I_c versus applied strain with the Pacman spring.

Index Terms—Bending, CICC, force, Nb₃Sn, strain, superconductor.

I. INTRODUCTION

THE multi-stage cabled conductors designed for ITER consist of about thousand strands of 0.8 mm diameter. The round cable with an internal cooling channel is swaged in a square conduit made of SS or Incoloy [1]. In ITER Model Coils and short sample tests on Nb₃Sn CICC's, a broader voltage-current (V) transition to the normal state was observed, compared to the basic strand performance, resulting in a degradation of the superconducting properties [2], [3]. The correlation of degradation with charging of the conductors strongly suggests that the transverse force change the strain state and hence the I_c of the filaments [4], [5].

The nominal void fraction in the cable area filled with strands of the CICC's and Model Coils tested up to now is 36%. At this relatively large void fraction, the individual strands have fairly large freedom and space to move when subjected to strong transverse forces. These transverse forces, definitively causing a deformation of the strand bundle [6], results into elastic and plastic

changes in terms of local pinching and bending of strands. This in turn affects the strain state of the Nb₃Sn filaments (reversible or irreversible) and causes a possible change of the conductor performance in terms of critical current (I_c) or current sharing temperature (T_{cs}). Some of these effects are simulated on single strands in a recently developed setup named TARSIS [7], [8]. However, the strands subjected to a periodic bending strain in TARSIS, were tested without any additional uni-axial thermal pre-strain. The strand was not glued to the Ti-6Al-4V sample holder but secured at the bend around the last pins toward the current leads. It is kept in place between the pins and bulges of the bending strain device [7].

It was shown earlier that there is a relation between the thermal cool-down (axial) pre-compression and the degree of permanent degradation in Nb₃Sn CICC's [6]. This pre-compression, caused by the conduit having higher coefficients of thermal expansion (CTE) than the strands, gives the filaments an enhanced protection against tensile strains, leading to less filament cracks or even recovery of I_c .

A way to create a thermal pre-strain, for a periodic bending test with TARSIS, is by swaging the strand tightly into a SS tube [9]. In order to explore this method and to gain experience and estimate the strain state, we performed some introductory experiments with "bare strands" and "strands in SS-tube" on standard ITER barrels. I_c -strain measurements were carried out on the Pacman [10] for a first order evaluation of the strain state. Although we realize that the radial component of the strain, introduced by the SS tube, may affect the superconducting properties and so the strain sensitivity, these effects are neglected here for reasons of simplicity [11], [12].

II. EXPERIMENTAL SETUP AND SAMPLE PREPARATION

A. Wire Samples on ITER Barrel

The strand that was used up to now in the TARSIS setup to investigate the impact of periodic bending is a high current density binary Powder in Tube (PIT) wire that was manufactured by Shape Metal Innovation (SMI). The same strand, with a diameter of 0.805 mm, was used for preparation of samples on standard ITER I_c barrels. Strand sections were swaged tightly into a SS (AISA-304) tube. The dimension of the commercially available SS tube is chosen such that the ratio of SS and sc-strand in the cross section is close to the ratio of a full-size ITER CICC (strand bundle vs. square conduit). The SS tube had an initial outer diameter of 1.30 mm and an inner diameter of 0.90 mm. The strand was carefully (but lightly) cleaned with a nitric acid

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Fig. 1. Detail of the I_c sample showing the wire crossing from copper ring (top) to Ti-6Al-4V barrel and then reaching the section with swaged SS tube.

solution and the inner wall of the SS tube was cleaned with ethanol. After swaging, the strand diameter (and inner SS tube diameter) became 0.78 mm, calculated on the basis of the elongation. The final outer tube measured diameter was 1.21 mm. The ratio of strand to SS conduit became 0.71. The strand to conduit ratio for a CS1 type of CICC is about 0.58 and for a CS2 type it is 0.41. This means that the strand-SS-tube is most dominated by the conduit material for this comparison.

In order to distinguish between the CTE of barrel holder material, two different alloys were chosen, the standard Ti-6Al-4V and SS-316.

Some laboratories prefer to glue the sample to the barrel prior to testing and others do not. In order to explore possible variations, we applied both methods. For gluing the wire to the barrel, we used Stycast 2850-FT.

For the samples indicated as Ti-1 (glued), Ti-3 (not glued), SS-1 (glued) and SS-3 (not glued) (see Table I), the strand section with SS tube wound around an I_c -barrel, comprises seven full turns. The last full turns, in the outer grooves of the barrel at both ends, are without SS tube (see Fig. 1). Ti and SS represent barrels made from Ti-6Al-4V and SS respectively. Also four samples were prepared without swaged SS tube, indicated as bare strand specimen Ti-2 (glued), Ti-4 (not glued), SS-2 (glued) and SS-4 (not glued). The ends of the wires were fixed by screws on the copper rings prior to heat treatment. The copper rings serve to transfer current to the current leads.

Two extra “strand-in-SS-tube” samples were prepared on Ti-barrels but with longer SS tube, containing the strand even along half a turn on the copper ring at both ends. Then the bare strand leaves the SS-tube for being soldered to the copper ring. These samples were clamped by additional screws at the end of the SS-tube. This way the bare ends are protected against lacing up during cool-down due to the tension on the wire-SS-tube generated by the lower CTE of the Ti-6Al-4V barrel. An overview of the I_c -barrel samples is given in Table I.

All samples were tightly wrapped with glass fiber tape to the sample holder for moderate support during the heat treatment (except Ti-6 and Ti-7), preventing additional yielding of the composite due to possible spring back from the SS-tube.

TABLE I
OVERVIEW OF SAMPLES

strand sample	Ti6AlV barrel (bare ends)	Ti6AlV barrel (SS-tube on copper ring)	SS barrel (bare ends)	X=glued 0=not glued
in SS tube	Ti-1	Ti-6	SS-1	X
bare	Ti-2	-	SS-2	X
in SS tube	Ti-3	Ti-7	SS-3	0
bare	Ti-4	-	SS-4	0

After the heat treatment and before further preparation we noticed that for samples Ti-1, Ti-2, Ti-4 the wires were tight in the grooves of the barrel, and just slightly movable on the copper rings. Only sample Ti-3, also being tight in the grooves, was a bit looser on the copper rings. For SS-1 and SS-3, the section in SS-tube was tight in the grooves while the bare sections were easy movable on the barrel and the copper rings. For sample SS-2 and SS-4, the wire was movable along the entire length. This is qualitatively in good agreement with expectations based on the CTE of the materials as the CTE of Ti-6Al-4V is smaller than that of SS, causing differences in compression from reaction heat treatment temperature to room temperature.

After the heat treatment for 24 hrs @ 675°C, the bare copper strand ends (with or without SS tube) were soldered to the copper rings with Pb50Sn at a temperature of about 500 K. This type of high current density strands can be unstable at the transfer from the copper ring to the barrel holder. That is why the bare wire extremities are shunted by soldering similar strand, from where the swaged SS-tube ends toward the copper ring, thus providing mechanical support and electrical stability.

The glued samples were heat treated at about 325 K for several hours to harden the epoxy. Two pairs of voltage taps were soldered to the turns symmetrical to the middle at each sample, one pair with three turns in between (292 mm) and one pair spanning five turns (486 mm).

B. I_c -Strain Measurements

The I_c and n -values of the same (PIT) wire were measured at various applied uni-axial strain values on the recently developed Pacman spring. The details of the experimental set up, measurement conditions and results were reported in [10]. A plot of the I_c at electric fields of 10 $\mu\text{V}/\text{m}$ and the n -value (between 10 $\mu\text{V}/\text{m}$ and 100 $\mu\text{V}/\text{m}$), at 12 T and 4.23 K is shown in Fig. 2 together with a best fit to the deviatoric strain relation [11]. This sample, coming from the same wire section, was heat treated and measured separately one year earlier. Unfortunately, the exact heat treatment schedule could not be retrieved for this sample.

III. RESULTS

The measurements were performed in liquid helium bath (~ 4.2 K) at magnetic field between 10 T to 15 T. The electromagnetic force on the turns was pointing toward the center of the barrel. The electric field was recorded until quench, mostly at a level of 300 $\mu\text{V}/\text{m}$, except the SS samples, which quenched close to the I_c criterion of 10 $\mu\text{V}/\text{m}$. The n -values

Fig. 2. I_c data and n -values versus intrinsic strain on the PIT conductor (SMI) at a voltage criterion of $E_c = 10 \mu\text{V/m}$ and magnetic field of 12 T [10].

Fig. 3. $I_c(B)$ data for all specimen on a Ti-6Al-4V barrel at a voltage criterion of $E_c = 10 \mu\text{V/m}$. The dashed lines connect between the calculated values.

Fig. 4. $I_c(B)$ data for all specimen on a SS barrel at a voltage criterion of $E_c = 10 \mu\text{V/m}$. The dashed lines represent the connection between calculated values.

are determined between $3 \mu\text{V/m}$ and $30 \mu\text{V/m}$ (when possible). The I_c at 4.2 K versus applied DC background field is depicted in Fig. 3 for the samples on the Ti-barrel and in Fig. 4 for the ones on the SS-barrel. Sample Ti-1 quenched at an E_c of $0.5 \mu\text{V/m}$ and sample Ti-3, although able to reach

TABLE II
 I_c , n -VALUE AND INTRINSIC STRAIN ON Ti-6Al-4V AND SS BARREL
SAMPLE HOLDERS AT 12 T

ID #	X = in SS-tube	X=Glued	I_c ($10 \mu\text{V/m}$) [A]	n -value [-]	Strain [%]
Ti-1	X	X	196.0	-	-0.41
Ti-2		X	316.0	53	-0.04
Ti-3	X		178.0	-	-0.46
Ti-4			297.0	48	-0.14
Ti-6	X	X	219*	-	-0.37
Ti-7	X		183.2	28	-0.45
SS-1	X	X	130	22	-0.58
SS-2		X	287	51	-0.17
SS-3	X		134	27	-0.57
SS-4			284	52	-0.18

* extrapolated by the deviatoric strain scaling relation.

higher voltages, showed an unusual S-shape of the VI -curve. The I_c at 12 T for sample Ti-6 could not be measured and is extrapolated by using the higher fields values.

A summary of the I_c , n -value and derived intrinsic strain, is shown in Table II.

IV. DISCUSSION

The intrinsic strain of the strand on the Ti-6Al-4V Pacman spring is considered similar to that of sample Ti-2. On the Pacman, the wire is soldered to the spring while on the Ti-6Al-4V barrel, the strand reaches practically the same temperature level during soldering to the copper rings, although a bit less defined. We assume that gluing with Stycast will force the strand to follow the compression of the Ti barrel, practically giving the same thermal cool-down strain (-0.03%) for sample Ti-2, as for the Pacman sample at zero applied strain.

It appears that the I_c from barrel sample Ti-2, exceeds by 11% that of the Pacman sample at zero applied strain, most likely due to a difference in heat treatment. We assume that the scaling parameters B_{c20m} and T_{c0m} remain identical and only an adjustment of the C_0 from the deviatoric strain model is required to achieve the correct scaling relation. In principle, this is not completely correct, as a different heat treatment scheme may result into a different tin concentration gradient in the Nb_3Sn filaments, causing a deviation in B_{c20m} and T_{c0m} accordingly. We also assume that the strand properties are homogeneous in the axial direction.

In order to determine the intrinsic axial strain of the various barrel samples, we use the deviatoric strain scaling relation and find the parameters to match the $I_c(\epsilon)$ data in Fig. 2 and all the barrel $I_c(B)$ data. It appears that Pacman $I_c(\epsilon)$ data and the barrel $I_c(B)$ data match quite well for $B_{c20m} = 24.4 \text{ T}$, $T_{c0m} = 16.9 \text{ K}$ and $C_0 = 33\,300 \text{ AT}$, $\epsilon_{0-a} = 0.00175$ and $C_a = 40.0$ ($C_0 = 30\,050 \text{ AT}$ for the curve in Fig. 2). The dashed lines in Figs. 3 and 4 represent the $I_c(B)$ according to the scaling relation for corresponding solutions of the strain. The impact of a difference in heat treatment between the Pacman sample and the barrel samples on B_{c2} is neglected, based on the excellent match for the calculated $I_c(B)$ values in Fig. 3 and 4. In most cases it is hardly possible to distinguish between dashed

Fig. 5. $I_c(\epsilon_i)$ data for the Pacman sample with the curve of the scaling relation (solid line) and the one with adjusted C0. All I_c values at 12 T are scaled to a strain to match the dashed curve.

lines (calculated) and solid lines connecting the measured data. Note that one experimental value of the I_c at 10 T of SS-4 in Fig. 4 deviates relatively far from the calculated curve, this point is neglected for further evaluation. The strain values, ϵ_i deduced for the barrel samples are listed in the right column of Table II and plotted in Fig. 5 on the derived $I_c(\epsilon)$ curve. Also here we neglect again impact of the radial strain component introduced by the SS tube on the I_c -strain characteristic.

In the case of a Ti-6Al-4V sample holder and bare strand, the intrinsic strain is more compressive ($\epsilon_i = -0.14\%$) when the sample is not glued. Without glue the strand is less engaged with the barrel compared to the glued state ($\epsilon_i = -0.04\%$). This is the same for a SS-tube swaged around the strand on Ti-6Al-4V barrel, although the difference is less pronounced and some relaxation seems allowed for the unglued sample ($\epsilon_i = -0.46\%$) not entirely following the dominant compression of the barrel (when glued $\epsilon_i = -0.41\%$).

The effect of the barrel compression is even stronger for Ti-6, with SS-tube until the copper rings, leading to $\epsilon_i = -0.37\%$. For Ti-3 and Ti-7, representing the possible TARSIS configuration, we find good agreement at a strain of -0.46% .

The most severe compressive intrinsic strain state of the strand-in-SS-tube is found on a SS ITER barrel and amounts to -0.58% . The effect of gluing is very small for SS barrels. A direct comparison to the situation for a cable bundle in a metal conduit is obviously more complex, in particular when electromagnetic transverse loads are playing a role.

The derived intrinsic strain levels of the barrel samples are corresponding well, in a qualitative sense, with the applied conditions in terms of CTE of the strand composite, barrel and SS-tube and the application of glue.

The engagement between the SS tube and the strand was assessed after cutting some samples by electric erosion. Only a very small gap could be observed in the cross section between inner wall and strand. It may be that this gap only exists at room temperature due to spring back and is closed at lower temperatures.

V. CONCLUSION

The method to apply a compressive uni-axial strain on a Nb₃Sn strand, by swaging into a SS-tube was successful although a full engagement between strand and surrounding tube is not guaranteed. The intrinsic strain in a high current density binary Powder in Tube (PIT) wire, in the TARSIS periodic bending probe configuration with “strand-in-SS-tube” on Ti-6Al-4V sample holder is -0.46% . The method will be considered for use in the TARSIS setup.

The intrinsic strain of the tested Nb₃Sn PIT strand in a SS-tube (strand/SS – tube cross section ratio = 0.71) on a SS ITER barrel is derived as -0.58% , neglecting strain interactions from radial components possibly affecting the superconducting properties.

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