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Influence of indentation on the critical current of Nb_3Sn strands

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Abstract

The Japan Atomic Energy Agency (JAEA) is procuring Central Solenoid (CS) conductors for all modules for ITER. The superconducting properties of the Nb_3Sn CS conductors will have to sustain 60,000 electromagnetic (EM) cycles. The current sharing temperatures (T_{cs}) were stable with EM cycles in short twist pitch conductors. However, the short twist pitch and tight cabling increases indented strands at the contact point between strands before heat treatment. The results of I_c measurement on artificially indented Nb_3Sn strands indicate that I_c was almost constant within a critical depth of the indentations.

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Keywords: ITER; Nb_3Sn strand; critical current; degradation; deformation before heat treatment;

1. Introduction

JAEA is procuring 100% of the CS conductors for ITER including 6 independent modules and a spare module. Each module consists of 7 CS conductors. The CS conductor is Nb_3Sn cable-in-conduit conductor which consists of

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a multistage Nb_3Sn cable, a central spiral, stainless steel wrap and a round-in-square stainless steel jacket. 576 Cr plated Nb_3Sn strands and 288 Cr plated Cu strands are used for the multistage Nb_3Sn cables. The CS will be driven by pulse current of 60,000 cycles in order to induce the plasma current. A maximum magnetic field of 13 T is generated at 40 kA creating a maximum electromagnetic load of 535 kN/m in the radial direction. The current sharing temperature (T_{cs}) of CS conductors have to sustain 60,000 electromagnetic (EM) cycles. It was found that T_{cs} of short-twist-pitch (STP) CS conductors was not degraded by EM cycles as a result of T_{cs} measurement at SULTAN test facility [1]-[2]. The STP conductor twist pitches were nearly half of the original design except for the 5^{th} stage cable. Therefore, improvement of the T_{cs} performance was achieved by the shorter twist pitch cabling.

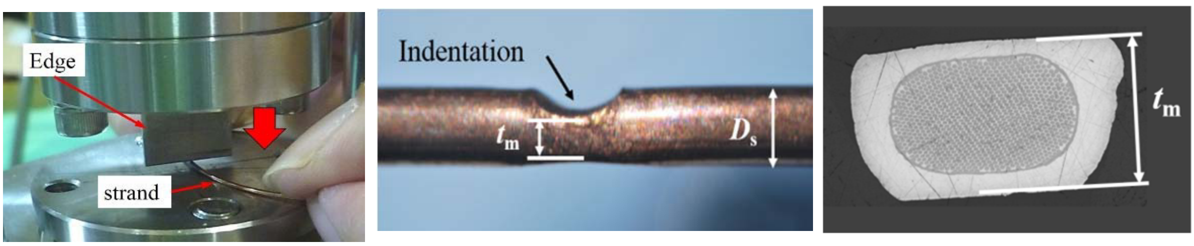
Manufacture of STP cable has a risk to increasing deformed strands because of the short twist pitch and tight cabling before the heat treatment. In the case of the Nb_3Sn strands after the Nb_3Sn reaction heat treatment, it was found that superconducting properties were influenced by the deformation under tensile and bending strains [3], but the effect of the deformation on the superconducting properties prior to the heat treatment is not clear. In the case of powder-in-tube and internal-tin restacked-rod-process Nb_3Sn strands for accelerator magnet, I_c was degraded by cross-sectional deformation during cabling [4]-[5]. In our previous study, it was found that I_c was also degraded on the ITER bronze-route strands with approximately more than 0.2 mm-deep indentation and optimization of the cabling process reduced number of the deformed strands [6]. For this reason, it seems that the increasing number of deformed strands during cabling degrades a performance of CS conductors. Therefore, the influence of an indentation on I_c before the heat treatment was investigated to determine the threshold of indentation depth in order to optimize the cabling process.

2. Experiments

Nb_3Sn strands were provided by three companies. The strands provided by two companies were ITER bronze-route (BR) Nb_3Sn strands. The strands provided by the other company were ITER internal-tin (IT) Nb_3Sn strands. The diameter of BR and IT Nb_3Sn strands are 0.83 and 0.82 mm, respectively.

To investigate the influence of an indentation, I_c measurements were carried out on artificially indented Nb_3Sn strands. The artificial indentation was applied to Nb_3Sn strands before the heat treatment as follows. Cr plate was removed on all surfaces of the strand. The strand was bent to the same shape as the outer surface of an ITER barrel to prevent to further breakage or damage to the strand during winding onto the barrel. The ITER barrel is the standard method of I_c measurement on ITER Nb_3Sn strands.

As shown in Fig. 1 (a), the strand was pressed and indented across the longitudinal direction of the strand. The indentation edge has a 0.5 mm radius which is almost same as the radius of the Nb_3Sn strands. As shown in Fig. 1(b), the diameter of the strand (D_s) and the minimum thickness (t_m) of the indented part are defined and were measured by using optical micrometer (as shown in Fig. 1 (c)). The depth of the indentation (d) was defined by $D_s - t_m$. The indented strand was wound onto the ITER barrel made from Ti6Al4V. The indented part on the strand was centered on the barrel. Then, the strand was heat treated in optimized process for each Nb_3Sn strand. I_c measurements were carried out at 12 T and 4.2 K by 4 probe method using electric field criterion of 10 μV/m. The distance between voltage taps was 250 mm. Further, the residual resistive ratio (RRR) was measured for indented IT Nb_3Sn strands by



(a) (b) (c)

Fig. 1 (a) The photo shows the pressing a Nb_3Sn strand with Cr plating removed. (b) The photo of an indented strand. The minimum thickness t_m and the diameter of strand D_s are shown. (c) Cross section of the strand at the indentation. In the case of a large indentation, both top and bottom side were deformed.

the 4-probe method at 1 A with 10 mm-long voltage taps. The RRR was defined as R(273 K)/R(20 K), where R is electrical resistance as a function of temperature.

The indented cross-section was observed after I_c measurement. Optical microscopy (OM) and scanning electron microscopy (SEM) were used to obtain low and high magnification image, respectively. The strand was impregnated with epoxy to hold the strand in place during the polishing. The impregnated sample was cut across the longitudinal direction, and then the sample was polished to obtain the cross-section at the indentation.

3. Results and discussion

3.1. I_c and RRR measurement on indented strands

The normalized I_c as a function of d for BR strands and IT strands are shown in Fig. 2(a). The normalized I_c was defined as $I_c/I_c(d = 0)$. The symbols of BR1 and BR2 show the results of BR strands for each company. The symbols of IT1 show the results of IT strands. The I_c of BR1 was measured in our previous study [6]. The I_c without indentations (i.e. $d = 0$) for BR1, BR2 and IT1 were 246, 315 and 278 A at 12 T and 4.2 K, respectively. The d of 95% $I_c(0)$ is defined as critical depth d_c. As shown in Fig. 2(a), I_c was almost constant with the indentation of less than d_c, but I_c was degraded drastically with the indentation of more than d_c. The d_c of the BR strands and the IT strands were 0.25 mm and 0.35 mm, respectively. The d_c of BR1 is the same as BR2 because the material and the structure of both strands are similar. The larger d_c of IT1 strands might be caused by softer material (e.g. Cu and Sn) in the IT strands. To maximize the I_c performance of Nb_3Sn strands in the CS conductor, the Nb_3Sn strands should be prevented from indenting more than d_c during the cabling. Therefore, optimization of the cabling process is required to keep indentation depth at less than d_c.

The result of the RRR measurement for IT1 with Cr plating removed is shown in Fig. 2(b). The degradation of RRR began from the indentation depth of 0.3 mm which is less than d_c of critical current. From cross-sectional observation, the RRR degradation was caused by breakage of the barrier layer. As a result, it is expected that the indentation can degrade not only I_c performance but also stability of the CS conductor.

3.2. Cross-sectional observation at indentation

Fig. 3 shows the cross section of each Nb_3Sn strand at the indentation after I_c measurement. The images were obtained by using OM. Fig. 3, (a-i), (b-i) and (c-i) show the cross sections of BR1, BR2, and IT1, respectively. The index i = 1 and 2 show the cross sections of I_c with the indentation of $d < d_c$ and $d > d_c$, respectively. As shown in Fig. 3 (a-1) and (b-1), also (a-2) and (b-2), deformation of the indented strands are almost same in both BR1 and BR2 because of similar materials. In the case of the BR strands, the multifilament area might withstand indenting

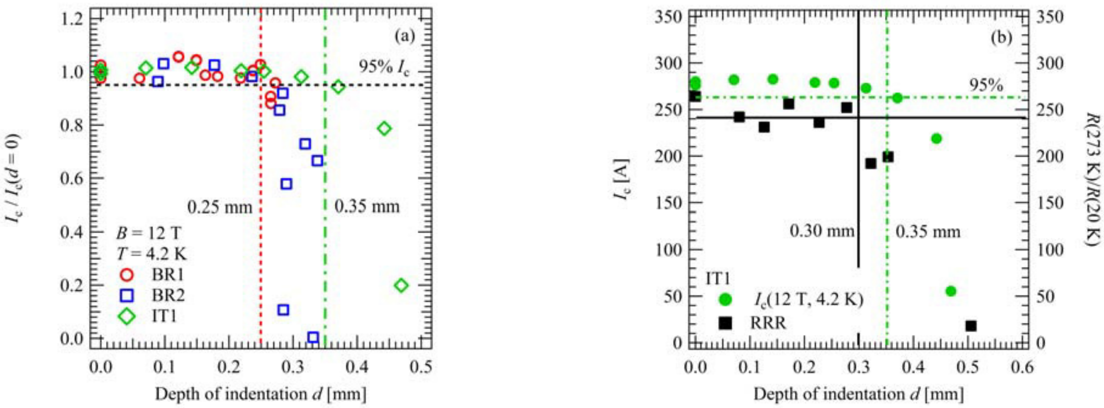
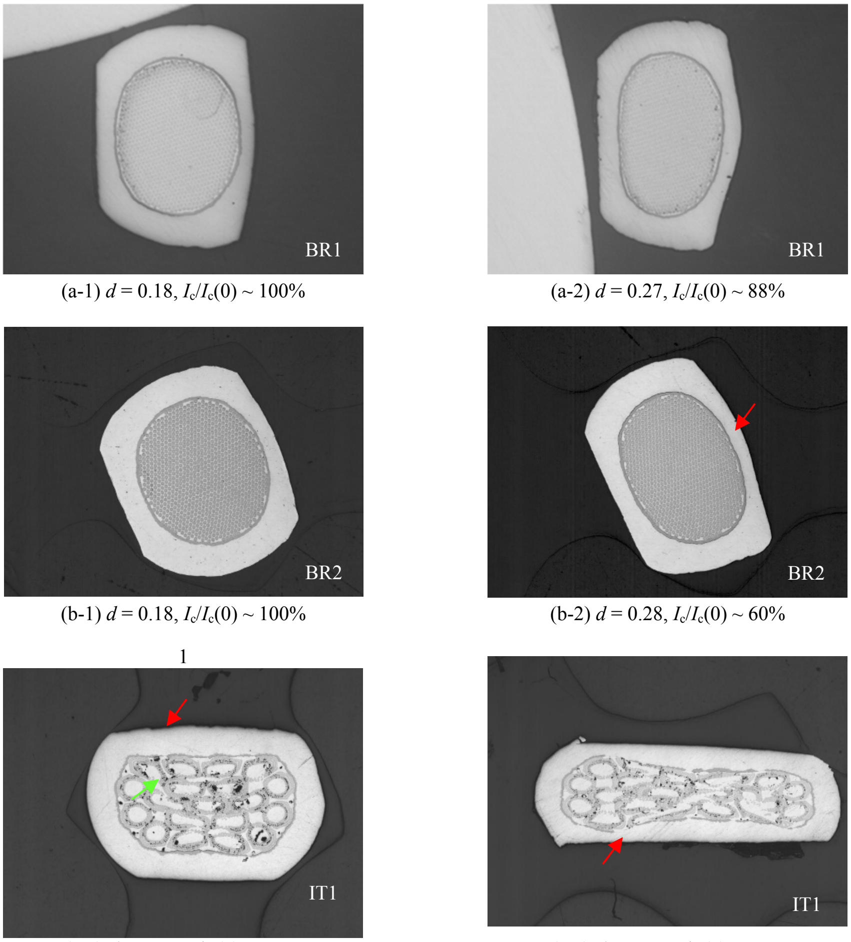


Fig. 2 (a) I_c as a function of the depth of indentation d at 4.2 K and 12 T. The dotted line and the dashed line show d_c of the BR and IT strands, respectively. (b) I_c and RRR (R(273 K)/R(20 K)) as a function of d on IT1. The dotted line and solid line show the results of I_c and RRR. The RRR was degraded from d less than d_c of critical current.



(a-1) $d = 0.18$, $I_c/I_c(0) \sim 100\%$ (a-2) $d = 0.27$, $I_c/I_c(0) \sim 88\%$

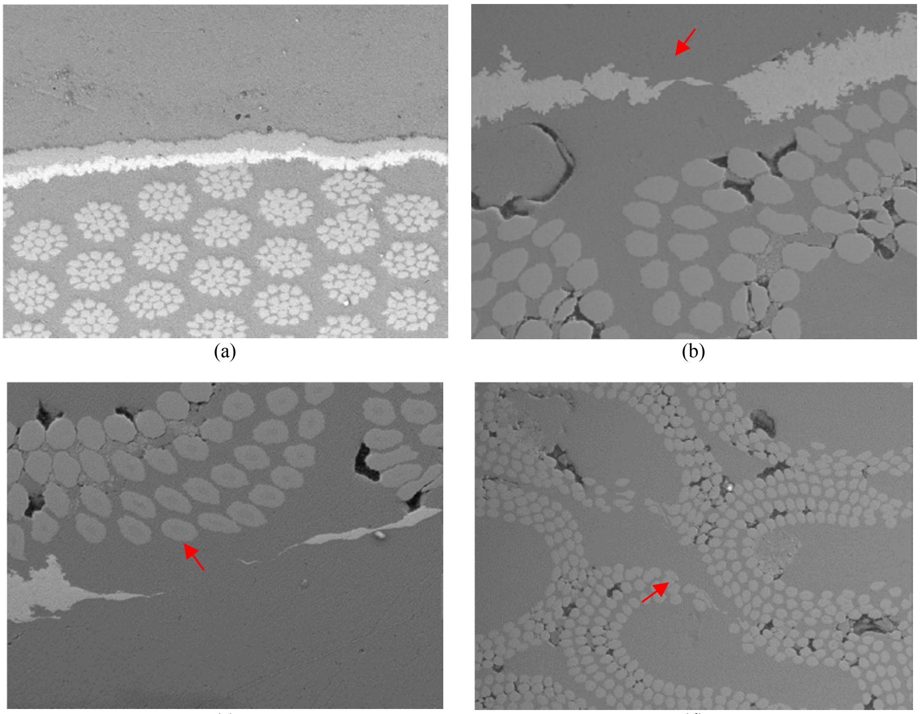
(b-1) $d = 0.18$, $I_c/I_c(0) \sim 100\%$ (b-2) $d = 0.28$, $I_c/I_c(0) \sim 60\%$

(c-1) $d = 0.22$, $I_c/I_c(0) \sim 100\%$ (c-2) $d = 0.44$, $I_c/I_c(0) \sim 80\%$

Fig. 3 Cross section of each Nb_3Sn strand at the indentation after I_c measurement. (a-i), (b-i) and (c-i) show the cross sections of BR1, BR2 and IT1, respectively. Index i = 1 and 2 show I_c with the indentations of $d < d_c$ and $d > d_c$, respectively.

force and stay elliptical (Fig. 3 (a-2) and (b-2)). On the other hand, the Cu stabilizer showed a relatively large deformation and had a flat top. The bronze in the multifilament area of ITER BR Nb_3Sn strands has approximately 15wt%-Sn which is around the maximum solubility of Sn in Cu. Because the bronze is stiffer than Cu, the multifilament area was deformed less than the Cu stabilizer area. In contrast, the multifilament area collapsed in IT1 (Fig. 3 (c-1) and (c-2)). Due to softer metal (i.e. Cu and Sn) in the sub-element, the multifilament area and Cu stabilizer were deformed similarly and both tops were flat. As shown in Fig. 3 (c-2), I_c was ~ 80% of $I_c(0)$, even though the thickness of the strand was almost half of the diameter and the multifilament area was largely collapsed.

Fig. 4 shows SEM images in the multifilament area. As shown in Fig. 4(a), in the case of the BR2, breakage of the barrier layer and the filaments was not found in the cross section even though I_c was degraded by the indentation of more than d_c. I_c may be degraded by the decreasing total area of Nb_3Sn filaments in the BR strands. In the case of BR1, the breakage in the cross section was not found either. On the other hand, small breakage of the barrier layer was found in IT1 with the indentation of 0.22 mm depth, less than d_c. The breakage of the barrier allowed Sn contamination of stabilized Cu during heat treatment. As a result, RRR was degraded on IT1 with the indentation of d less than d_c in Fig. 2(b). As shown in Fig. 4(c), it was found Nb cores which were not able to react to Sn near the large breakage of the barrier because of the Sn contamination to the Cu stabilizer. It is likely that the lack of Sn in the multifilament area is one of reasons for I_c degradation. As shown by the arrow in Fig. 4(d), it was seen that some filaments were deformed from the typical round shape.



(a) (b) (c) (d)

Fig. 4 High magnification image by SEM. (a), (b) and (c) show enlarged view at point of red arrows in Fig. 3(b-2), (c-1) and (c-2). (d) shows an enlarged view at point of green arrows in Fig. 3(c-2).

Additionally, it appears that some filaments are coupled to neighboring filaments or almost broken, although I_c maintained at ~100% of $I_c(0)$. As the results of cross-sectional observation, in order to explain the I_c degradation by the indentation, it is required that transversal cross-sectional observation be performed for statistical assessment of filament breakage and estimation of total area in the filaments for assessment of critical current density of Nb_3Sn.

4. Conclusion

The I_c measurements were carried out at 12 T and 4.2 K on ITER bronze-route and internal-tin Nb_3Sn strands which were artificially indented. The d_c of BR and IT strand were 0.25 mm and 0.35 mm, respectively. In order to maximize I_c performance of the strands in STP CS cable, it is required that the depth of indentations is kept at less than d_c. However, it was found that RRR degradation was caused by the breakage of barrier layer in the IT strands with indentations of less than d_c. JAEA has established the cabling process to keep indentations at less than 0.2 mm using the bronze-route strands. In the case of the internal-tin strands, we are working on the optimization of the cabling process to include less than 0.35 mm deep indentations in the STP cable.

As the results of cross-sectional observation in BR strands, breakage of the filaments and the barrier was not found, whereas, in the case of the IT strands, the breakage was found. That different behavior is caused by the different mechanical property of the material between the BR and IT Nb_3Sn strands. However, the correlation between I_c degradation and the cross section at the indentation was not found. Therefore, the transversal cross-sectional observation and the estimation of total area in Nb_3Sn filaments will be carried out for specific I_c analysis and assessment.

*The views and opinions expressed herein do not necessarily reflect those of the ITER Organization nor the official positions of Kiswire Advanced Technology Ltd. And the National Fusion Research Institute.

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