Impact of Indentation on the Critical Current of Bi2212 Round Wire

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***Abstract*—CFETR, "China Fusion Engineering Test Reactor," is a new tokamak device. Its magnet system includes the toroidal field (TF), central solenoid (CS), and poloidal field coils. The main goal of this project is to build a fusion engineering tokamak reactor with fusion power of 50–200 MW and self-sufficiency by blanket. The maximum field of CS and TF will get around 16 T, which is much higher than that of other reactors. New materials could be used to develop the technology of magnet for the next generation of fusion reactors. $Bi_2Sr_2CaCu_2O_x$ as a potential material is considered. However, the Bi-2212 phase is brittle, and the sheath of the round wire (RW) is Ag/Ag-Mg alloy with high plasticity and low strength. During cabling or conductor manufacturing, the compression on wire is inevitable, which could cause severe indentation on wire. With the aim of investigating the impact of indentations on the critical current of Bi-2212, the artificially indented wires were made, and I_c was measured. The results show that I_c of a Bi-2212 RW, unlike Nb_3Sn and NbTi wires, linearly decreased by the increased depth of indentation. The results are foreseen to be useful for Bi-2212 conductor design and manufacturing.**

***Index Terms*—Artificial indentations, Bi2212, critical current.**

I. Introduction

CHINESE Fusion Engineering Test Reactor (CFETR) is a new tokamak device in China. The geometry and target parameters of plasma are given according to physics design [1], [2]. The magnet system for CFETR consists of sixteen Toroidal Field coils (TF), a Central Solenoid (which consists of 6 coils) (CS) and six Poloidal Field coils (PF) [3]. Magnet is the core of CFETR, whose technology is a challenge, especially for CS and TF coils. The maximum field of CS and TF will be much higher than present devices, which could reach to 16 T. New materials have been considered to apply for the next generation magnet system.

Manuscript received October 18, 2015; accepted February 16, 2016. Date of publication February 19, 2016; date of current version March 8, 2016. This work was supported in part by the National Magnetic Confinement Fusion Science Program under Grant 2014GB105001 and in part by the National Natural Sciences Foundation of China under Grant 51207157.

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Digital Object Identifier 10.1109/TASC.2016.2532324

Fig. 1. Bi-2212 cable (left: before compaction, right: after compaction).

New opportunities at magnetic fields above 20 T are beyond the reach of present Nb-based superconducting materials. Bi2212 is a promising material for the development of superconducting magnets in the 25–30 T range. Compared to Nb_3Sn, Bi2212 has a bigger temperature margin during operation under peak magnetic field in the range of 12–15 T of the magnet system for fusion reactor. It is economical for next generation of fusion reactor to use Bi2212 conductor, considering the possibility of high operational temperature (10–30 K) to get rid of cooling with liquid Helium, even though the cost of Bi2212 is higher than Nb_3Sn at present. Bi2212 is also the only cuprate superconductor that can be made into round wire (RW) [4]–[6], which makes it possible to develop a CICC with Bi2212 RW. At present, cable-in-conduit conductor (CICC) is mainly made of Nb_3Sn and NbTi strands, such as ITER conductors [7]. During manufacturing of CS conductor with short twist pitches cable pattern [8], large number of indentations was found on the strands. Researches on this topic have been performed, showing that the indentations less than a certain value do not affect the Nb_3Sn performance [9]–[11].

In order to optimize the manufacturing technique of Bi2212 CICC cable, one small cable with short twist pitches was made, shown in Fig. 1. The parameters of cable are shown in Table I. The cable was manufactured by cage machine, and compacted by steel rollers. After final compaction, destructive examination was performed, and indentations on wires were found, as shown in Fig. 2. The indentation was caused by adjacent wires during compaction. The maximum depth of indentation is 0.1 mm.

Generally, the final stage of CICC cable needs compaction [7]–[11], as indicated in Fig. 1. The process exhibits a risk to increase the number of deformed wires, especially for the big cable with short twist pitches [7]. In the case of the Bi2212

TABLE I
PARAMETERS OF CABLE

Layout	2 x 3 x (6+1)
Twist pitch	
Stage 1	20 mm
Stage 2	50 mm
Stage 3	87 mm
Diameter (no compaction)	10 mm
Diameter (after compaction)	8.5 mm

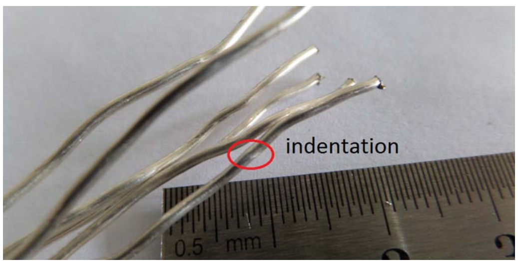

Fig. 2. Indentation on a Bi-2212 wire after cable compaction.

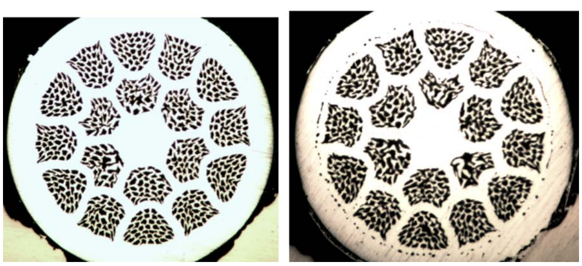

Fig. 3. The cross-sectional micrographs of an unreacted (left) and a reacted (right) Bi-2212 RW.

wires after the heat treatment, it was found that superconducting properties in terms of I_c were influenced by the deformation under tensile and bending strains [12]–[15], but the effect of the deformation on the superconducting properties prior to the heat treatment is still not clear.

To investigate the impact of the indentation, the artificial indentations were made on reacted and unreacted strands, respectively. Critical measurements have been carried out on artificially indented Bi2212 wires. The results are given and compared to that of Nb_3Sn and NbTi strands in this paper. The results are also useful for Bi2212 conductor design.

II. SAMPLE PREPARATION AND EXPERIMENTS

Bi2212 RW samples were manufactured using the powder in tube (PIT) method by Northwest Institute for Non-ferrous Metal Research (NIN). The cross-sectional micrographs are shown in Fig. 3 for the wires before and after heat treatment. The strand parameters are listed in Table II.

The indentation is found, which means that the compression on strand makes it yield. The mechanical properties of Bi2212 wire are listed in Table III. From Table III, the yield strength of unreacted strand is much higher than the one with reaction at 300 K.

TABLE II
PARAMETERS OF THE TESTED Bi-2212 RW

Material	Ag-alloy sheathed Bi-2212
Diameter	1.0 mm
Filament configuration	19 x 18
Ag/Mg:Ag:Bi2212	1.8:1:0.9
I_c at 0 T, 4.2 K	~ 400 A
I_c at 12 T, 4.2 K	~ 146 A

TABLE III
MECHANICAL PROPERTIES OF Bi-2212 WIRE

status	Temperature K	YS MPa	UTS MPa	E GPa
Unreacted	300	143	151	68
Reacted	300	86	124	54
	77	107	146	106
	4.2	131	217	116

Fig. 4. The process of artificial indentation is applied on a Bi-2212 strand.

The indentation was marked with one anvil with a rounded end. Two types of sample were made with artificial indentation. One is unreacted, and the other is reacted. The samples with a length of 50 mm were pressed and indented in the transverse direction of the strand, as shown in Fig. 4. All samples were heat treated at $T_{\max} = 890$ °C for 30 minutes. The temperature reduced to 830 °C with the speed of 5 °C /h, and then heat treated at $T_{\max} = 830$ °C for 48 hours in a standard oxygen environment. It is a standard heat treatment for Bi2212. The over pressure heat treatment introduced by Oxford Superconducting Technology and Florida State University [16]–[18] with much higher current density will be considered in the future research.

As shown in Fig. 5, the depth of indentation was investigated by micrometer and an auxiliary wire. The depth of the indentation (depth) was defined by $(d_1 + d_2) - d$.

I_c measurements were carried out on artificially indented wires (shown in Fig. 6), in order to identify the influence of the indentation. The samples were soldered vertically at the ITER barrel in order to match the testing conditions, as shown in Fig. 6, because the winding and Lorentz force could caused more damage on indented wire. All samples were tested at 4.2 K with different background fields. The applied external magnetic field is from 0 T, up to the maximum field of 12 T.

The indented cross-section was observed after I_c measurement with optical microscopy. The wire was impregnated with epoxy to hold the wire in place during the polishing. The

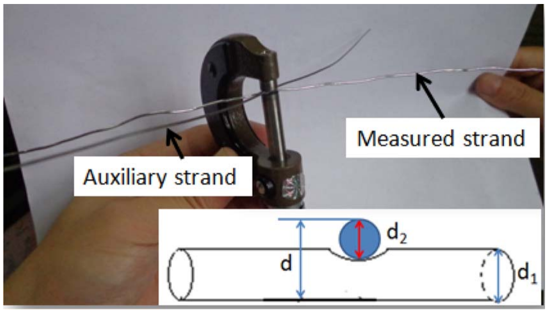

Fig. 5. Definition and measurement for strand indentation.

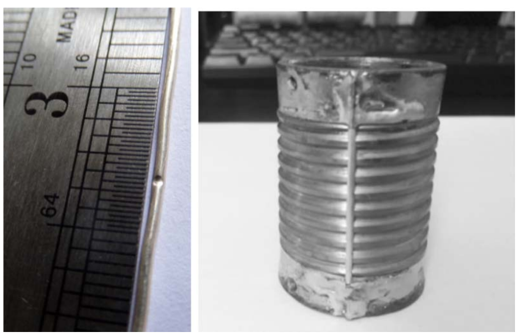

Fig. 6. Testing samples (left: artificially indented strand, right: sample barrel for I_c measurement).

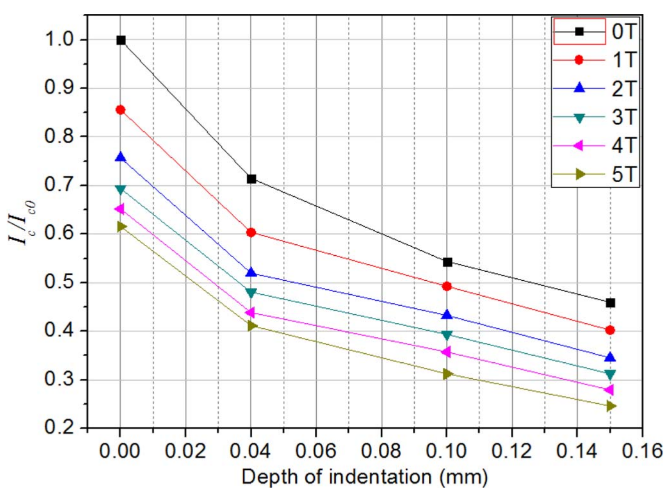

Fig. 7. Curves of I_c/I_{c0} versus indentation depth for a reacted Bi-2212 RW at different magnetic background fields.

impregnated sample was cut, and then polished to obtain the image of the strand cross-section with indentation.

III. Results

The normalized Ic at various magnetic fields was defined as I_c/I_{c0} (depth $= 0$, $B = 0$) and I_c/I_{cB} (depth $= 0$). The indentation depth with wire I_c 95% of the I_{cB} is defined as critical depth.

The reacted wire with artificial indentation by compressing was made (see Fig. 4), whose I_c test was performed before the compression. The results are shown in Fig. 7. It can be found that the I_c decreases sharply by increased depth of indentation. The I_c decreases about 30% with indentation depth of 0.04 mm. From the results, it's clear that the reacted wire is very sensitive to deformation.

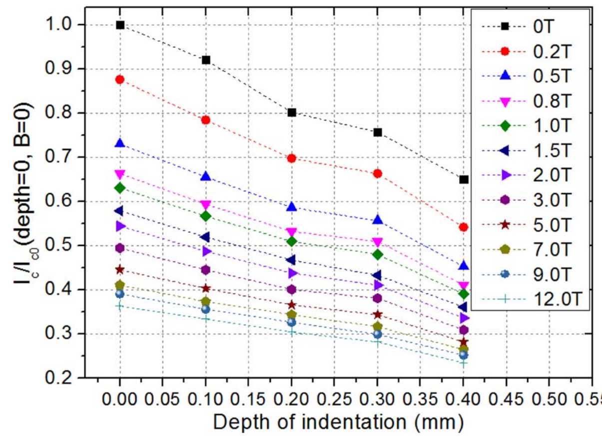

Fig. 8. Curves of I_c/I_{c0} versus indentation depth for an unreacted Bi-2212 RW at different magnetic background fields.

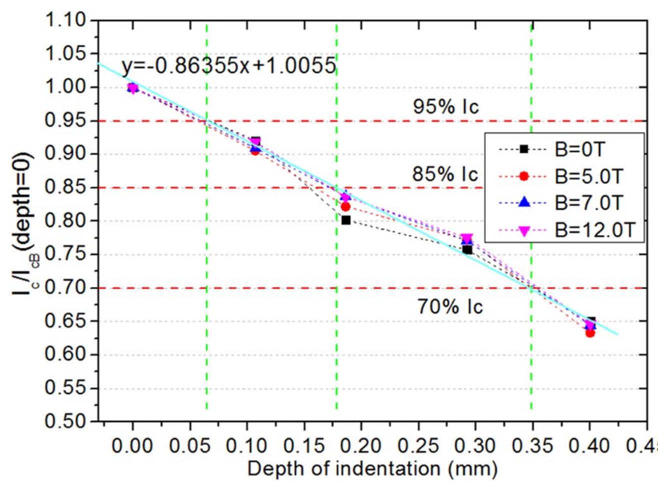

Fig. 9. Curves of I_c/I_{cB} versus indentation depth for an unreacted Bi-2212 RW at different magnetic background fields.

For the unreacted Bi2212 RW, the artificial indentation was made, and then heat treated. The results were shown in Figs. 8 and 9. I_c decreased by the increased indentation, which is similar to behavior of reacted Bi2212 wire under compression. But the unreacted wire is much less sensitive to indentation than the reacted one.

As shown in Fig. 9, the I_c reduction of Bi2212 wire at different background fields exhibits similar behavior. One linear fitting function is proposed to evaluate the I_c reduction at different indentation depth. The I_c decreases about 30% while the depth of indention is about 0.35 mm. The value is much higher than that for the Bi2212 wire which is reacted before the compression. The results also indicate that indentation depths above 0.06 mm lead to I_c reduction with more than 5%.

IV. Discussions and Comparison With Nb_3Sn and NbTi Strand

In this section, the comparison on the impact of indentations among different materials was made. The tested Nb_3Sn and

TABLE IV
MECHANICAL PROPERTIES OF Nb_3Sn AND NbTi STRANDS

Material	Diameter	Ic testing condition	YS/MPa (300 K)	UTS/MPa (300 K)	E/GPa (300 K)
Nb_3Sn	0.82 mm	4.2 K @ 12 T	364	643	60
NbTi	0.73 mm	4.2 K @ 5 T	407	513	85

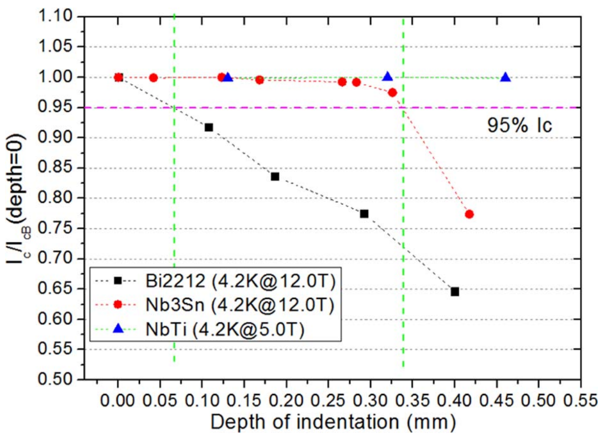

Fig. 10. Curves of I_c/I_{cB} versus indentation depth for Bi-2212, Nb_3Sn, and NbTi strands.

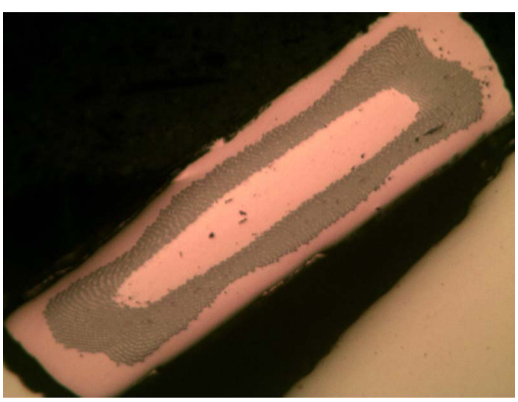

Fig. 11. Cross section of NbTi strand (depth $= 0.45$ mm, $I_c/I_{cB} = 100\%$).

NbTi strand are from Western Superconducting Technologies Co., Ltd. (WST) in China. Nb_3Sn strand is internal tin with a diameter of 0.82 mm. NbTi strand's diameter is 0.73 mm. The main parameters of them are listed in Table IV.

The artificial indentation on strands was made and tested following the same procedures described above. As shown in Fig. 10, I_c with indentation depth of less than 0.33 mm is not degraded for internal-tin Nb_3Sn strand. Furthermore, although the maximum indentation reached to 0.45 mm for NbTi strand, no visible I_c reduction was found, indicating NbTi is not sensitive to indentation. Compared to Nb_3Sn and NbTi strand, the I_c of Bi2212 wire shows one linear reduction, reduces dramatically by increased depth of indentation.

The cross-sectional observations are shown in Figs. 11–13. The NbTi strand was almost compressed as a plate, as shown in Fig. 11. But its critical current doesn't show any visible reduction. NbTi is ductile and it is not affected by the compression with indentation.

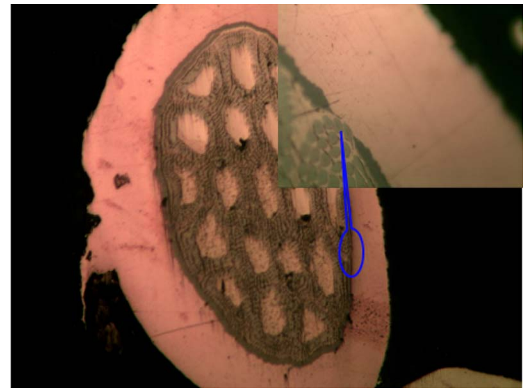

Fig. 12. Cross section of internal-tin Nb_3Sn strand (depth $= 0.325$ mm, $I_c/I_{cB} = 97\%$).

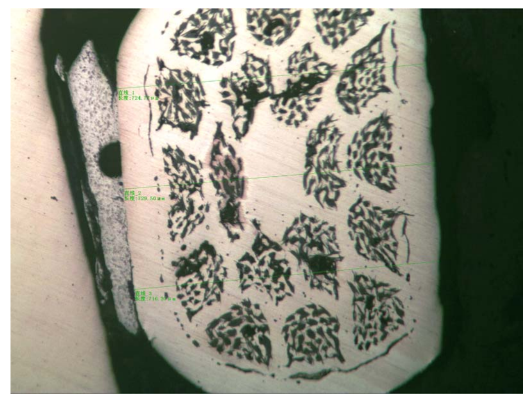

Fig. 13. Cross section of Bi2212 wire (depth $= 0.292$ mm, $I_c/I_{cB} = 77\%$).

The breakage of the diffusion barrier was found in the Nb_3Sn sample with indentation, as shown in Fig. 12, which was caused by the compression at room temperature before heat treatment. The breakage of the barrier results to Sn contamination to stabilized Cu in outer sheath during heat treatment. The lack of Sn in the multifilamentary region is one main reason for I_c degradation for Nb_3Sn.

Nb_3Sn and NbTi wires with alloy phase, show good mechanical properties, e.g. high yield strength. But compared to NbTi, the Nb_3Sn filaments are brittle after heat treatment. When indentation depth reaches the limit, the performance will reduce sharply. Compare to Nb_3Sn, Bi2212 filament is even more brittle and easier to be fractured under stress. So the I_c of reacted Bi2212 RW with compression decreased dramatically. The outer sheath of Bi2212 strand is Ag-Mg alloy with thickness of 0.05 mm. For an indentation with 0.05 mm depth, it has no influence on I_c for Nb_3Sn strand, while the percent of I_c reduction is about 95% for Bi2212 RW. From the former research, the Ag-Mg strength is much higher than one of Ag [19]. During compression, the outer stress could cause more deformation of Ag tube, which could cause the reduction of cross section or breakage of filament (Fig. 13). This will reduce the current transport. In order to explain the I_c degradation deeper by the indentation, more samples are required for further investigation.

V. Conclusion

The I_c measurements were carried out at different parallel background fields and 4.2 K on Bi2212 RW which were artificially indented. The impacts were also compared to that for Nb_3Sn and NbTi strands. As a result, for Bi2212 RW, I_c is significantly decreased by increased depth of indentation, which is much different from the behavior of Nb_3Sn and NbTi strands. The I_c of Bi2212 RW shows linearly reduction. The results provide us useful information on Bi2212 conductor design and manufacture. Low void fraction, short cable twist pitches and big compression force during manufacturing could cause more indentations on Bi2212 wire, which should be avoided by optimizing conductor design and manufacturing technology.

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