Impact of Indentation on the Performance of MgB_2 Round Wire

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***Abstract*—MgB_2 round wire is a promising material for future fusion Cable in Conduit Conductor applied in low magnetic field, due to its larger T-margin compare with NbTi. It's a competitive candidate for feeders, poloidal field or correction coils. Since MgB_2 is sensitive to strain, a short twist pitch cable pattern will be taken into consideration. During cabling and conductor manufacturing, the compression on the strand is inevitable, for a cable with short twist pitch can make more severe indentation on the strands. Previous studies have shown that indentation can caused degradation of the critical current of Nb_3Sn and Bi-2212 round wires. So the same research is performed on MgB_2 round wire, in this paper, the critical current of artificially indented samples is measured, and the results are compared with artificially indented Nb_3Sn, NbTi and Bi-2212 round wires.**

***Index Terms*—Artificial indentation, MgB_2 round wire, critical current.**

I. INTRODUCTION

SINCE the discovery of MgB_2 15 years ago, much effort has been undertaken to optimize and improve its performance [1]–[5]. Now, it has become a competitive superconducting material because of its high-T_c, the relatively low cost and it can be made as an untextured wire without weak links [2], [6]. These made it be a good choice for magnetic resonance (MR) application [7], [8] and future cable-in-conduit conductor (CICC) [9], [10]. Recently an advanced MgB_2 conductor with internal Mg diffusion process, which is a dense MgB_2 structure with not only a high J_c, but also a high J_e can be achieved. This advanced MgB_2 round wire is very promising for future applications [11].

For the International Collaboration for Advancement of Magnesium diboride Superconductors program (ICAMS), a new idea developed at ASIPP, is under investigation for possible application in a MgB_2 CICC. For the superconducting materials which are sensitive to the strain, short twist pitch (STP) could help to resist the Lorentz force, which could make the cable more stable under operation condition. But short twist pitch means big stiffness of cable, it will cause the indentation on the strand during cable compaction [12], [13]. Because MgB_2 wire has similar matrix material to Nb_3Sn, its stiffness could be similar to the ITER CS cable, which could also cause indentation on MgB_2 wire. The aim of this is to reduce the superconducting MgB_2 round wire deformation as much as possible while increasing the superconducting strand support, but keep the stiffness similar to as the ITER CS cable to avoid degradation of transport properties.

Before the MgB_2 round wire will be used in this program, the properties of this wire type should be understood. Such as transport properties, AC loss and mechanical performance of some MgB_2 wires have been studied in previous research [14]. However, another potential problem could be the indentation caused by adjacent wires during cable compaction. Previous studies showed that indentation of the wire caused critical current degradation in Nb_3Sn and Bi-2212 round wires [15]. So it's important to figure out whether the degradation could occur in MgB_2 round wire as well [15]–[17].

To investigate the impact of the indentation, artificial indentations were made on unreacted samples. Critical current measurements have been carried out on the artificially indented MgB_2 samples after heat treatment. The results are given and compared to those of Nb_3Sn, NbTi and Bi-2212 round wire in this paper. The results are a basis for MgB_2 CICC design.

II. EXPERIMENTAL SETUP

A. Sample Preparation

The MgB_2 round wires are produced by Hypertech Research Inc., USA, through a powder-in-tube (PIT) in situ route with Nb barriers around each filament and a monel (a high-tensile, corrosion-resistant, Ni–Cu alloy) outer sheath. The cross-section of the MgB_2 round wire is shown in Fig. 1, and the parameters of the wire are listed in Table I.

The indentations were created by an anvil with a round end. The diameter of the round end is similar to the sample wire diameter. The unreacted MgB_2 wire samples with a length of

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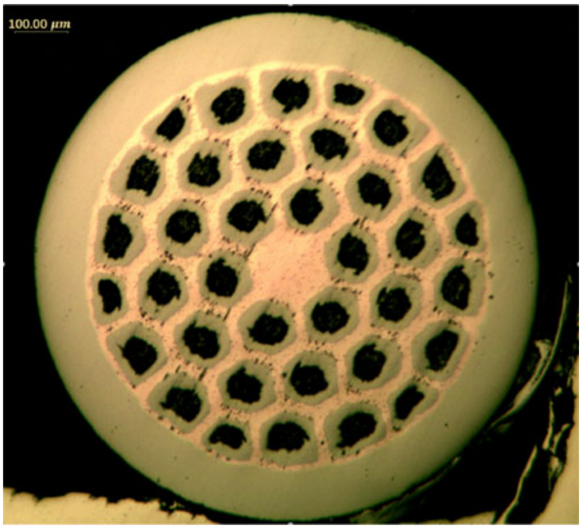

Fig. 1. The cross-sectional micrographs of MgB_2 round wire.

TABLE I
PARAMETERS OF THE TESTED MgB_2 WIRE

Parameter of wire	
Number of filaments	36
Matrix material	copper
Barrier	Nb
Multisheath	Monel
Twist pitch (mm)	100
Wire diameter (mm)	0.83

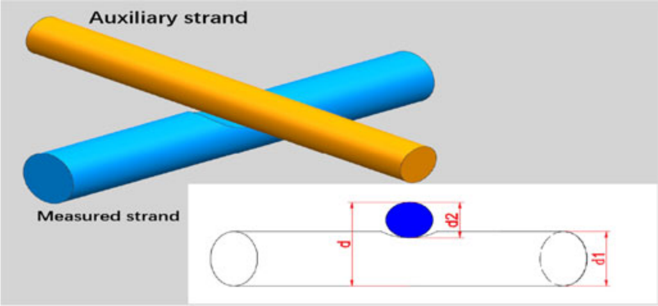

Fig. 2. Definition and measurement for strand indentation.

150 mm were indented with different depths. Then the depth of the indentations was checked by a micrometer and an auxiliary wire. The principle set up is shown in Fig. 2. The depth of the indentation was defined by (d1+d2)-d [15].

The samples were heat treated at Northwest Institute for Non-Ferrous Metal Research (NIN). The heat treatment temperature is 675 °C for a hold time of one hour, and the atmosphere is argon gas. During the heat treatment, the temperature should be above 600 °C for 90 minutes. The temperature curve of the heat treatment is shown in Fig. 3. To avoid Mg vapor leak at the wire ends, the end of the samples should be rolled or flattened. And the length of the samples for measurement is 60 mm. Two voltage tap is attached on the wire surface at the center of the tested sample, with the distance of 20 mm.

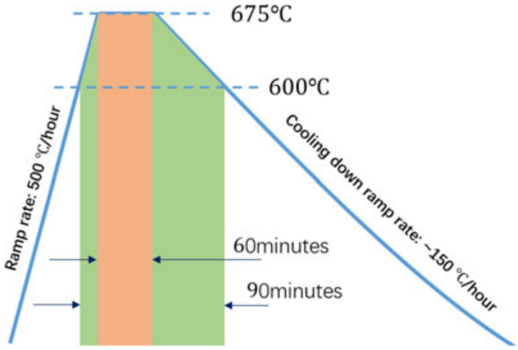

Fig. 3. The temperature curve of the heat treatment.

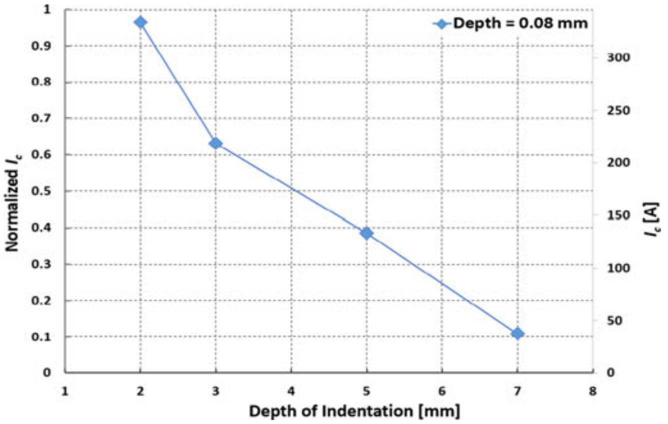

Fig. 4. The I_c versus background field of the sample with 0.08 mm indentation.

B. Experimental Procedure

The artificially indented MgB_2 round wire samples were tested at 4.2 K and 5 T. I_c measurements were performed with a Cryogenic Limited magnet system, and the samples were soldered and tested with an insert for the short sample.

After the I_c test, the indented cross-section was observed by optical microscopy. The impregnated samples were cut and then polished to obtain the images of the strand cross-section with indentation.

III. RESULTS

Each sample was tested at 4.2 K and various magnetic fields. The electric-field criterion used for the critical current is $E_c = 100\,\mu\mathrm{V/m}$. It should be noted that some samples (including all the reference samples, which are without indentation) burned out when the current reached 600 A during the test, but the reason for this problem isn't clear. To avoid losing more samples, the tests at low magnetic field of the remaining samples were canceled.

Fig. 4 shows the normalized I_c at various magnetic fields. The normalized I_c was defined as I_c/I_{c0} (the I_{c0} is the critical current of the sample with the indentation depth of 0.07 mm and in a magnetic field of 2 T).

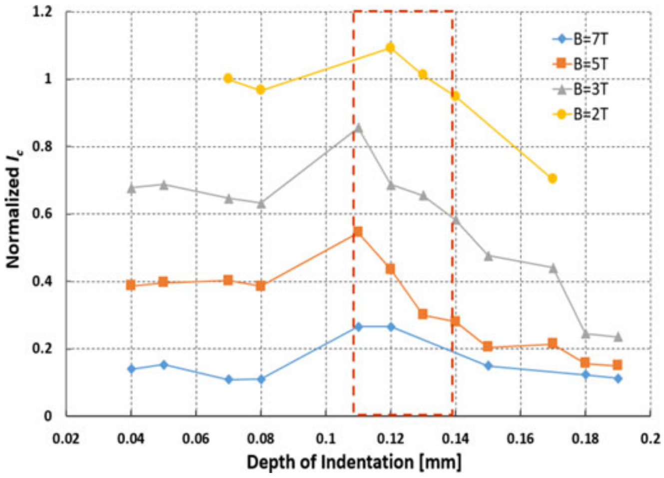

Fig. 5. The I_c versus depth of indentation at various magnetic fields at 4.2 K.

TABLE II
PARAMETERS OF SUPERCONDUCTING MATERIALS IN THE COMPARISON

SC strand	Diameter [mm]	Artificial indented state	I_c test condition
MgB$_2$	0.83	Pre-reaction	5 T @ 4.2 K
Nb$_3$Sn	0.82	Pre-reaction	12 T @ 4.2 K
NbTi	0.73	-	5 T @ 4.2 K
Bi-2212	1.0	Pre-reaction	12 T @ 4.2 K

From Fig. 5, it can be seen that when the depth of indentation on the sample is less than 0.1 mm, no obvious I_c degradation occurs to the sample. But when the depth of indentation approaches to 0.11∼0.12 mm, the critical current increases to a maximum value. Then the critical current degrades drastically with increasing depth of indentation.

IV. DISCUSSIONS AND COMPARISON WITH NB$_3$SN, NBTI AND BI-2212 ROUND WIRE

In previous studies, Nb$_3$Sn, NbTi and Bi-2212 strands were indented artificially to investigate the impact of indentation on unreacted strand on the I_c after the reaction [13], [15]. In this section, the impact of indentation on MgB$_2$ wire was taken into comparison with the results in the previous paper [15]. The Nb$_3$Sn and NbTi strand are from Western Superconducting Technologies Co., Ltd. (WST), the Bi-2212 round wire is from NIN. The main parameters of compared strands are listed in Table II [15].

All strands were artificially indented and tested following the same procedures as described in Section II. As shown in Fig. 6, an indentation depth of less than 0.33 mm does not degrade the I_c for internal-tin Nb$_3$Sn strand. For NbTi strand, however, although the depth of indentation reached to 0.45 mm, even larger than its radius, no visible I_c degradation was observed. The I_c of Bi-2212 wire shows a reduction already from the first indentation and decreases linearly with increasing depth of indentation. Compared to Nb$_3$Sn, NbTi and Bi-2212, the I_c of MgB$_2$ wire shows a different behavior. Firstly, it increased by the increased indentation depth less than 0.1 mm. After that, it decreased sharply.

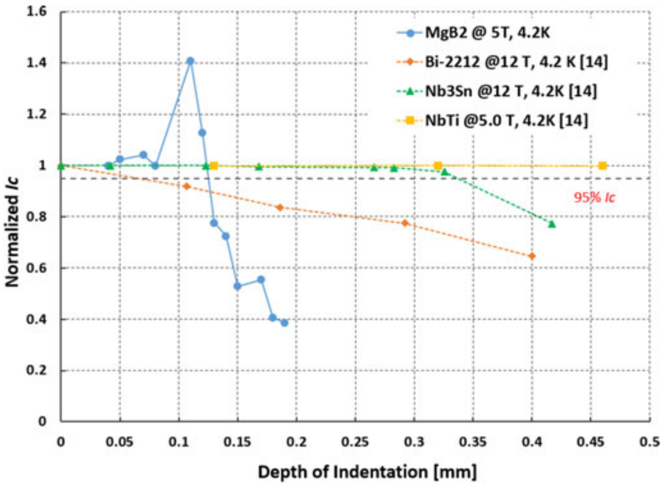

Fig. 6. Curves of I_c/I_{c0} versus indentation depth for Bi-2212, Nb$_3$Sn, NbTi, Bi-2212 and MgB2 strands.

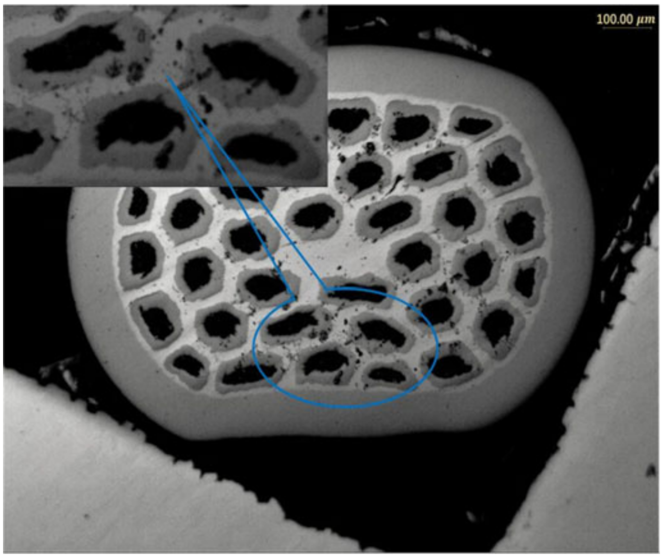

Fig. 7. Cross section of MgB$_2$ wire (depth = 0.173 mm, $I_c/I_{cB} = 55.4\%$).

From the former research [15], [16], [18], it's clear that the alloy phase superconductors, NbTi and Nb$_3$Sn show good mechanical properties, e.g. high yield strength although Nb$_3$Sn filament shows more brittle compared with NbTi filament after heat treatment. NbTi strand consists of Cu matrix and NbTi filaments, the NbTi filaments are ductile and stronger than Cu. Consequently, indentation is not likely to cause filament breakage in NbTi strand. For Nb$_3$Sn, the indentation could cause the breakage of the diffusion barrier. The breakage of the barrier causes Sn contamination of the stabilizing Cu in outer sheath during the heat treatment. The lack of Sn in the multifilamentary region is the main reason for the I_c degradation for Nb$_3$Sn.

Different from these two low-T_c superconductors, Bi-2212 is a ceramic like superconductor which is fabricated by the

Powder-In-Tube (PIT) method. For Bi-2212, compression of the strand can cause a reduction of transport properties by cracks or filament fracture [15]. But, MgB_2 shows a different behavior from Bi-2212 wire.

It's easily to be found from Fig. 6, a relatively small compression could increase the critical current, which could be caused by the increased powder density in the indentation area [19]. As the depth of indentation increases, the critical current of MgB_2 round wire degrades drastically. However, from the cross section of the sample (Fig. 7), no visible barrier breakage can be observed. So the critical current degradation might be mainly attributed to the reduction of the cross-section of filaments. More samples and tests are needed for investigating the mechanism of the critical current degradation MgB_2 after indentation.

V. CONCLUSION

Critical current measurements were carried out at various background fields and 4.2 K on MgB_2 round wires, which were artificially indented with different depth before reaction. The impact of indentation was also compared to that for Nb_3Sn, NbTi and Bi-2212 strands. The result shows that, for MgB_2 round wire, I_c is a function of the depth of indentation. But the behavior differs from Nb_3Sn, NbTi and Bi-2212 strands. A moderate indentation which is around 0.12 mm can increase the critical current of MgB_2 round wire, likely due to compression increasing the density of the powder. But when the depth of indentation exceeds a critical value, the I_c degrades drastically. The results provide us useful information on the twist pitch and tension setup of MgB_2 cable. The combination of low void fraction, short cable twist pitches and large compression force during manufacturing may cause more severe indentations on MgB_2 wire. This should be avoided by optimizing conductor design and manufacturing.

Generally, two methods - in situ and ex situ route-were used to manufacture MgB_2 wires. In this experiment, only wire with in situ route was made research. It's not clear whether the same experiment made on wire with ex situ route or different filaments configuration could cause different results. It could be interesting to compare the behaviors of indented wires with different route and filaments configuration in future.

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