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Electrical Characteristics of Twisted Soldered-Stacked-Square (3S) Wires Consisting of HTS Narrow Tapes with 1mm Width

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Abstract**—**To reduce the effect of external magnetic field, we proposed a novel wire with a square cross section of 1 mm × 1 mm which is named Soldered-Stacked-Square (3S) HTS wire. 3S HTS wire has great advantages in HTS applications due to its small square dimension, but it is inevitable to endure twisting. To study the twist structure of 3S HTS wire, a series of twisted 3S HTS wire samples are prepared, and we evaluate the typical electrical characteristics: twist pitch, critical current, self-field AC loss and so on. It is shown that the critical current of twisted 3S wire is constant up to a twist pitch of 80 mm, and the minimum twist pitch is approximately 50 mm. Measured AC losses are independent of frequency and are in good agreement with the thin strip theoretical values. Specially, measured AC losses are a little smaller than the thin strip theoretical value when peak transport current is reaching critical current. Besides, the measured AC losses of twisted 3S wire and 3S wire are almost identical.

1. Introduction

External magnetic field would influence the performance of HTS wires including critical current, AC loss and so on, especially when the magnetic field is perpendicular to the HTS wire's surface [1]. In order to reduce the effect of external magnetic field, many studies have been done, which mainly focus on stack or twist multifilament structures: tapes stacked and transposed according to the Roebel Assembled Coated Conductors technique [2], tapes stacked and twisted along the longitudinal direction [3], round strand composed of coated conductor cable [4] and so on. However, these studies are usually based on HTS tapes with more than 4 mm width.

Different from above studies, we proposed a novel wire with a square cross section of 1 mm × 1 mm which is named Soldered-Stacked-Square (3S) HTS wire [5]. Due to the low width-to-thickness ratio and small square dimension, 3S HTS wire has great advantages in cabling, but it is inevitable to endure twisting in actual applications. Therefore, it is necessary to have further study on the twist structure of 3S HTS wire.

In this paper, we investigate the basic electrical characteristics for the twisted 3S HTS wires: twist pitch, critical current, self-field AC loss and so on. We firstly fabricate several 3S HTS wire samples, (2+7b)-wire samples through narrowing, soldering and stacking process, and then twist the samples with different twist pitches. The entire fabrication process will be introduced in detail. Then we study the critical current characteristics versus twist pitch of the (2+7b)-T-wire. Furthermore, we investigate the self-field AC loss characteristics of the (2+7b)-T-wire, including dependence on frequency and twist pitch.

2. Experiment

2.1 Fabrication process of twisted 3S HTS wire

Fig. 1 shows the schematic view of the fabrication process of the twisted Soldered-Stacked-Square (3S) HTS wire. As depicted in Fig. 1, an original second generation (2G) HTS tape with 4 mm width is incised into four narrow tapes with 1 mm width. This process is accomplished by a modified commercial cutting device which is widely used to flat copper plate cutting. Then several 2G HTS narrow tapes and brass narrow tapes are immersed together into a solder bath and undergone stacking and soldering process simultaneously ensuring that the cross section is square. Finally, the 3S HTS wire is twisted by a torsion device. In this work, we used the original 2G wires with 4 mm width provided from SuNAM company from Korea.

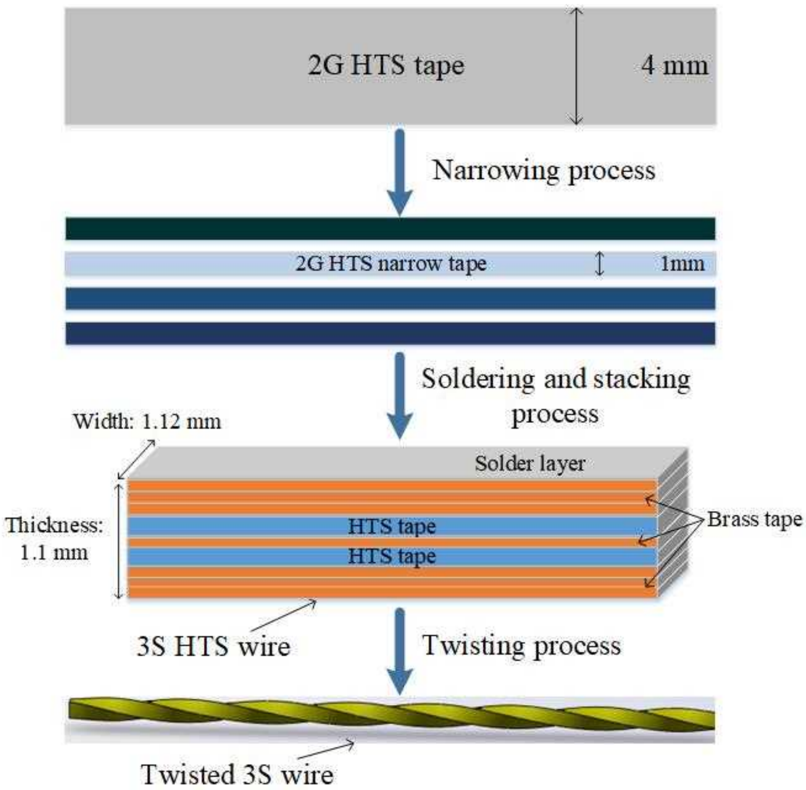

Fig. 1. Fabrication process of twisted 3S HTS wire.

In this study the prepared 3S HTS wire samples consist of two layers of HTS narrow tapes with 1 mm width and seven layers of brass narrow tapes (7b). This kind of 3S HTS wire is named (2+7b)-wire. Here the thicknesses of HTS and brass narrows tapes are 0.15 mm and 0.10 mm, respectively. In the fabrication of (2+7b)-wire samples, two pieces (piece 1 and 2) of HTS narrow wires are used, whose uniformity of critical current along length direction is shown good, as shown in Fig. 2. The main specifications of the HTS narrow tape and (2+7b)-wire are listed in Table I.

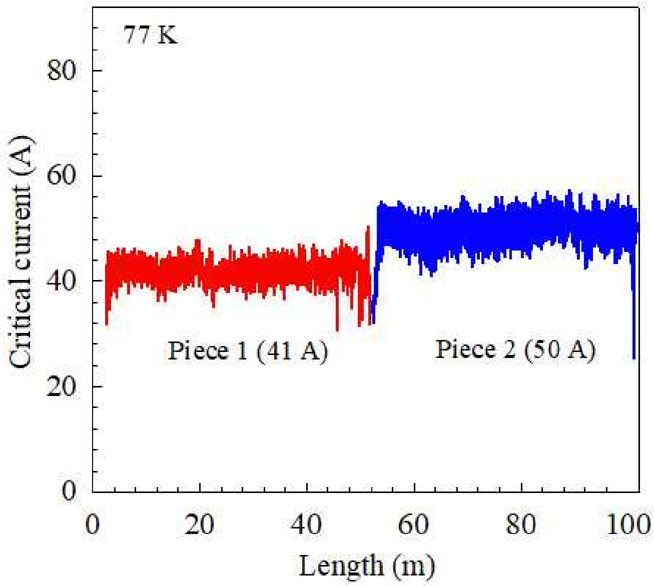

Fig. 2. Uniformity along length direction of critical current distribution for HTS narrow tapes used in fabrication of (2+7b)-wire samples.

TABLE I
SPECIFICATIONS OF 3S HTS WIRES

HTS narrow tape	
Width and thickness	1.0 mm × 0.15 mm
Thickness of superconducting layer	~1.3 μm
Thickness of silver layers	~1 μm
Thickness of substrate layer (including buffer)	~108 μm
Thickness of copper plating layer, each side	~20 μm
3S (2+7b)-wire	
Width and thickness of 3S wire	1.12 mm × 1.10 mm
Width and thickness of brass tape	1.0 mm × 0.1 mm
Number of HTS narrow tapes	2
Number of brass narrow tapes	7

2.2 Measurement of twisted 3S HTS wire

In this study, the critical current of the HTS narrow tapes were firstly measured by magnetic measurement method through hall sensors and calibrated by the value of critical current for the short length sample of piece 1 and piece 2 measured from a standard electrical four-point method, and the result is shown in Fig. 2.

The AC loss is measured by pickup coil method. The major equipment of the experiment setup includes waveform generator, AC current transducer, oscilloscope, amplifier and pickup coil. AC loss could be worked out by integrating product of transport current and the voltage picked up after compensating the inductive component using pickup coil.

Fig. 3 shows the photos of the torsion device and twisted 3S wire samples. Ends of the 3S HTS wire sample are fixed on the plate connected to current leads. The rotation shaft can be rotated at any angle to apply a twist to the 3S HTS wire with specified twist pitch. At the bottom of the device, there are three springs connected to a moveable plate, so that we can test the twisted 3S wire samples in changeable lengths. The allowed length of 3S wire samples is 300 ~ 400 mm. The whole torsion device will be put into the LN_2 vessel after fixing the 3S HTS wire. The (2+7b)-wire through twisting process is named (2+7b)-T-wire.

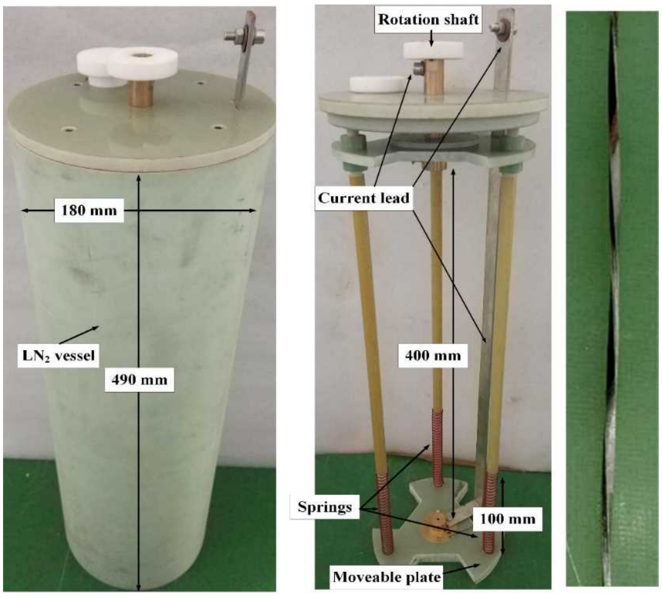

Fig. 3. Photos of the torsion device for short 3S samples and twisted 3S sample, (2+7b)-T-wire.

3. Test results of twisted 3S HTS wire

We investigate the basic characteristics for the twisted 3S HTS wire samples: twist pitch, critical current, self-field AC loss and so on. Here, all 3S wires of (2+7b)-wire are fabricated using the narrow tapes of piece 1 and 2 shown in Fig. 2. All performance tests are carried out at liquid nitrogen temperature of 77 K.

3.1 Twist pitch vs. critical current

To check the allowable twist pitch of the (2+7b)-wire in terms of critical current, we first measure the critical currents of three virgin wires without twisting process, and record their curves of voltage and current. Fig. 4 shows the measured critical currents of three (2+7b)-wire samples 1, 2, and 3. And the length between voltage taps is 220 mm. As shown in Fig. 4, the measured critical currents of samples 1, 2, and 3 are 86, 90, and 94 A, respectively. From the test results we can see the curves of voltage and current for three samples are typical ones of HTS wires.

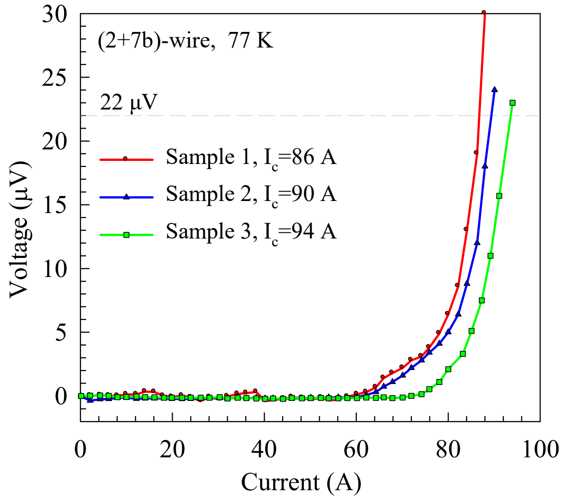

Fig. 4. Measured critical currents of three 3S HTS wire samples.

In Fig. 5, critical current measurement under various twist pitches is performed on the (2+7b)-T-wire sample 1 in Fig. 4, as a typical case. Here, we choose the reprehensive curves for four different twist pitches from whole measured data to show them more clearly. It can be seen from Fig. 5 that the curves of (2+7b)-T-wire with different twist pitches show typical superconducting characteristics. Besides, the critical current of sample 1 degrades rapidly when the twist pitch approaches 55 mm.

Fig. 6 shows the critical current versus twist pitch of (2+7b)-T-wire samples. Data shown in Fig. 6 are obtained from the three samples, whose length of voltage taps is 220 mm length. The measured critical currents after twisting process are normalized by the initial critical currents (I_{c0}), and the criterion of minimum twist pitch is defined as 95% retention of the initial critical current. As seen in Fig. 6 the critical current is constant up to a twist pitch of approximately 80 mm, and the minimum twist pitch of (2+7b)-T-wire is approximately 50 mm. In order to keep a certain margin for the following self-field AC loss tests, we set the twist pitch as 100 mm for fabricating the (2+7b)-T-wire samples.

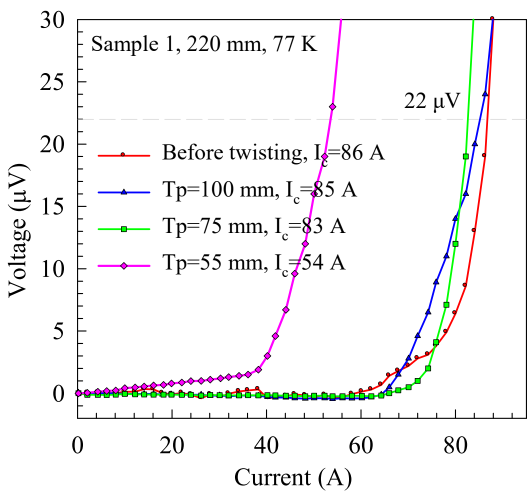

Fig. 5. Measured critical currents of (2+7b)-T-wire, sample 1, under various twist conditions.

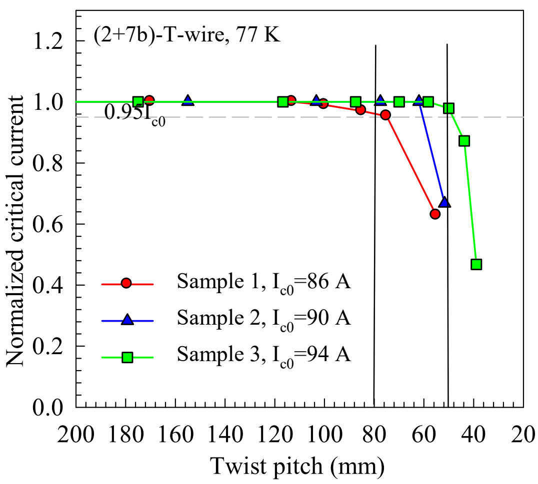

Fig. 6. Critical current vs. twist pitch of (2+7b)-T-wire samples.

3.2 Self-field AC loss characteristics

In this section, we test the basic characteristics of self-field AC loss for twisted 3S HTS wire, (2+7b)-T-wire, which is another important reference data for electrical characteristics of HTS tapes in superconducting applications. The AC loss is evaluated by integrating the product of transport current and voltage after compensating the inductive component during one period [6]. In addition, the self-field AC loss are compared with two theoretical values from the ellipse and thin strip equations of Norris model.

Fig. 7 shows the results of frequency dependence on AC loss of (2+7b)-T-wire sample 1. The (2+7b)-T-wire sample is tested with the frequency, 50, 100, and 200 Hz, respectively. As depicted in Fig. 7, the measured self-field AC loss of (2+7b)-T-wire is independent of the frequencies. This means that hysteresis loss is a major component in self-field loss and the eddy current loss generated from brass layers is so small that can be ignored. Besides, the self-field AC loss of (2+7b)-T-wire matches very well with the thin strip theoretical values of Norris model. When the transport current is low, the measured result is slightly above the thin strip theoretical values. With the increasing of transport current, measured result becomes a little smaller than the thin strip theoretical value.

Fig. 8 indicates the comparison of the self-field AC loss between (2+7b)-wire and (2+7b)-T-wire sample 1. The 3S wire sample is tested with the frequency 100 Hz. It can be seen that the measured AC losses of (2+7b)-T-wire and (2+7b)-wire are almost identical, from which we can see that the twist structure cannot affect the self-field loss of the 3S HTS wires.

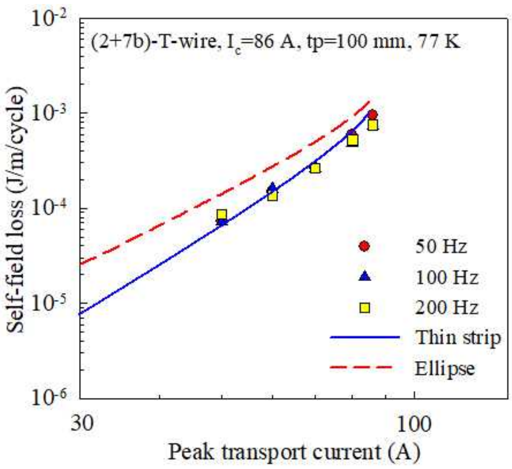

Fig. 7. Frequency dependence on AC loss of twisted 3S HTS wire, (2+7b)-T-wire.

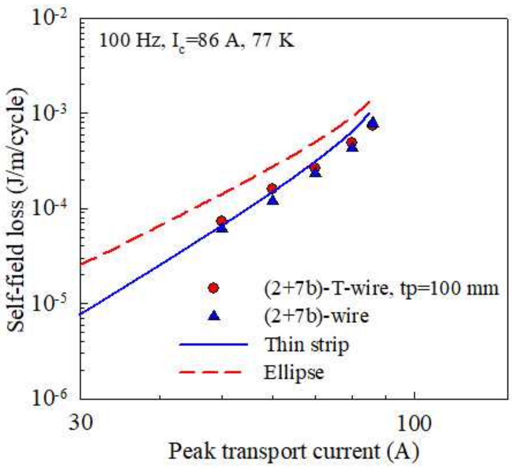

Fig. 8. Comparison of AC loss between (2+7b)-wire and (2+7b)-T-wire.

Fig. 9 shows the comparison of the self-field AC loss among three (2+7b)-T-wire samples. The (2+7b)-T-wire samples are tested with the twist pitch of 100 mm and the frequency 100 Hz. As seen in Fig. 9, the measured AC loss of three twisted 3S wire samples are almost identical.

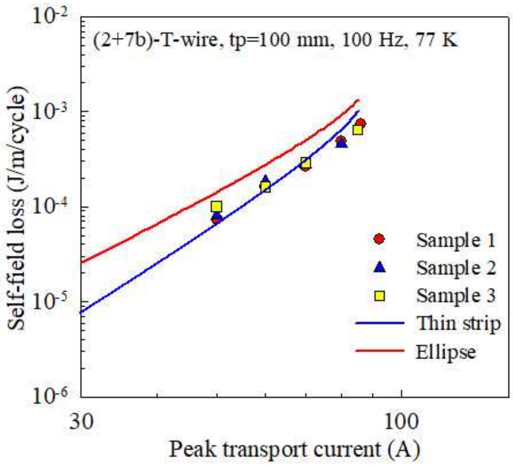

Fig. 9. Comparison of AC loss among three (2+7b)-T-wire samples.

4. Conclusion

In this paper, we firstly fabricate several 3S HTS wire samples through narrowing, soldering and stacking process, and then twist the samples with different twist pitches. Furthermore, we investigate the basic electrical characteristics for the twisted 3S HTS wire samples: twist pitch, critical current, self-field AC loss and so on.

From the test results, we can see that the critical current of the (2+7b)-T-wire is constant up to a twist pitch of approximately 80 mm, and the minimum twist pitch is approximately 50 mm. Besides, measured AC losses are independent of frequency and are in good agreement with the thin strip theoretical values. This means that hysteresis loss is a major component in self-field loss and the eddy current loss generated from brass layers is so small that can be ignored, and the measured AC losses are a little smaller than the thin strip theoretical value when peak transport current is reaching critical current. Furthermore, the measured AC losses of (2+7b)-T-wire and (2+7b)-wire are almost identical. Therefore, we can see that twist structure cannot affect the self-field loss of the 3S HTS wires.

Acknowledgement

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