A Study on Critical Current of Twisted Soldered-Stacked-Square (3S) HTS Wire with 1mm Width

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Abstract--In high temperature superconducting (HTS) applications, the external magnetic field affects the performance of the critical current and the AC loss. To improve the performance, a novel soldered-stacked-square (3S) HTS wire is developed through narrowing, stacking and soldering processes using 2G narrow wires with 1 mm width. In this paper, the narrowing process of the wire with 4 mm width was showed and the stacking and soldering processes were also presented. The 3S wire was made of three narrow HTS tapes and four brass strips. For the 3S HTS samples, the typical electrical and mechanical properties have been tested. Based on that, single 3S wire and double 3S wires were twisted. Then the critical currents of the samples were tested at different twist pitches. The test results showed that the measured critical currents of 3S wire samples were between 120 A and 150 A. The critical current of the single 3S wire at average twist pitch of 50~70 mm was about 8% lower than that of the original wire. And the critical current of double 3S wires was about 10% lower than the original critical current at a twist pitch of 65 mm.

1. Introduction
The second generation high temperature superconductor tapes with excellent high current performance have been applied to different areas. However, the external magnetic field could reduce the performance of critical current and AC loss. Many different structures such as assembled, stacked, or twisted of tapes were explored in order to reduce influence of the external magnetic field on the critical current and AC loss. The results showed that magnetization losses were apparently reduced,
however the transport current losses increased slightly \cite{1}. In this paper \cite{2}, the fabrication process and the characteristics of Twisted Stacked-Tape Cable with width of 4 mm was recommended. In the paper \cite{3}, the AC loss of the twisted and non-twisted BSCCO tapes were measured at different frequency. The critical current was measured according to different torsion of YBCO and BSCCO conductors with width of 4.5 mm, and the results showed that when the twist pitch was close to 60 mm, the critical current was reduced to 70\% in the paper \cite{4}. Though various structures have been developed, they are mostly based on 4 mm or over 4 mm width HTS wires.

However, in this paper, a novel wire was suggested and successfully developed through narrowing, stacking and soldering processes using 2G narrow wires with 1 mm width, which is named Soldered-Stacked-Square (3S) HTS wire. The content of this paper was described as follows. Firstly, the narrowing process of the wire with 4 mm width and the stacking and soldering processes were presented in detail. Secondly, several samples were prepared and the critical currents were tested. Then the samples were twisted with single 3S wire and double 3S wires. And the critical currents of twisted samples were measured and analyzed at different pitches.

![Figure 1. Schematic illustration for the manufacture process of novel 3S HTS narrow wires.](image)

2. **Manufacture process of 3S wires**

Figure 1 shows the schematic illustration for fabrication processes of the soldered-stacked-square (3S) HTS wire including twisted wires. Firstly, an original 2G tape with 4 mm width is incised into several narrow wires with the same width 1 mm by a cutting device which is the commercial one frequently used to fabricate flat copper wires for conventional transformers. The 1 mm HTS wire is the narrowest width of the HTS tape, and it is firstly reported by our research group \cite{1}. Then the narrow wires are immersed together into a solder bath, and undergone stacking and soldering processes simultaneously. As shown in figure 2 (a), all of the fabrication processes are completed in a reel-to-reel machine, which is mainly composed of several unwinding reels, a solder bath and one winding reel. In this study, the fabricated 3S wires were made of three narrow HTS wires and four brass strips. Thus the cross section of the 3S wire was near to square. The parameters of the narrow HTS wire and brass strip were listed in table 1. The arrangement of the narrow HTS wires and brass strips are shown in figure 2 (b).
Table 1. Parameters of the HTS wire and brass strip.

| Material     | Width | Thickness |
|--------------|-------|-----------|
| 2G HTS tape  | 1 mm  | 0.1 mm    |
| Brass        | 1 mm  | 0.2 mm    |

Figure 2. Schematic illustration: (a) stacking process of narrow wires. (b) the cross section of the 3S wire.

Figure 3 (a) and (b) show the photos of the twisted 3S wire samples with single wire and double wires, respectively. The full length of the single wire and the double wires were 420 mm and 400 mm. Double 3S wires should be twisted around each other as tightly as possible. Their cross-sections were square shape with 1 mm width, just as figure 2 (b) shows. In order to evaluate the effect of twist pitch on the critical current of 3S wires, several 3S wire samples have been prepared. The samples were divided into two groups: A) Single 3S wire, such as No.1 No.2 and No.3 samples. B) Double 3S wires, such as No.4 and No.5 samples. The specifications of the samples were listed in table 2. The cross-section of the 3S wire is approximately $1 \times 1 \text{ mm}^2$.

Figure 3. Schematic diagram of twisted 3S wires: (a) with single wire, (b) with double wires.
Table 2. Specifications of 3S wire samples.

| 3S wire samples | Cross-section area | Length  | Number of 3S wires |
|-----------------|--------------------|---------|-------------------|
| No.1            | 1 × 1 mm$^2$       | 420 mm  | 1                 |
| No.2            | 1 × 1 mm$^2$       | 420 mm  | 1                 |
| No.3            | 1 × 1 mm$^2$       | 420 mm  | 1                 |
| No.4            | 1 × 1 mm$^2$       | 400 mm  | 2                 |
| No.5            | 1 × 1 mm$^2$       | 400 mm  | 2                 |

3. Results and analysis

3.1 Critical currents of the 1 mm HTS wires

The original 2G tape with 4 mm width was incised into four narrow wires with the same width of 1 mm. In this paper the four narrow wires were named as piece 1~4. Firstly, the critical currents of the narrow wires were tested in liquid nitrogen of 77 K by the four-terminal method. As shown in figure 4, the critical current distributions in length direction show good uniformity. Meanwhile, except for pieces 1~4, many other narrow wires were also cut and tested. The critical current distributions in length direction of them also showed good uniformity. The feasibility of the narrowing process was verified. However, although they are cut from the same original tape, the critical currents among narrow wires are different. The non-uniformity of critical current in width direction might accounts for the difference. The critical current of 3S wire could be designed by using narrow wires with different number and critical current.

![Figure 4. Critical currents of the narrow HTS wires.](image)
3.2 Measurement of twist pitch of 3S wire

Firstly, all samples were fabricated using the narrow wires of piece 2. Before being twisted, the critical currents of all samples were tested. Figure 5 indicates the critical currents of the group A. The lengths of the three single samples were the same with 420 mm. The length between the two voltage leads was 250 mm. The critical currents of sample 1~3 are 143 A, 138 A and 138 A, respectively. The critical current of group A without any degradation is 150 A. Therefore, the critical current of the sample 1 decline 5% and the critical currents of the sample 2 and sample 3 decline 8% after stacking and soldering process. For group B, the lengths of the sample 4 and sample 5 are the same with 400 mm and the length of between the two voltage leads is 200 mm. The critical currents of sample 4 and sample 5 are 260 A and 252 A, respectively. The critical current of group B without any degradation is 300 A. Therefore, the critical current of the sample 4 and sample 5 decline 13% and 16% after stacking and soldering process. Then these samples were twisted by a device whose one side was fixed and the other side could be rotated. The details of the test machine and method were described in the paper [5]. The critical current was tested at different twist pitches.

![Figure 5. Measured critical currents of samples with single 3S](image1)

![Figure 6. Measured critical currents of samples with two 3S](image2)

The normalized critical current means that the measured critical current after being twisted is divided by the original critical current before being twisted. The tolerable twist pitch is defined as the pitch when the original critical current remains 90%. In figure 7, we could observe that the critical current will decline as the twist pitch decreases. The average tolerable twist pitch of sample 1 is approximately 50 mm and the average twist pitch of sample 2 and sample 3 are both 70 mm. The uncertainty and nonuniformity of the twist process might account for the difference of twist pitch. Thus, we could obtain that the tolerable twist pitch of the single sample is between 50 mm and 70 mm. This value could meet the requirement of actual superconducting applications. The influence of twist pitch on the critical currents of double 3S wires is shown in figure 8. As can be seen in figure 8, the critical current increase a little when the twist pitch is bigger than 200 mm. However, when the twist pitch is smaller than 200 mm, the critical current declines as the twist pitch decreases, just the same as
that of single 3S wires. The critical current is smaller than the original critical current when the twist pitch is smaller than 80 mm. The tolerable twist pitch of double 3S wires is about 65 mm. The tolerable twist pitch of double 3S wire is near to that of the single 3S wire.

4. Conclusion
In this paper, a novel soldered-stacked-square (3S) HTS wire is developed through narrowing, stacking and soldering processes using 2G narrow wires with 1 mm width. The critical currents of single and two 3S HTS wires were tested in liquid nitrogen of 77 K before and after being twisted. The following conclusions could be obtained based on the experiment results.

The critical currents of the 3S wires approximately decline 5%~8% after the stacking and soldering process. The tolerable twist pitch of the single 3S wire is approximately between 50 mm and 70 mm. And the tolerable twist pitch of double 3S wires is approximately 65 mm. Therefore, the 3S HTS wires could be applied to several actual superconducting applications such as large HTS coil, HTS cable, HTS motor and so on. Next we will study the influence of the number of 1 mm HTS wires on the performance of 3S HTS wires.

Acknowledgement
This work was supported in part by the National Natural Science Foundation of China (Project 51577119).
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