Influence of Mechanical Cutting Methods on Critical Current of 1 mm HTS Tapes

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Abstract. Over the past decade, the critical current of the tape with 4 mm width exceeds 200 A. Due to the high critical current, the narrowing process to 1 mm width for the HTS tape becomes a feasible technology, and the value of critical current for the 1 mm tape is able to above 50 A. In this paper, critical current loss of 1 mm HTS tape was observed after the mechanical narrowing process. This significantly affects the properties of the 1 mm HTS tape. To understand the influence of narrowing process on critical current, we proposed mechanical cutting methods to manufacture the 1 mm tapes. Meanwhile, the solder plating process was also considered in the manufacturing process of 1 mm tape. The critical current measurements were carried out in order to study the loss of critical current. The detailed results about the critical current measurement experiment, the microscope observation experiment, and the solder plating process were presented and discussed in this study.

1. Introduction

Over the last few decades, the second generation (2G) high temperature superconducting (HTS) tapes with better performance have been widely applied in the field of power equipment, such as superconducting power applications, e.g., transformers, superconducting fault current limiters, superconducting cables, etc. In practical applications, external magnetic field will reduce the performance of 2G HTS wires including critical current and AC loss\textsuperscript{1}. To reduce the influence of external magnetic field, many new tape structures and new processes including mechanical cutting methods have been proposed\textsuperscript{2}. However, they are usually based on the HTS tapes with width of 2 mm – 12 mm. The 1 mm width HTS tape is firstly studied by our research group in 2016\textsuperscript{3}.

In this paper, a 1 mm narrow tape was successfully obtained through mechanical cutting method. The entire method will be introduced in detail. Moreover, for the 1 mm tape, the critical current
properties were studied and the microscope observation experiments were carried out to show the details in the surface and cutting section. Meanwhile, the solder plating process were considered for comparison.

2. Sample preparation

2.1. Narrowing process

Figure 1 shows the cutting machine for narrowing process. Figure 1 (a) is the mechanical narrowing machine and figure 1 (b) is the two cutting tools. The mechanical cutting machine we used is a modified one which is frequently used to cut flat copper wires[4]. In order to ensure that narrowing process is effective, the horizontal position of two cutting tools must be adjusted precisely and the cutting depth should match the thickness and hardness of HTS tapes. During the narrowing process, machine operating parameters such as cutting speed and shaft tension also should be adjusted to obtain 1 mm tapes with better performance. The specific parameters of the 4 mm tape are shown in table 1. In this paper, two 4 mm HTS tapes provided from Superconductor, Nano & Advanced Materials Co., Ltd. (SuNAM) in Korea with 100 cm length, sample 1 and 2, were prepared. For each sample, four 1 mm HTS tapes of 100 cm length, sample No.01, 02, 03, 04, were obtained. Only one side of sample No.01 and No.04 was cut and both two sides of sample No.02 and No.03 were cut during the mechanical narrowing process. So, we got 8 samples with 100 cm length in total.

Table 1. Specific parameters of 4 mm tapes.

| Parameters                                      | Value           |
|------------------------------------------------|-----------------|
| Width and Thickness                            | 4.0 mm × 0.15 mm|
| Thickness of superconducting layer             | ~1 µm           |
| Thickness of silver layers                     | ~1 µm           |
| Thickness of copper plating layer, each side   | ~20 µm          |
| Thickness of substrate layer (including buffer)| ~108 µm         |

Figure 1. Cutting machine. (a) mechanical narrowing machine; (b) two cutting tools;
2.2. Solder plating process

Figure 2 shows the solder plating machine of HTS wires. This machine consisted of six guide wheels, flux platform, solder bath and control system was also used to manufacture the soldered-stacked-square (3S) wire which was firstly suggested by our group [5]. An appropriate amount of flux should be added to the flux platform in advance, which can dissolve the oxide film on the surface of the 1 mm tape, reduce the surface tension of the solder and stick the solder and the tape together better. During the solder plating process, the 1 mm tape entered the flux platform through the guide wheels firstly. Then, the 1 mm tape was immersed in the solder bath and moved at a certain speed through the guide wheel in the solder bath until it left the solder bath. In this study, the temperature of solder bath was 200 °C and the tape speed was 3 m/min. Excessive temperature and slow speed will affect the superconducting properties of 1 mm HTS tape. As mentioned before, eight samples with 100 cm length were obtained through mechanical narrowing process. Now, for each sample, half of each 1 mm tape, 50 cm length, was processed. Finally, we got 16 samples with 50 cm length in total.

![Figure 2. Solder plating machine. (a) guide wheels; (b) flux platform; (c) solder bath; (d) control system;](image)

3. Results and discussions

3.1 The critical current experiments

A four-lead method was applied to measure the critical current, at liquid nitrogen temperature, 77 K, and a distance between voltage leads was 30 cm. According to the 1 µV / cm threshold, the critical voltage is 30 µV. The four 1 mm tapes obtained from one 4 mm tape were placed in sequence on the mold shown in figure 3. The measured critical current of two set of four 1 mm tapes manufactured from sample 1 and sample 2 were 42 A, 36 A, 34 A, 32 A and 42 A, 39 A, 36 A, 32 A, respectively. Meanwhile, more critical current experiments were carried out every few hours. Each group of experiments last about 200-300 hours. Critical current loss (I_c loss) was observed during these experiments as shown in figure 4-7. Moreover, figure 4 and 5 corresponded to the measurement results of the no solder-plated 1 mm tapes obtained from sample 1 and sample 2. Figure 6 and 7 corresponded to the measurement results
of the solder-plated 1 mm tapes obtained from sample 1 and sample 2. The normalized critical current means that the measured critical current divided by the initially measured data ($I_{c0}$). The tolerable critical current loss is defined as 5% of initial critical current.

Figure 3. Mold for critical current experiments.

Figure 4 (a)-(d) indicate that the critical current of sample No.01, No.02 and No.03 oscillated near the initial critical current, without attenuation. The critical current of sample No.04 decayed around 150th hour and eventually stabilized at 10%. Figure 5 (a)-(d) indicate that the critical current of this four samples was slightly higher than the original critical current. The critical current measurements were carried out 300 hours after the mechanical narrowing process, and the 1 mm tapes were previously stored in a cabinet with constant temperature and humidity. Different from the results shown above, we observed obvious current loss in figure 6 (a)-(d) and figure 7 (a)-(d). Particularly, figure 6 (b) and (c), figure 7 (b) and (d) indicate that a sharp decrease of critical current more than 50% formed in a short time which was mainly related to human factors such as tape bending and excessive welding temperature during experiment. Furthermore, figure 6 (d), figure 7 (a) and 7 (c) indicate stepped decrease of critical current.

Figure 4. Measured critical current of no solder-plated 1 mm HTS tapes manufactured from sample 1. (a) sample No.01; (b) sample No.02; (c) sample No.03; (d) sample No.04;
Figure 5. Measured critical current of no solder-plated 1 mm HTS tapes manufactured from sample 2. (a) sample No.01; (b) sample No.02; (c) sample No.03; (d) sample No.04;

Figure 6. Measured critical current of solder-plated 1 mm HTS tapes manufactured from sample 1. (a) sample No.01; (b) sample No.02; (c) sample No.03; (d) sample No.04;

Figure 7. Measured critical current of solder-plated 1 mm HTS tapes manufactured from sample 2. (a) sample No.01; (b) sample No.02; (c) sample No.03; (d) sample No.04;

In the above experiments, the length of 1 mm tapes was 50 cm and the distance between voltage leads was 30 cm. For the 1 mm tapes with critical current loss such as shown in figure 7 (a) and (d), it’s necessary to know whether the critical current loss occurred across the entire measurement area or just a certain area. As shown in figure 8 (c) and (d), we added more voltage leads, six in total, at the 400th hour and the distance between every two lead points was 6 cm. It can be seen from figure 8 (a) and (b) that critical current loss was different along the length direction. Not the entire tape was damaged under large critical current loss.
Figure 8. Measured critical current with different voltage lead combinations of solder-plated 1 mm HTS tapes manufactured from sample 2 and the distribution of voltage leads. (a) sample No.01; (b) sample No.04; (c) schematic diagram of voltage lead distribution; (d) voltage lead distribution;

3.2 The microscope observation tests

In order to have a further study on the critical current loss of the mechanical narrowing process on the HTS tapes, microscope observation experiments were carried out on the cutting sections along the cutting direction and the surface of the sample No.01 without solder plating manufactured from sample 1. In the experiments, we used a metallographic optical microscope (MOM), which can display the image formed by a common optical microscope on the computer with photoelectric conversion and image processing technology. The MOM could provide clearer images and the operation was easier.

Figure 9 (a) shows the surface with 500x magnification. Figure 9 (b), (c) and (d) are the image of area 1, area 2, area 3 with 5000x magnification. It can be seen that some damages occurred at the edge during the mechanical cutting process, which would damage the superconducting layer and the protective layer of the 1 mm HTS tapes[6]. For this sample, although there was no I_c loss as shown in figure 4 (a), mechanical cutting process caused some damages to the 1 mm tapes.

Figure 9. Results of microscope observation of the sample No.01 without solder plating manufactured from sample 1. (a) surface; (b) area 1; (c) area 2; (d) area 3;
Figure 10. Results of microscope observation of the sample No.01 without solder plating manufactured from sample 1. (a) less than half covered; (b) more than half covered;

Figure 10 shows the cutting section of 1 mm HTS tape with 2000x magnification. Obviously, the copper layer extended downward in the cutting direction and covered the other layers during the mechanical cutting process. Well-distributed extension surface as shown in figure 10 (a) meant higher quality of the mechanical cutting process. Meanwhile, according to the area covered by the copper layer, the cutting sections can be divided into two tapes, less than half covered and more than half covered, as shown in figure 10 (a) and (b). The coverage area and the uniformity of the extended surface were related to many factors such as the cutting strength, cutting speed and etc.

4. Conclusion

In this paper, the mechanical cutting method was used to manufacture the 1 mm HTS tapes. Critical current experiments were carried out to study the influence of mechanical cutting methods on critical current of 1 mm HTS tapes. Solder plating process was considered for comparison and the microscope observation experiments using MOM were carried out to show the details in the surface and cross-section of the 1 mm tapes. The following are our conclusions:

1) The 1 mm HTS tapes accomplished through mechanical narrowing method showed stable critical current properties, which means the mechanical narrowing method is available for manufacturing the 1 mm HTS tapes.

2) However, the solder-plated 1 mm HTS tapes showed obvious critical current loss in the critical current experiments. This suggests the solder plating process will damage the properties of 1 mm HTS tapes. Meanwhile, critical current loss of 1 mm HTS tapes varies along the length direction.

3) In the microscope observation, the cutting side was clearly visible. Because of the stress from the cutting tools, obvious defects which damage the superconducting layer and the protective layer were observed. In addition, the extension surface formed by the copper layer was well-distributed with high-quality mechanical cutting process.

The above results show that the mechanical method is available for manufacturing the 1 mm HTS tapes. However, significant improvement needs to be developed in the solder plating process. This paper could provide a possible reference for manufacturing the narrow HTS tapes. Subsequent studies include improvements in mechanical cutting processes and solder plating process.
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