A Study on different Narrowing Processes in the Manufacturing of 1mm HTS Tapes

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Abstract—This paper provides a reference for manufacturing the narrow HTS tapes. The narrow tapes have many advantages such as smaller AC (Alternating Current) loss and suppressed screen current compared with normal tapes. Therefore, it’s meaningful to manufacture the narrow tapes. Traditionally, the way to manufacture the 1 mm HTS tapes is to use the mechanic narrowing process. In this paper, we proposed two narrowing processes to manufacture the 1 mm HTS (high temperature superconducting) tapes, one is using the cutting machine, the other is using the laser. The critical current tests and microscope observation tests were carried out in order to make a comparison with these two methods. Results show that the laser narrowing process has a smaller critical current loss but has dross, and the mechanical narrowing process shows a larger critical current loss but clearer section stratification.

1. Introduction

Since the discovery of the second generation (2G) high temperature superconducting (HTS) tapes in the early 1990s, it has been rapidly developed and used in various fields, such as superconducting machines, superconducting transformers, magnetic levitation, etc[1]. With the development of the 2G HTS tapes[2], the narrowing and packaging process[3] of the HTS tapes has been widely concerned, because of the smaller AC loss and more suppressed screen current[4], and making good quality tapes is always a concern for future use. Moreover, the narrowing process has a great influence on the quality of the tapes, in this paper, we studied and tested two narrowing processes for comparison.

Traditionally, the commercial HTS tapes have width of 2 mm-12 mm. In this paper, a 1 mm-width HTS tape is manufactured and tested, and a novel narrowing process for such width of the HTS tape is proposed by the laser. Two narrowing processes are tested in this paper in order to compare and verify the feasibility of these two methods. One is cut mechanically by a cutting machine and the other one is by laser. In the experiments, a 4 mm 2G HTS tape is incised into four 1 mm wide HTS tapes. The used
HTS tapes are the second generation HTS wires, i.e., REBCO tapes, manufactured by SuNAM Company, the specific parameters of the tapes is listed in Table I. Different sections of the 1 mm HTS tapes which is cut by different method is observed and compared using the microscope. Moreover, current-voltage tests are carried on these 1 mm HTS tapes and the critical currents are studied and compared.

| Parameters                                      | Value                                      |
|-------------------------------------------------|--------------------------------------------|
| Manufacturer                                    | SuNAM                                      |
| Type                                            | REBCO                                      |
| Insulation                                      | No                                         |
| Width and Thickness                             | 4.1 mm × 0.142 mm                          |
| Material of the metal substrate                 | Non-magnetic stainless steel                |
| 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                                     |

2. Narrowing process

Fig. 1 shows the two different narrowing equipments, Fig.1(a) is the mechanical narrowing machine and Fig.1(b) is the laser one. We used the rolling shearing machine to narrow the HTS tapes, and two cutting tools are used in this rolling shearing machine for manufacturing the 1mm HTS tapes. The tool bits used in the machine narrowing process has 4×1mm knife edge. Mechanical narrowing process is using the cutting machine (XTF 80 made by our laboratory) to incise the 4 mm wide HTS tape into narrower HTS tapes. The mechanical cutting machine we used is the commercial one frequently used to fabricate flat copper wires for conventional transformers [5]. After aligning the equipment and the tapes, select an appropriate cutter, keep prosper cutting strength and cutting speed, then incise the 4 mm wide HTS tapes into 1 mm wide tapes. In the mechanical narrowing process, the cutting speed is 3m/s, and the human factors such as the alignment of the blade position and artificial tensile may have an impact on the HTS tapes.

![Fig. 1. The narrowing equipment. (a) mechanical narrowing machine; (b) laser narrowing machine;](image-url)
Laser narrowing machine is using the laser beam to heat the HTS tapes. In this study, the machine we used is a UV (ultraviolet) laser marking machine modeled SWLASER-F3W made by Shanghai SW Laser Technology CO., LTD. In the laser narrowing process, the laser narrowing machine we used has the following conditions: the laser oscillation method we used is a solid-state laser and the Q-switch frequency range of the laser is 20-200kHz. Moreover, the laser UV-wavelength is 355 nm, and no more assist gas is used in the process. The maximum processing speed of the laser narrowing machine is 100 m/h. Furthermore, the laser narrowing machine has a closed loop control with tension and speed, and the processing jigs is absent but limit screws are present.

Adjust the position of the laser lens in order to make the reflect laser focuses on the tapes first during the laser narrowing process. Then, fix the position of the strip and adjust the parameters and marking position of the laser marking. Finally, open the air extracting device to absorb the air between the cutting platform and the HTS tape, and run the device. In this study, the cutting speed is set at 50 m/s for the accordance with that of the mechanical narrowing machine, and the frequency is 40 kHz with the pulse width is 25 μs.

In order to test the different narrowing methods on manufacturing 1mm-width HTS tapes, the critical current tests and the microscope observation tests of the HTS tapes are performed. In this paper, the brief analysis and comparison of these two narrowing methods for manufacturing the 1mm HTS tapes is discussed based on these two tests (i.e. critical current test and microscope observation tests).

3. Results and discussions

3.1 The critical current tests

The critical current tests are performed on the 4mm-width HTS tapes firstly, then blow-dry these tapes quickly. After that, using these two narrowing processes to incise the 4mm HTS tapes into 1mm wide. Then perform the same critical current tests on these 1mm HTS tapes. We used transport measurement method, i.e., four-probe method in the critical current tests. The HTS tapes we used are 1m long, and the voltage terminals of the HTS tape is approximately 50 cm long. According to the 1 μV/cm threshold, the critical voltage is 50 μV. The ramping rates of the applied current are the same, i.e., 1 A/s. All of the critical current tests were performed in a liquid nitrogen (LN2) bath at 77 K. The results are shown in table II.

| Table II. Critical currents of the test tapes. |
|---------------------------------------------|
| Mechanical narrowing                        |
| Ic of the 1mm HTS tapes                    |
|  | 1 | 2 | 3 | 4 | Sum of Ic of 4mm HTS tapes | Ic of the 4.1mm HTS tapes | Ic loss percent  |
| 1 | 40 | 40 | 44 | 30 | 154 | 202 | 23.8% |
| 2 | 40 | 40 | 35 | 36 | 151 | 200 | 24.5% |
| 3 | 40 | 46 | 37 | 47 | 170 | 204 | 16.7% |
| Laser narrowing                            |
| 1 | 28 | 53 | 64 | 62 | 207 | 212 | 2.4%  |
| 2 | 40 | 40 | 50 | 61 | 191 | 204 | 6.4%  |
| 3 | 51 | 40 | 44 | 60 | 195 | 204 | 4.4%  |
As it showed, the critical current of the 4mm HTS tapes are similar which is around 200A. The sum of the critical current of the four 1mm HTS tapes in the same narrowing process is also similar, which is 155 A for mechanical narrowing process and 195 A for laser narrowing process. The Ic(critical current) loss in the mechanical narrowing process is around 20%, while 5% of that in the laser narrowing process. From the results, the critical current is almost no loss during the laser narrowing process.

3.2 The microscope observation tests
In order to have a deep study on the critical current influence of the narrowing process on the HTS tapes, some microscope observation tests are performed on these cutting sections of the 1mm tapes along the narrowing direction. Fig. 2 and fig. 3 show the photos of the sections of the mechanical narrowing process and laser narrowing process, respectively. The figure (a) and (b) shows the sections of the tapes under an optical microscope and an electron microscope, respectively. And figure (c), (d) and (e) is the elemental analysis using the EDS (Energy Disperse Spectroscopy) which is component analysis in the red box in figure (b). As the figure shows, (c), (d) and (e) represent the distribution of copper, silver and REBCO on the cutting surface of the tapes, respectively.

As the fig. 2 (a) and fig. 3 (a) show, the layer construction of the superconductors of the mechanical narrowing process is much clearer than in laser cutting, and the surface is much more unsmooth. As shown in the figures, the cutting sections of the tapes are damaged due to the slitting methods. Referring to the papers [6]-[7], the distributions of critical current densities in narrowing tapes are uneven, this contributes to the $I_c$ suppresses due to mechanical and laser narrowing.

![Fig. 2. The microscope sections of the mechanical narrowing process. (a) optical microscope; (b) electron microscope; (c) Cu in EDS (Energy Disperse Spectroscopy); (d) Ag in EDS; (e) GdBCO in EDS.](image)
As the elemental analysis diagrams in (b), (c) and (e) show, the diffusion range of the copper and silver layer of the mechanical narrowing process is less related as they permeate to other layers in the laser narrowing process. Since the melting point of the silver in the HTS tapes is the lowest and it has a high fluidity after liquefaction, the distribution of silver is wide in the laser narrowing process. Moreover, the silver filaments can be seen figure 3 (a).

In addition, the GdBCO disperses to all parts of the sections both in these two narrowing processes. Therefore, compared with the mechanical narrowing process, using the laser to cut may “burn” the surface of the tapes, and the material in all layers will mix together. The main reason for the above results is that the formation mechanism is different. Mechanical cutting is due to the pressure, while the laser cutting is due to excessive energy.

![Fig. 3](image1)

**Fig. 3.** The microscope sections of the laser narrowing process. (a) optical microscope; (b) electron microscope; (c) Cu in EDS; (d) Ag in EDS; (e) GdBCO in EDS.

![Fig. 4](image2)

**Fig. 4.** The microscope sections of the mechanical narrowing process. (a) No wrapped; (b) Half rapped; (c) All wrapped.
Moreover, in the mechanical narrowing process, the quality of the narrowing process has a great influence on the cutting sections. According to the proportion of the area covered by the copper layer to the total section, the cutting sections in the mechanical narrowing process is divided into three categories: no wrapped, half wrapped and all wrapped, which are showed in fig. 4. The copper layer wrapped part of the other layers downward along the cutting direction. The coverage area of the copper layer is uncertain which is related to many human factors such as the cutting speed, cutting strength and etc. In the mechanical narrowing process, the interface defects are easy to occur on the cutting sections, i.e., cracks. In contrast, the laser narrowing process is more stable for the cutting sections are similar.

4. Conclusion

In this paper, two narrowing methods used to manufacture the 1 mm-width HTS tapes were experimentally investigated and compared. In the experiment, the 1 mm HTS tapes were manufactured by the mechanical narrowing process and laser narrowing process, respectively. And the critical current tests and microscope observations are performed on these tapes. The microscope tests including using an optical microscope and an electron microscope, and an elemental analysis using the EDS is also performed. The following are the conclusions were derived:

1) In the critical current tests, the 1mm tapes manufactured by the mechanical narrowing process have larger critical current loss than that in the laser narrowing process, which shows the mechanical narrowing process caused greater loss.

2) In the microscope tests, the stratification of the HTS tapes is much clear in the mechanical narrowing process, while it seems the laser cutting is more scattered.

3) The mechanical narrowing process has many advantages, it will not affect by the thickness of the tapes, the process is simple, and the section looks better. But it’s relative to the human factors so it’s not very stable, and the Ic loss is a little large.

4) Laser narrowing process can be used in narrowing long HTS tapes, and it has high precision and low critical current loss. However, it has dross and high narrowing costs.

The results demonstrate that the mechanical narrowing process and laser narrowing process cut both ways and are both feasible for manufacturing the 1 mm tapes. This paper could provide a possible reference for manufacturing the narrow HTS tapes. Process improvements for manufacturing narrow tapes are included in subsequent studies.

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