The Manufacture and Performance of Low Temperature Superconductors

Xuheng Han
SCU (Jiang'an Campus), 1st, Chuanda Road, Chengdu, China
hanxuheng@stu.scu.edu.cn

Abstract. The application of Nb3Sn superconductor joints is an important part in the production of ITER, MRI, and so on. This paper first introduced the application, like coil of MRI, and basic information including the micro crystal structure of Nb3Sn superconductor, which includes the theoretical critical temperature of 18.1K, even mostly, experiments take place under 4.2K, which is the boiling point of liquid helium. Second, it talked a little about the production of CICC joints in industry. Then, mainly introduced the testing device, material parameters and testing procedures of resistance testing of Nb3Sn joints. Concluded all the data from several tests and summarized it. At last, it displayed some of its mechanical property especially about its brittle property and discussed some details in manufacture. Finally conclude about them all.

Keywords. superconductor, low temperature superconductor, joint, manufacture, resistance measurement.

1. Introduction
Superconducting phenomenon was first observed by Heike Kamerlingh Onnes in 1911. He noticed that when Hg is cooled under 1.15–4.25K, the resistance disappeared. That phenomenon created new fields for material. Then, superconductors are classified into several classes due to their structure, critical temperature or explain theory, like alloy superconductor, low temperature superconductor, high temperature superconductor etc. [1] However, even today, the system of superconductor is still under studied, while the application of low temperature superconductor is mature by comparison.

Today, the energy provided by controlled nuclear fusion is the future of human beings. In order to achieve that, it needs high current and high magnetic field. However, massive amount of heat will be released using normal material with "high" electric resistance. Therefore, the application of superconducting material is essential in those fields. Nb3Sn and NbTi alloy are the most widely used in reality and Nb3Sn is mentioned as it is a kind of superconducting material with A15 [2] crystal structure with critical temperature of 18.1K [3], which is already been used in the superconducting magnets for the ITER fusion reactor [3] as high field of Toroidal Field (TF) coils [4] due to its high critical magnetic field, high resistance to magnetic field and good electromagnetic properties.

However, even the manufacturing of kilometer Nb3Sn is mature now, the joints are still essential in many devices which are used to connect bunches of single coils. In MRI and NMR [5], the application of superconducting material joints is common, and the cost of coolant and the loss of current deeply depend on the quality of joints. Because of the brittle property of Nb3Sn due to A15 structure and the complex mechanical properties it has. The manufacturing of Nb3Sn wires is important and researchable, and a lot of research have been done on that.
This paper first generally introduced the manufacture of Nb3Sn joints based on its microstructure and compared with NbTi alloy about their properties. Then, it introduced the testing theory and device and analyzed the digits, which is the resistance. Finally concluded the reason of resistance difference and mentioned some important mechanical properties of low temperature superconductor. Making it a reference for processing superconductor joints.

2. Joint processing
The processing of joints is complex and can be classed into several types. Normally we have brazing, cold pressure welding, diffusion welding, explosion welding, sintering etc. method as joints within wire. Those are the most common and widely used method of processing joints, and mostly used to producing single wires. However, when talking about CICC wires, those simple welding methods cannot be used since the internal structure is complex and mostly it needs some more complex welding method which it has not been discussed in this paper. But it is still essential to say about that.

3. Electromagnetic property
Normally, when talking about electromagnetic properties of superconductors joints, resistance under different magnetic fields is always mentioned when critical current and magnetic field are close. Typically, the measurement of superconductor joints is using electromagnetic induction method. The Four-Probe Method is more widely used to test critical current and field.

The theory of induction method is that: First we connect the measured superconducting joints into a circuit; then charging the circuit; then remove the battery and close the circuit. Since small quantity of resistance still exists in the joints, the current attenuating gradually. By measuring the speed of attenuation, resistance received.

4. Experiment

4.1. Testing device
Wrap a 50 mm diameter super-conducting coil around an epoxy fiberglass spool located inside the lower conductor coil and a length of straight section containing a straight section of the test connector. Wrap the heating wire around the 10mm-long part of the ring. The Hall probe is put in the FRP spool of the winding ring. The lower super-conducting solenoid is put around the loop in order to induce the current in the loop. The upper super-conducting coil is put approximately 230mm above the test ring to generate the magnetic field on the connector. The upper coil is run under continuous power supply. The voltage leads attached to the connector are connected with the terminals of voltmeter. As for this measurement, the ring is immersed in liquid helium, 4.2K. Current is induced in the loop and current attenuation is measured by measuring the magnetic field which is generated by the induced current in the loop using a Hall probe. Calibration is performed under the same superconducting loop with already known current.

4.2. Procedure

4.2.1. Charging process.
1). Install the test loop system on the experimental device as shown in figure 1.
2). Insert the measurement framework into the cryostat.
3). Immerse all the superconducting system in liquid helium; then wait for 30 min in order to release the termal stress in the Hall sensor.
4). Excite the test loop by turning on the battery or any power supply.
5). At t1. Stop exciting the current transformer.
6). At t2, turn on the heater; at t3, quench the test loop, then the current in the test loop decreases suddenly to 0 at t4.
7). At t5, turn off the heater.
8). At t6, start to reduce the current in the transformer to 0.
9). At t7, the current in the transformer decreases to 0.

Figure 1. The charging circuit.

Figure 2. Ideal condition of charging. (schematic) [6]

4.2.2. Attenuation Process.

1). Keeping the circuit in low T condition in order to keep them in superconducting state.
2). Moving into an electromagnetic shielding room.
3). Waiting for a few days (1-2 days) for the attenuation of current and measuring and recording the data.

The measurement circuit is shown in figure 4

Some points need to be mentioned:
a) the electromagnetic fielding room might not essential since the Magnetic Interference is much smaller than the magnetic field produced in the experiment. (geo-magnetic field is around 5-6\(\mu\)T, phone is around 200-600 \(\mu\)T, transformer substation is around 1 \(\mu\)T).
b) the theory of measuring circuit is the same as a transformer. We use larger \(\frac{N_{\text{induced}}}{N_{\text{original}}}\) to magnify the signal so the error is smaller.
c) normally we use 2-3 days as the time range in order to magnify the attenuation of current for better result. And normally starts after some time since the signal might not be stable due to many surrounding interferences.
For Nb3Sn, normally, there are 3 methods of fabricating: bronze process, internal tin process and powder casting process. Experimentally, materials have the best electric quality using powder casting process. The fraction of different components also creates different electric properties. Typically, the increase in Ti concentration accelerates the forming of Nb3Sn and increases the strength of material.  

- In Chen's experiment, R (inner joint) = 1.3 nΩ, R (outer joint) = 0.45 nΩ. [7]
- In Vincenzo's experiment, R = 0.22 nΩ under 0T 63.3 kA; R = 0.38 nΩ under 4T, R = 0.58 nΩ under 8T, R = 0.83 nΩ under 10T, and increases after cyclic loads, decreases after warming up [8]
- In Shi's experiment, the resistance of Nb3Sn superconductor wire is approximately near 0.57 nΩ under low magnetic field, no Ic is given [9].
- In Fabrizio's experiment, resistance is about 0.5-1.2 nΩ, [10].
- It is clear that the resistance is still under $10^{-3}$ Ω magnitude. Which is under acceptable range in extreme condition.
- Classed by their fabrication pressure, 6 joints of NbTi alloy wire with size: "bare diameter of 0.4 mm, Cu/SC ratio of 1.35 and 54 filaments" [6] which are all measured under 1 T of background magnetic field:
Table 1. Resistance of NbTi joints with different fabrication pressure. (M=0 T) [6]

| Joint (MPa) | R (Ω) under 1T | I (A) |
|------------|----------------|-------|
| 4 - 1#     | < 1 × 10^{-13} | 270   |
| 7 - 2#     | < 1 × 10^{-13} | 240   |
| 10 - 3#    | < 1 × 10^{-13} | 252   |
| 13 - 4#    | < 1 × 10^{-13} | 222   |
| 16 - 5#    | < 1 × 10^{-13} | 293.5 |
| 20 - 6#    | < 1 × 10^{-13} | 300   |

Where I is the current where the resistance of joints are measured. We see that the resistance of joints is all under 1 × 10^{-13} Ω from Table 1 under 0 T magnet field, which are satisfied results.

Experimentally, the performance of NbTi and Nb3Sn is close, mostly their applications are switchable, the digits in paper are different due to size difference. Nb3Sn is mostly CICC with high Ic while NbTi is smaller. However, due to the price, replace NbTi by Nb3Sn is not essential in common environment. The advantage of Nb3Sn is high resistance to magnetic field. Nb3Sn still in superconducting state under 22.5 T. And under low magnetic field, magnetic flux jump happened frequently to Nb3Sn. So, Nb3Sn is mostly used in extreme conditions, and the brittle property of Nb3Sn is also affecting its application a lot.

5. Mechanical property
An important characteristic of Nb3Sn is its brittle property. Nb3Sn is a brittle material. Therefore, many cracks and dislocations are produced if the method is not suitable, which effects superconducting property a lot. So, in practice, it cannot be produced first and then winding. We normally wind it first and heat them at last to complete the diffusion process. Another problem needs to be pointed out is that when winding, due to the internal stress include but not only: thermal stress, stress due to Ampere's force, stress due to winding. Due to the difficult structure in CICC, minor change in stress affects electronic property a lot. The method should be reconsidered.

6. Conclusion
In conclusion, Nb3Sn is a widely used low temperature alloy superconductors. Normally, the resistance range varies from 10^{-9}~10^{-13} Ω, depending on the size of wire. But generally, they are satisfying results and such cost of current and loss heat is accepta

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