Different Techniques of Producing Superconducting Joints and Methods of Joints Characterization

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Abstract—In this paper, the method of producing superconducting joint will be briefly discussed. Cold press welding method, ultrasonic welding, spot welding and Thornton’s replacement method will be discussed. The characteristics of the superconducting joint are also discussed by using four probe method and IRT method.

1. Introduction
Superconducting magnet is commonly used commercially and academically. For superconducting magnet to sustain the high intensity field, large and persistent current is required. Due to the charge conservation, current running in the wire is not infinitely large and therefore, after applying ohm’s law we can easily see a fact that there will be attenuation in the current. The attenuation of current might cause instability of magnetic field if the superconducting magnet operates a longtime and eventually the goal of using the magnet will be compromised. The desire of decreasing attenuation motivates the development of persistent joint. Usually, the current loss can be compensated by either increasing current-carrying capacity or reducing the joint resistance. [1] These two goals can be achieved by using different fabricating method and different kind of materials. Persistent joint can be fabricated with different methods and those different fabricating methods will produce different joint structure. In this paper, methods of fabrication will be listed and discussed. Properties of persistent joint vary when materials are different. Different properties used for persistent joint’s fabrication will also be discussed.

2. Method of Fabrication
Different methods of production will result in different joint architecture. The first structure is done by connecting two superconducting wires head to tails and then sealing the connection with silver layer or other superconducting solder materials. This way of production is often used for producing long superconducting wire. Furthermore, the tip to tip connection make sure that the homogeneity of magnetic field will be preserved. However, the disadvantage of this method is that because the cross section of connection is small compared to other method of production, outer layer of solder material might penetrate inner space between two wires such that the resistance increases largely.

Another method will be connecting two wires with one wire overlapping on another. Compared to the tip to tip connection method, the contacting area between two wires are substantially larger. Thus, the transition of current will be larger than the previous method. The current transition rate is related to how the overlap is made. In cold pressing welding method, the transition rate is related to the pressure imposed on the wires. The detailed description is presented in the patent paper [8]. In Liu’s exploration of joints produced by cold press method [6], the outer layer of wires is removed by acidic solution and then wires
are twisted together. The twisted wires are inserted into a tube made with the same material and then the tube will be pressed in a cold-welding machine in open air. Usually the quality of joint depends on several factors. First one is the filamentary structure inside the tube. Second factor is the actual pressure applied when manufacturing the joint. The third factor is the surface condition of the filaments. The influence of pressure is explored and measured by Liu’s group with NbTi joints [6]. It is reported that flux creep will be observed in most of the joint produced by cold pressed method. In Liu’s experiment, the test results for joints made with different mechanical pressure show that the current carrying capacity (joint performance) is weakly related to the mechanical pressure [6]. However, interestingly in their experiment it’s shown that flux creep is strongly linked to the mechanical pressure. Joints produced with pressure from 4MPa to 20MPa have resistance less than 10^{-13} \Omega in 1 T magnetic field. The current in these joints varies around 260A. In Liu’s experiment, the test results for joints made with different mechanical pressure show that the current carrying capacity (joint performance) is weakly related to the mechanical pressure. [6]

3. Ultrasonic Welding

Ultrasonic welding is basically a welding method, but it utilized ultrasonic vibration to fortify bonding between surfaces of jointing metals with 0.3-0.5 cm thickness [4]. The sample is held on a fixed anvil and pressure with 1400kPa and vibration of 15kHz frequency are applied to the joint. [4] In order to fabricate the joint, the outer solder layer of received conductors or conductors of interest need to be removed because the outer layer can absorb substantial amount energy from high frequency vibration. Because solder layer serves a role of protecting superconducting materials inside, therefore there should be extreme care when removing solder. [4] After the solder layer is removed from the welding area, the conductor will be firstly carefully grinding by fine grit abrasive cloth and then cleaned with acetone. Then two conductors will be welded with 1034kPa clamping force and at the same time vibration of 15kHz will be applied during the whole welding process which last 1.5s. [4] After welding, the thickness of combined joint is trimmed in order to make sure normal function of magnet windings. It is reported by J.Hasfstrom’s group that the resistance of joint produced this way can has 9 \times 10^{-10} \Omega for 5cm long joint. [4]

4. Cold Press Welding

Cold press welding and USW are chosen for production of NbTi joints, however, if the surface is contaminated by oxidation barriers, forming bond become problems in these two method after moving those barriers because during the process of pealing oxidation contamination layer, properties of the joint might be changed. At this moment, spot welded joints become a good solution because the bond can be formed soon as the barriers are dissolved. This is a method usually for producing joints between two sheets of superconducting material. In this method, work piece is held by two electrodes and the bond is formed by resistive heating when send a large amount of current through the work piece. The oxidation barrier will be dissolved right before the bond is formed. Joints produced by spot welding method is reported to have lower current carrying performance especially at the joint region. In this technique, multiple soldering spots implies that the super-conducting wires might be influenced by high temperature. Multiple high temperature soldering spots might disturb the carefully arrangement of pinning nanostructure of the NbTi filaments, and therefore the superconducting properties might also be disturbed [1].

5. Soldering joint

The standard method of soldering is based on Thornton’s matrix replacement technique [10]. This method prevents the oxidization of inner superconducting wire. The inner wire is usually surrounded by other materials. For example, for NbTi conductors, the NbTi wires are soaked into molten Tin bath at temperature of 350 degrees of Celsius after removing the insulating outer layer. This step is to avoid oxidization of NbTi wires. Then the wires will be put into molten superconducting materials at the same temperature. [9] Due to the difficulty of removing the inner layer (Nb [3]), the conventional solder dip
A new soldering method is developed by T. Fukuzaki et al. [3]. This method is developed without removing the intermediate layer. This method is used for production of NbAl-NbTi superconducting joint. The surface treatment is applied to NbAl conductor first.

- Cover joint of Nb3Al conductor with low Sn composition solder and apply 800 degrees of Celsius heat treatment for 10 hours. Sn-Cu layer will form by diffusion. Nb3Sn layer will be formed outside the Nb matrix by reaction of Nb and Sn-Cu layer. It is shown in paper that the state of Nb-Sn layer in this step is decided by the solder composition. The width of Nb-Sn layer depends on the Sn composition in solder composition. 

- Then the joint is dipped in molten solder with high Sn composition. Cu-Sn layer will be removed by diffusion reaction at a temperature between 300-400 degrees of Celsius. The process is lasting for 30 min and is air sensitive. The environment is usually in either vacuum or argon.

- The joint is dipped in molten SnBiPb solder (300-400 degrees of Celsius). High Sn composition will be replaced by SnBiPb during 30 min. The environment is in argon or vacuum. For NbTi conductor, the surface treatment is described as following [3]:

- The insulating layer outside NbTi conductor is removed.

- After the outer layer is removed, the NbTi conductor is dipped into solder with high Sn composition at a temperature between 300 and 400 degrees of Celsius. The solder materials remove the Cu matrix outside the NbTi conductor by diffusion reaction. Similarly, this process is under vacuum or argon.

- Same as NbAl conductor, the joint of NbTi is dipped into molten SnBiPb solder with temperature to be 300-400 degrees of Celsius for 30 min. The reaction is air sensitive therefore the environment is also in either vacuum or argon. The Ti alloy is replaced by the SnBiPb solder. The joint produced by Fukuzaki et al. with this method is with 1 cm length. It is reported that the superconducting joint can remain superconductive up to 0.4T magnetic field. [3] The measurement of current and voltage under different magnetic field in the joint shows that the joint has desirable superconducting property at 0.1T [3].

Figure 1. Four probe measurement of current and voltage in the 1 cm joint produced with new solder joint method. The temperature is at 4.2K which is the superconducting temperature of SnBiPb. The figure is from [3].
6. Measurement and Characterization of Produced Joints

There are two ways of characterizing the superconductive joint: four probe method and IRT. For four probe method, the joint of interest is kept in a preset magnetic field and the voltage of the joint induced by a small current will be measured. This is the most common used method for characterization because of the easy access. However, the limit of sensitivity is $10^{-11}$ ohms and it is much higher compared to the sensitivity of another method to be discussed next. Low sensitivity might cause larger uncertainty especially when the temperature is close to absolute zero. Therefore, the four probe method is usually used for high temperature superconductor. The second method is called IRT, which is also named as current decay method.

The IRT method is a more precise method to measure the resistance of the superconducting joint. The measurement can be shown by figure (2) below [6].

![Figure 2. Illustration of IRT measurement. This is a setup measuring the current in a produced joint with changing temperature. The current is induced by current transformer and the heater below persistent joint is used to control the temperature around the joint. The figure is from Liu’s paper. [6]](image)

IRT measurement begins by exciting a current in the test coil with current transformer. The circulating current in the coil will be monitored and the resistive voltage generated in the coil will also be measured. The overall temperature of the inner apparatus is cooling down to the temperature between 60K and 70K and the heater below the persistent joint is used for temperature variation. The resistance can be described by standard L-R circuit model. There is one problem with this method, however. Not only would the resistive process have effect on V-I characteristics but also the transient settling phenomenon would have influence on characteristics. The factor which has the largest contribution to IRT’s error in measurement is the settling: the induced current falls faster than normal V-I behavior of the wires. This arises from redistribution of initially inhomogeneous current densities over available cross section. Therefore, in the actual measurement, one needs to wait for certain time to let the transient settling disappears. In other words, data collection will begin when the normal decaying pattern appears. An equation is used for determining the end of data collection [1]:
\[ R_{min} = \left( \frac{L}{(t-t_c)} \right) \frac{\delta I}{I} \]  

(1)

where \( t_s \) is the time for settling effect to vanish.

7. Summary and Discussion

Joint produced by Liu’s group has resistance all less than \( 10^{-13} \) \( \Omega \) at 1T magnetic field. There is no clear relevance between mechanical pressure and current carrying capacity; however, it has shown that current carrying performance is related to the flux creep [6]. Joint produced by cold press welding has stable performance in current carrying. Even though there are advantages such as better interlock between metal surfaces and less deformation of conductors in ultrasonic welding method, compared to joint produced by ultrasonic welding, joint produced by cold press welding method has less resistance and more stable current carrying performance. Micrograph of joint produced by ultrasonic welding method shows gap between interface is continuous; however, bond line is still distinguishable under 200 times magnification. In cold pressed joint, bond line begins to disappear after increasing the mechanical pressure. The produced joint is characterized with either four probe method or IRT. Although these two methods give observation of resistance of joints, the sensitivity is different. IRT has higher sensitivity. The precision of resistance measured with IRT method is \( 10^{-13} \) \( \Omega \). However, the precision of IRT method is usually disturbed by the transient settling of induced current. After decades’ development, researchers are expanding the boundary persistent joint’s researching. Superconducting current is important in operation of superconducting magnet and the goal of keeping superconducting current from attenuation motivates the development of different joints produced by different methods. The comparison between different joints are made and the comparison between methods for making joints with the same materials is also made. Although people have large experimental data for the joints produced, the theoretical understanding of joints has yet to be made in the future. Serious modeling of physical properties of joint need to be built.

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