Experimental studies of diffusion welding of YBCO to copper using solder layers

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Abstract: The welding technology is of great importance in YBCO application. To make better joints, the diffusion welding of YBCO tape to copper has been carried out in a vacuum environment. In consideration of high welding temperature (above 200 °C) could do damage to the material performance, a new kind of diffusion welding method with temperature below 200 °C has been developed recently. A new welding appliance which can offer pressure over 35Kg/mm² and controlled temperature has been designed and built; several YBCO coated conductors joints soldered with different melting points of tins has been tested. The results showed that the diffusion can perfectly connect YBCO to copper as well as stainless steel and resistance of the joint was low, and the YBCO tape could bear 217 °C for at least 15mins.

Key words: YBCO, diffusion welding, joint, resistance;

1. Introduction
Joint techniques of YBCO to copper are essential for its practical applications. It can be usually seen on the superconducting devices. When it’s used as current lead joint, it’s important to reduce the resistance because the critical current density Jc would be reduced due to the high joint resistance and also the high joule heat may cause great mount of liquid helium usage during the magnet operation. Compared to the 1st generation high temperature superconducting material Bi2223, the 2nd generation YBCO has a more fragile property which is the performance will be degraded above 200 °C because of its sensitivity to temperature. Further more, YBCO tape could be totally damaged when the welding temperature is over 300 °C [1]. Lots of research has been done in making YBCO-YBCO joints [2]–[5] and expected those power apparatuses will be put into practical uses. In a superconducting tape, there is no resistance causing losses when it’s in superconducting state, however in a realistic joints, because of welding, material like tin/indium solder has resistance all the time which lead a dropping efficiency of superconducting apparatuses. In this research, a closed facility for fabricating the joints was built and made several YBCO-COPPER/YBCO-SS (stainless steel) joints with different solder. The joints were tested in liquid nitrogen bath using four-probe method.

2. Experiment
2.1. Preparation
The YBCO coated conductor was used for joint experiment, which has stacked layers of Gd2Zr2O7 (GZO, with the thickness of 0.8 μm), CeO2 (1.2 μm), YBCO (2.0 μm) and Ag (13 μm) on Hastelloy substrate (100 μm) [5]. The YBCO tape has no copper coating, so the base face and the silver face can be easily recognized. After several ordinary tests, silver and hastelloy showed totally different compatibility with solder, see table 1.

| Solder surface | Solder | Method | Level of difficulty |
|---------------|--------|--------|-------------------|
| Sliver        | SnAg3.0Cu0.5 | electric soldering iron heat | Easy |
|               | Sn6Pb37 |        |                   |
|               | Bi50Sn10Pb31 |        |                   |
| Hastelloy     | SnAg3.0Cu0.5 | electric soldering iron heat | can't be soldered |
|               | Sn6Pb37 |        |                   |
|               | Bi50Sn10Pb31 |        |                   |

Compared sliver and hastelloy surface, it was suggested that the sliver surface is much easier to be soldered. So we chose the sliver surface of the tape to do the experiments.

2.2. Equipment
Fig.1 shows the fabricating system we built. The welding process took place in vacuum environment in order to prevent the metal from being oxidized. The solubility of diatomic gas, such as O2 and H2, in metal can be expressed as:

\[ S = kp^{1/2} \]

where \( S \) is the gas solubility, \( k \) is a constant, and \( p \) is the gas pressure.

This designed facility for welding can supply the maximum pressure of 2 tons, and set different welding temperature for different solder. Take a notice to that after the displayed temperature reach the set point, heater stop working while the temperature still rise 10 °C ~15 °C because of copper thermal inertia, and it would be tested by PT100 temperature sensor. So that we should choose the proper setting temperature before we get started. After fabricating, nitrogen gas is ventilated to cool the joint down to room temperature.

![Fig.1 Photograph of the welding facility we designed](image)
2.2.1. **joins.** We made each joint sample by the following brief steps:

We prepared two copper blocks and soldered stainless steel tube with one block on each side; then sliced a plane on the tube and the copper blocks and laid a layer of solder tin on the plane (see Fig. 2). Before heating, we vacuumed the working zone and applied an 1500kg load right before the joint temperature reached the solder melting point. After heating, we turned off the power supply and cool down the sample to room temperature in pure nitrogen. A completed sample was a current lead with stainless steel in between worked as the current diverter.

![Fig. 2 Photograph of one sample](image)

2.2.2. **Solder tin.**

Three different solder with different melting points (138°C, 183°C and 217°C) were chosen in our experiment. The joints connected by each solder were marked as sample 1, 2 and 3 separately [1]. The length of welding joint is unified to 14cm among which 10cm is connected to stainless steel and 2cm is connected to copper joint both ends each.

2.3. **Measurement and analysis**

In order to investigate the joint characteristics of the samples, V-I characteristic curves of the samples were measured in a saturated liquid nitrogen bath by the four-probe method [4]. Critical current and contact resistance of the samples were obtained from the characteristic curves. According to IEC61788-3, the critical current $I_c$ shall be determined by using an electric field criterion $E_c$ or a resistivity criterion $\rho_c$ where the total cross-sectional area $S$ of the composite superconductor is preferred for the estimation of the resistivity [6]. In the case of the electric field criterion, two values of $I_c$ shall be determined at criteria of 100µV/m and 500µV/m. When using a resistivity criterion:

$$U_c = I_c \rho_c L / S$$

where $U_c$, $I_c$ and $\rho_c$ are the corresponding voltage, current and resistivity in square meters. KEITHLEY2700 was used in voltage measurement.

3. **Results and discussion**
Fig. 3 shows the V-I curves of the samples using different solders. It was clear that the Ic value decreased after heating. Surprisingly, the heat applied to the samples had an adverse effect on the superconducting layers in the YBCO tapes. Compared the resistances in table 2, it was clear to figure out that the joint welded by solder with a higher melting point has a better performance, containing higher Ic and lower resistance. When making a YBCO joint, while the melting temperature was limited, it was suggested that we use the soldering tin with a higher melting point within the temperature limit. One thing we should take consideration is that YBCO tape can’t bear a temperature above 200°C [1], so the validity of the curve of sample 3 should be doubted. But in our experiments, the curve showed nothing like the tape is badly damaged by the heating.

For how long time the welding process took also produced an effect on the joint property and was plotted in Fig 4. It was calculated that the Ic decreased about 6% if welding time took twice as long. Since the long time heating did harm to the tape, the welding time should be shorted as long as the welding temperature was reached and the joint was completed.

The resistances in table 2 was calculated per mm² area. Results suggested it has the same tendency as the critical current test.

**Table 2** Resistances of different samples
4. Conclusions

We tried to make the joints perfect, anyhow there was Ic decrease remained. This paper showed the facility we designed for processing and examined the characteristics of various YBCO-COPPER/YBCO-SS joints. The joint resistance was decreased by using the solder tin with higher melting point. And shorter the welding time was good for YBCO remain higher critical current. The idea that YBCO tape gets a great performance degradation when the welding temperature is higher than 200 °C should be more specific and responding. However in our experiments, the results showed that the degradation from high temperature process is lower than other temperature processes. And we hopefully think that the YBCO tape can bear 217°C for at least 15mins from our experiments.

In addition, the facility we designed for welding still needed to be improved for the following defects we found during the experiments: 1) the welding temperature can not be precisely controlled which makes the process less reliable; 2) it took at least 1hour to make one sample and samples were made one by one, which was far away from efficient; 3) the facility needed a intelligent control system instead of people’s full time watching.

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