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Development of a Superconducting Joint between Bi-2212 Round Wires for Persistent Mode Operation

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***Abstract*—Superconducting joints are one of the key components needed to make $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) superconducting round wire (RW) successful for high-field, high-homogeneity magnet applications, such as for nuclear magnetic resonance (NMR) magnets in which persistent current mode (PCM) operation is highly desired. In this study, a procedure for fabricating superconducting joints between Bi-2212 RWs was developed. Melting temperatures of Bi-2212 precursor mixtures with a variable composition of Ag additions to be used in the joint region were investigated by differential thermal analysis (DTA). Test joints were fabricated and heat treated, and their voltage-current (*V-I*) properties were measured using the conventional four-point method at 4.2 K and in magnetic fields up to 14 T. Microstructures of the joint areas were examined by scanning electron microscopy (SEM). The test results will be presented.**

I. Introduction

As the only high temperature superconductor (HTS) with round wire (RW) geometry, $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) superconducting wire has the advantages of being multi-filamentary, macroscopically isotropic and twistable. With overpressure (OP) processing techniques recently developed by our group at the National High Magnetic Field Laboratory (NHMFL), the engineering current density (*Je*) of Bi-2212 RW can be dramatically increased [1]. With these intrinsically beneficial properties and recent processing progress, Bi-2212 RW has become very attractive for high field magnet applications, especially for nuclear magnetic resonance (NMR) magnets and accelerator magnets *etc*.

Superconducting joints are one of the key components needed to make Bi-2212 superconducting RW successful for high-field, high-homogeneity NMR magnets in which persistent current mode (PCM) operation is highly desired. Since Bi-2212 coils employ the Wind and React (W&R) approach [2], it would be highly practical if joints can be heat treated together with the coil winding pack allowing the superconducting joints to be fully formed during the standard Bi-2212 heat treatment (HT) processing.

In this paper, a Bi-2212 superconducting joint technique is presented [3, 4]. First, the melting temperatures of Bi-2212 precursor mixtures with a variable composition of Ag additions to be used in the joint region were investigated by differential thermal analysis (DTA). Then, test joints were fabricated and heat treated in 1 bar flowing oxygen using the standard Bi-2212 HT schedule detailed in [5]. Their voltage-current (*V-I*) properties were measured using the conventional four-point method at 4.2 K and in magnetic fields up to 14 T and microstructures of the joint areas were examined by scanning electron microscopy (SEM).

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II. Experimental

In this study, Bi-2212 multi-filamentary RW manufactured by Oxford Superconducting Technology (OST) using the PIT method was used for test joints. The as-drawn wire, with a diameter of 1.3 mm, is composed of 18×121 Bi-2212 filaments embedded in Ag stabilizer with an outer sheath of Ag-0.2 wt% Mg alloy. The transverse cross section of the as-drawn Bi-2212 RW is shown in figure 1.

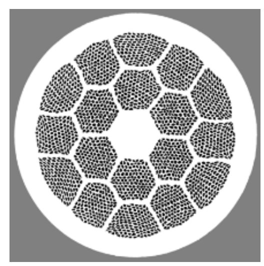

Fig. 1. SEM image of a transverse cross section of an as-drawn Bi-2212 RW manufactured by OST.

To build up superconducting network between Bi-2212 filaments after the standard partial melt processing, it is crucial to have compatible joint filler materials. In this study, Bi-2212 granulated powder manufactured by Nexans Superconductor (NSC) and Ag power were used as components of joint filler materials. The study of melting temperatures of Bi-2212 precursor mixtures with a variable composition of Ag additions was carried out using DTA in flowing oxygen. Bi-2212 powder with 2 wt% Ag additions was selected as the joint filler material.

Following the joint fabrication procedure detailed in [3, 4], joint samples were fabricated and heat treated in 1 bar flowing oxygen using the standard Bi-2212 HT profile. After the standard Bi-2212 HT processing, the *V-I* properties of joints were evaluated using a standard four-point method at 4.2 K and background magnetic fields from 0 T to 14 T. Some joints were cut and polished, and the microstructures were examined by SEM.

III. Results and Discussion

A. *Melting temperature study on joint filler materials*

Since Bi-2212 coils employ the W&R approach, it would be highly practical if joints can be heat treated together with the coil winding pack so that the superconducting joints are fully formed during Bi-2212 reaction. The DTA data, shown in figure 2, reveal endothermic peaks at different temperatures corresponding to the melting or partial melting of materials. The partial melting onset temperature of Bi-2212 RW was found to be 873 °C, while the melting onset temperature of Bi-2212 granulated powder was found to be 902 °C, which is significantly higher than the maximum temperature 890 °C of the standard Bi-2212 HT processing. DTA curves in figure 2 also reveal endothermic peaks of Bi-2212 precursor powder with different Ag addition concentrations from 1 wt% to 10 wt%. It is clear that the melting temperature of Bi-2212 decreases if Ag-doping is applied. On the basis of the DTA analysis, we chose Bi-2212 precursor powder with 2 wt% Ag additions as the joint filler material, which gives a melting onset temperature of 883 °C.

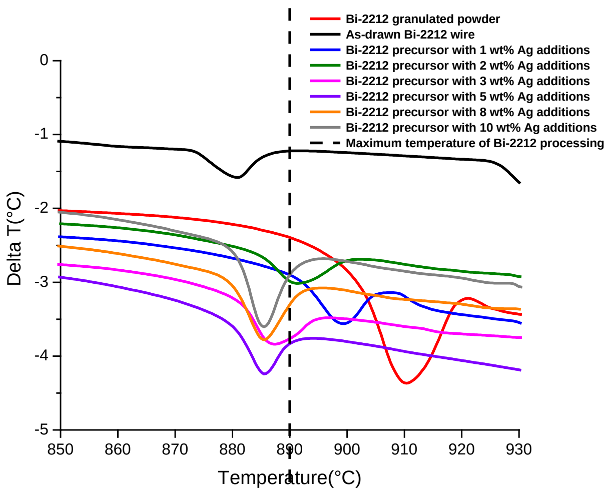

Fig. 2. DTA melting temperature study of mixtures of Bi-2212 precursor and Ag powder. The endothermic peaks of the DTA curves clearly indicate the melting temperatures of powder mixtures. The vertical dash line indicates the maximum temperature 890 °C of the standard Bi-2212 HT process.

B. *Voltage-current properties of superconducting joints*

To evaluate the *V-I* properties of Bi-2212 superconducting joints, four-point measurement was carried out at 4.2 K and magnetic fields up to 14 T, and the magnetic field direction is parallel to the conjunction part of joints.

As shown in figure 3, test joints presented good superconducting properties at 4.2 K. A maximum supercurrent of ~850 A with extremely low resistance was achieved at self-field. With increase of external field, the supercurrent was gradually suppressed as expected, and ~450 A supercurrent was achieved at 14 T, which demonstrated the potential use of Bi-2212 superconducting joints in high field magnets. The power-law transition from the superconducting state to the normal state is very smooth with a typical n-value of ~ 8, which is smaller than that of Bi-2212 conductor in a typical range of 18-20.

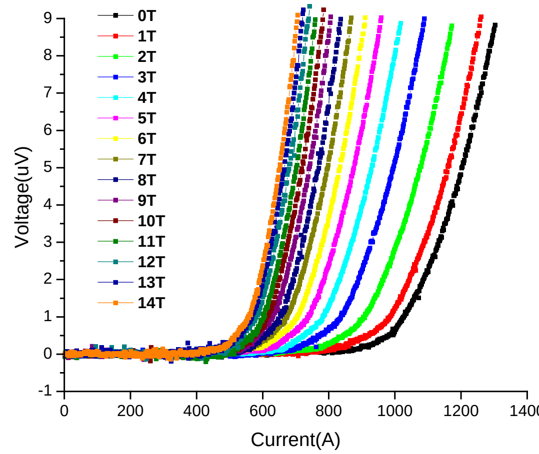

Fig. 3. *V-I* curves of a typical Bi-2212 superconducting joint at 4.2 K and variable fields up to 14 T.

C. *Microstructure of superconducting joints*

Figure 4 shows an SEM image of the longitudinal cross section of a typical superconducting joint. The microstructure clearly shows that Ag additions uniformly dissolved in the Bi-2212 liquid at the partial melting stage, and that the interface of Bi-2212 RWs was enclosed with well textured Bi-2212 crystal colonies which are indicated by white arrows in figure 4. The outcome is a well-connected superconducting network between Bi-2212 filaments.

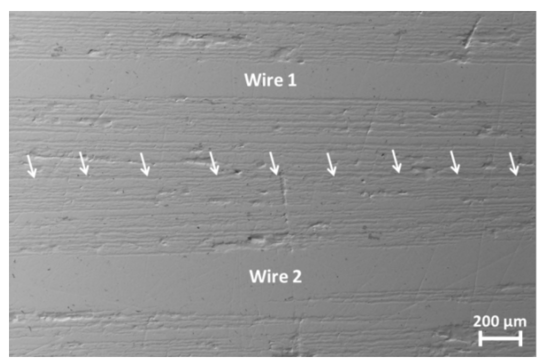

Fig. 4. SEM image of a longitudinal cross section of a typical B-2212 superconducting joint.

IV. Conclusion

We successfully developed a Bi-2212 superconducting joint for persistent magnet operation. The joint fabrication procedure is effective and practical, enabling joints to be achieved during standard Bi-2212 HT processing. The Bi-2212 superconducting joints presented good superconducting properties. SEM analysis clearly presented the formation of a superconducting Bi-2212 interface between two independent Bi-2212 round wire conductors.

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