DEVELOPMENT OF SUPERCONDUCTING SOLDERED JOINTS BETWEEN BI-2212/AG WIRES

T. Mousavi, T. Davies, Z. Melhem, C.R.M. Grovenor and S.C. Speller

Abstract—Bi-2212/Ag superconducting wires are being considered as key conductor candidates for the development of high field magnets (up to 25 T), but it is recognised that a reliable joining process between these wires is a critical challenge for most high-field applications. This work focuses on the design and testing of jointing processes between multifilamentary Bi-2212 wires to make persistent mode joints using soldering techniques. The ability of several different superconducting solder alloys from the PbBi and SnInBi systems to remove and replace the Ag matrix in fully reacted Bi-2212 wires has been explored. The SnInBi lead-free solder was found to be relatively effective at removing the Ag matrix, but does not make good contact with the Bi-2212 filaments. PbBi solder wets the Bi-2212 filaments more effectively, but is slower at removing the Ag matrix. Therefore, a two-stage process has been developed using molten Sn to first remove the Ag matrix followed by PbBi to replace the non-superconducting Sn. Joints made using this two-stage process have higher critical currents (133 A in self-field and 4 K) than joints made using PbBi alone (120 A in self-field 4 K).

Index Terms—Superconducting filaments and wires, Multifilamentary superconductors, Joints, Lead-free solder

I. INTRODUCTION

Bi-2212/Ag multifilamentary round wires are fabricated by a powder-in-tube technique [1]. The as-drawn wires are subsequently melt-processed using a complex heat treatment to form high critical current (I_c) superconducting wire [2,3]. Since the wire is very brittle following this reaction process, magnets are wound before heat-treatment. Two approaches are being explored for fabricating persistent mode joints in these wires: melt-processing [4] and soldering [5]. In the melt-processing method, the Bi-2212 filaments of unreacted wires are exposed and joints are made between them using extra Bi-2212 powder. The entire assembly is then melt-processed at the same time. In contrast, soldering methods can be used to form joints between wires that have already been reacted. This has the advantage of

enabling joints to be made after the magnet assembly using techniques similar to those deployed in conventional NbTi magnets [6], allowing joints to be re-made if necessary. PbBi alloys are typically used to join NbTi wires owing to their relatively high T_c and B_{c2} values [7]. Here we have investigated both standard PbBi solder and our best lead-free SnInBi solder alloy with composition close to a ternary eutectic, Sn-50In-35Bi [8].

Figure 1: Backscattered electron images taken in a Zeiss EVO scanning electron microscope showing (a) the architecture of the Bi-2212/Ag strand, (b) the microstructure of a typical cross-section of a bundle of reacted Bi-2212/Ag wire.

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II. SAMPLE PROCESSING AND MICROSTRUCTURAL ANALYSIS

A. Wire characterization and Ag matrix removal

Bi-2212/Ag multifilamentary wires used in this work were provided by OST. The as-received wires (with an I_c value of ~ 250 A at 4 K, 3 T) were already exposed to the standard industrial heat treatment process. The architecture and the typical microstructure of the as-received wire are shown in Figure 1 a and b respectively. Each wire includes 18 bundles of 120 Bi-2212 filaments within Ag matrix. The needlelike superconducting phase is seen to escape from the original filaments as a result of the heat treatment process.

In order to make direct bonds between the Bi-2212 filaments and the superconducting solder, the Ag matrix surrounding the filaments needs to be removed. The filaments could be exposed using an acidic etch prior to soldering, but the exposed filaments are easily damaged when the matrix has been removed. Here we instead investigate the ability of molten solder alloys to dissolve the Ag matrix, resulting in the replacement of the non-superconducting Ag matrix with superconducting solder without the need for a prior acid etch. To make a joint using this technique, lengths of reacted Bi-2212/Ag wire were immersed in molten solder baths held at 350 °C for 30 to 90 minutes. Then the immersed lengths were held next to each other with overlaps of 5 mm and 10 mm. A small amount of molten solder was finally dropped in the overlap area to make joints.

B. Mapping the solder interactions

Figure 2 shows energy dispersive x-ray (EDX) phase maps of wire cross-sections taken using a Zeiss EVO scanning electron microscope (SEM). After 30 minutes immersion in SnInBi, the outer layer of Ag has been successfully removed and the solder has started to infiltrate between the outer bundles of the Bi-2212 filaments. Increasing the immersion time to 90 minutes results in the solder penetrating almost to the centre of the wire. However, the solder does not seem to wet the Bi-2212 filaments very effectively, resulting in gaps between the solder and the filaments which appear black in Figure 2 (b). In contrast, PbBi solder does not dissolve the Ag matrix as quickly as SnInBi, so that the PbBi solder does not fully penetrate the inner filament bundles even after 90 minutes. However, PbBi solder appears to form better interfaces with the Bi-2212 filaments, as can be seen by the high resolution EDX maps in Figure 3.

Since the PbBi solder is not very effective at infiltrating the Bi-2212 wires, a two-stage process was developed using non-superconducting pure Sn to initially remove the Ag matrix. As seen in Figure 2 (e), molten Sn is very effective, infiltrating the entire wire within 60 minutes. The Sn matrix is subsequently replaced by superconducting PbBi alloy in a second process. This resulted in much better infiltration of PbBi into the core of the wire compared with the single stage PbBi process. However, high resolution EDX analysis revealed a residual Sn-O interfacial layer about 500 nm thick around each filament Figure 4. This layer is likely to act as a barrier to superconducting current transfer, potentially limiting joint performance. Further

Figure 2: SEM/EDX phase maps showing infiltration of solder after immersion in SnInBi alloy for (a) 30 mins and (b) 90 mins, PbBi solder for (c) 30 mins and (d) 90 mins, (e) pure Sn for 60 mins, and (f) Sn for 60 mins followed by PbBi for 60 mins.

Figure 3: SEM/EDX maps for (a) SnInBi and (b) PbBi solder. Black cracks are seen around the Bi-2212/SnInBi interfaces. These cracks are not seen when PbBi solder is used. Some residual Ag alloy particles remain in the solder.

experimental work is needed to explore whether the formation of this undesirable reaction layer can be minimized by optimization of the tinning temperature and time.

Figure 4: High resolution EDX phase map taken in a Zeiss Merlin FEGSEM shows a thin Sn-O interfacial layer. The line scan shows the layer is about 500 nm thick.

III. JOINT PROPERTIES

The superconducting properties of joints made using the single stage (PbBi) process and the two stage (Sn+PbBi) process have been compared.

Figure 5 shows low resolution EDX maps of the joint cross-section, confirming that the two-stage process is significantly more effective at removing the Ag matrix. The superconducting performance of joints have been measured at 4 K using 4-terminal transport measurements on short straight sections of wire containing a single lap-style joint in applied magnetic fields of 0 to 1.8 T in a direction parallel to the wire axis. As shown in Figure 6, a 10 mm long joint fabricated using the single stage PbBi solder process (PbBi joint) is found to have comparable I_c performance to a 5 mm long joint fabricated using

Figure 5: EDX/SEM phase maps of PbBi cross-sections of joints made by (a) single stage 90 minute PbBi solder process, and (b) two stage process using Sn for 60 minutes followed by PbBi for 60 minutes.

the two stage process (Sn+PbBi joint). Using a standard electric field criterion of $100 \mu\text{V m}^{-1}$, the PbBi joint and Sn+PbBi joints had I_c values of 120 A and 133 A in self-field, respectively. In 1 T field, the I_c values dropped to 40 A and 49 A, respectively. Under these conditions, the critical current density of the PbBi solder will be significantly lower as the upper critical field for this alloy is 1.77 T at 4 K [7]. SnInBi alloy has a B_{c2} value that is too low (about 0.2 T at 4 K) to use in this application, so the performance of joints made using this solder are not reported here [8].

Figure 6: Transport measurements of PbBi joints made by (a) single stage process (10 mm long joint), and (b) two stage process (5 mm long joint).

IV. CONCLUSIONS

Soldering techniques have been investigated for fabricating superconducting lap joints between reacted Bi-2212 wires. PbBi solder is found to form good quality interfaces with Bi-2212 filaments, whereas lead-free SnInBi solder alloy does not appear to wet Bi-2212 effectively. However, PbBi solder does not remove the Ag matrix from the wires very effectively, so a two stage process has been developed initially using pure molten Sn to remove the Ag matrix followed by immersion in PbBi to replace the Sn. This significantly improves the infiltration of PbBi to the centre of the Bi-2212 wires. However, high resolution EDX analysis has revealed that a thin layer of Sn-O remains at the interface between the Bi-2212 filaments and the solder. Despite the presence of this non-superconducting layer around all the filaments, the performance of joints fabricated using the two-stage process were superior, with a 5 mm long joint having better performance than a 10 mm joint made using the single stage process. As can be seen in Figure 6, the joints here have a finite resistance even at low currents and their critical current density is much lower than the parent

wire (~250 A at 4 K, 3 T), so further improvements are required to enable persistent mode operation for NMR/MRI applications.

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