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Superconducting joining of MT-YBCO

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Abstract

Superconducting (SC) properties of joined (soldered using $TmBa_2Cu_3O_{7-\delta}$ powder) melt-textured YBCO samples have been investigated by vibrating sample magnetometer (VSM), magneto-optical technique and field mapping (from which the map of critical current density distribution throughout the sample has been calculated and plotted). The critical current densities j_c calculated from the field mapping and the values obtained from the VSM data are in good agreement and give us grounds to conclude that j_c through the seam has been higher than 3.4×10^4 A/cm^2 in zero field at 77 K. All methods used for SC properties characterization have shown that current flows homogeneously through the seam and bulk material and made us sure that in soldering process the superconductive properties of the joined material were not deteriorated.

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Keywords: Superconductive joining; Melt-textured $YBa_2Cu_3O_{7-\delta}$ (MT-YBCO); $TmBa_2Cu_3O_{7-\delta}$ (Tm123)-powdered solder

1. Introduction

At present seed-grown melt-textured (MT) MeBCO (Me = Y, Nd, Sm, Eu) are considered to be the most promising materials for practical application in cryogenic devices such as HTS electromotors, generators, flying-wheel-based energy storage devices, bearings, current limiters, maglev transport, etc., working under the liquid nitrogen temperature (77 K). But the developed technologies of MT-MeBCO impose limitations on materials size: the dimensions of the bulk block that can trap magnetic fields high enough for the efficient use in cryogenics are limited to a few centimeters. The farther the material located from the seed, the more its structure and composition deviate from the optimal ones. To produce parts or elements of HTS devices with big dimensions or complex-shaped, the technique of superconducting (SC) joining is being developed.

The main demands for SC joining are the following: the uniform current of the same level as

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through the joined material should flow through the junction and the level of SC properties of the material should not be decreased while making a junction.

From literature several principal methods of SC joining are known: (a) multi-seeded melt growth, which allows good boundaries to be produced if the distance between two neighboring seeds is of about few millimeters (≈4 mm) [1,2]; (b) diffusion joining by a direct contact method with loading or some axial pressure application in the absence of the solder or of the slices of consolidated material [3–7]; (c) joining (or soldering) using solders or materials produced on the base of compounds of Y123 structural type that have lower melting temperatures than main superconductive matrix component of MT-MeBCO. As a base component of a solder for MT-YBCO $YbBa_2Cu_3O_{7-\delta}$, $ErBa_2Cu_3O_{7-\delta}$, $TmBa_2Cu_3O_{7-\delta}$ and Ag-doped YBCO were tested [8–17]; for MT-NdBCO, the $YBa_2Cu_3O_{7-\delta}$ have been used [18]. For the last method (c) the following solders were tested: (1) mixtures of $MeBa_2Cu_3O_{7-\delta}$ with Me_2BaCuO_5 or Me_2O_3 powders with a few percents of CeO_2, PtO_2 or Pt added; (2) pastes on the base of above components of powder mixtures prepared with glycerin or toluene; (3) thin bulk layers (of about 1 mm thick) cut from the sintered or melt-textured bulk (prepared as well from the above components of powder mixtures). Usually, in all methods (a, b, and c) of joining, the thermal processing schedule contained the step of a very slow cooling: at a rate of 0.5–2 K/h (to decrease the temperature by 20–80°).

The joining process may be conducted in air or in the oxygen atmosphere. The MT-YBCO blocks may be joined both before the oxygenation (just after the melt-textured process, i.e. the material is nonsuperconductive) and after melt-texturing and oxygenation (the material superconductive). In all the above cases, after the formation of the junction the long-term oxygenation process (under the temperatures lower than that of junction formation) should be conducted in order to restore the SC properties of the joined bulk.

In [8,9] we have suggested the $TmBa_2Cu_3O_{7-\delta}$ powder (without any admixtions) to use as a solder and the elimination of the step of slow cooling. Here the results are presented of the study of junction produced in a comparatively quick process (the chamber furnace was heated to the temperature of soldering at the highest possible rate and then switched off, so cooling occurred with furnace).

The indirect estimation of the current density through the seam is a rather complicated problem. Because of this we investigated the SC characteristics of the junction and joined material using all available techniques to us. The results obtained by different techniques were in good agreement and pointed to the high level of critical current densities both in the material and in the seam.

2. Experimental and results

Initial single-domained rings were drilled from the MT-YBCO superconductive blocks in the way shown in Fig. 1a. Then rings were placed inside the Oxford Instrument 3001 vibrating sample magnetometer (VSM) and from magnetization loops the j_c has been estimated using the equation $j_c = 3M/H\pi \cdot (R_2^3 - R_1^3)$, where M—magnetic moment, R_1, R_2—inner and outer radii of the ring, respectively, H—the ring height (see curve 1 in Fig. 2). After this the rings were cut (Fig. 2b) by a diamond wheel. A thin layer (less than 0.3 mm thick) of $TmBa_2Cu_3O_{7-\delta}$ (Tm123) powder was put onto the both surfaces of the cut by sieving or sedimentation from the suspension in acetone (Fig. 1c). DTA study has shown that the melting temperature of Tm123 was about 983–987 °C, while the powdered MT-YBCO started to melt at 1026 °C. The halves of the ring were put together by the places of cut and fixed using screws and metallic strips (Fig. 1d). Then the rings were heated up to 990–1050 °C in the flowing oxygen at rates of about 1000 K/h up to 900 °C and 500 K/h up to the highest temperature (980–1050 °C), hold at the highest temperature (980–1050 °C) for 6 min or under and then the heater of the furnace was switched off. The oxygen continued to flow through the furnace until the temperature decreased to room temperature. After this the j_c in the soldered sample using VSM has been estimated (see curve 2 in Fig. 2).

The magneto-optical study of the ring soldered under the optimal conditions (1010 °C) ring has been carried out by the procedure described in

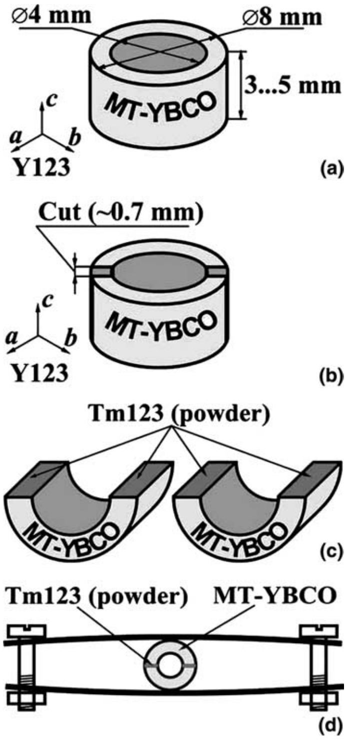

Fig. 1. Experimental details of the process of soldering: (a) initial ring drilled from a single-domained material; (b) ring cut along the diameter; (c) places of future soldering covered with powdered Tm123 by sieving; (d) ring arranged for soldering.

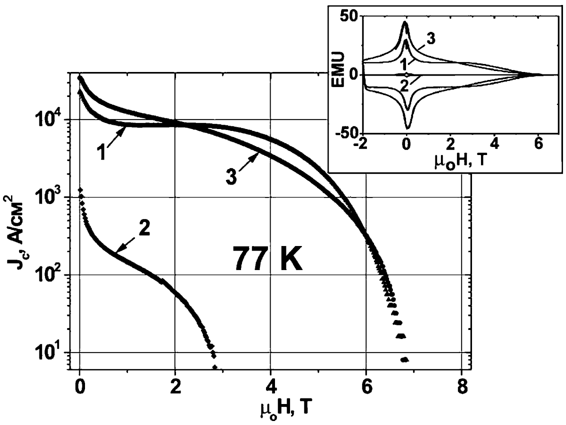

Fig. 2. The critical current density j_c vs. the magnetic field $\mu_0 H(T)$ of the single-domained ring before cutting (curve 1), after cutting and soldering (curve 2) and after cutting, soldering using the optimal regime (at $T = 1010$ °C) and the soldering followed by oxygenation (curve 3). In the upper right corner the initial magnetization loops used for the j_c calculation are given.

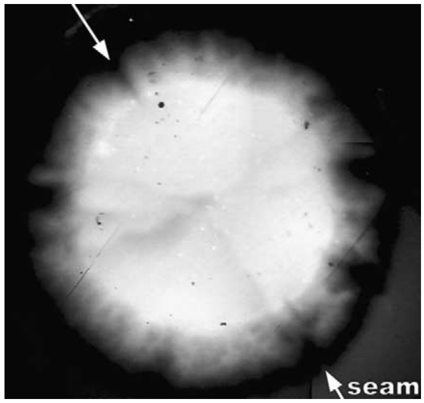

Fig. 3. Magneto-optical image of the joined ring obtained at 61 K in the first second after switching off the external field (3000 Oe).

[19]. The distribution of the normal (transverse) component of the trapped magnetic flux field cooled at 3000 Oe is shown in Fig. 3. The image was obtained in the first second after switching off the external field. The brighter is the local area of the image, the larger is the local magnetic induction. Fig. 3 shows the induction distribution over the near-surface region of the ring because the normal component of the induction in the material and just above the material is the same. So, the induction distribution at the distance of a few micrometers over the sample surface is visualized. The distance was determined by the spatial resolution of the technique.

The distribution of the trapped magnetic field (field-mapping, FM) in the field-cooled soldered ring was investigated using the Hall probe (the distance from the Hall probe to the sample surface was 0.8 mm) and shown in Fig. 4. From the field maps data, critical current density distribution in the ring have been calculated using the technique developed by Perkins et al. [20] (Figs. 5 and 6).

Fig. 7 describes the structure of the seam obtained by polarizing microscope at different magnifications.

3. Discussion

The ring soldered at 1010 °C demonstrated the highest SC characteristics. In this ring (Fig. 2) the increase of j_c after soldering and oxygenation was

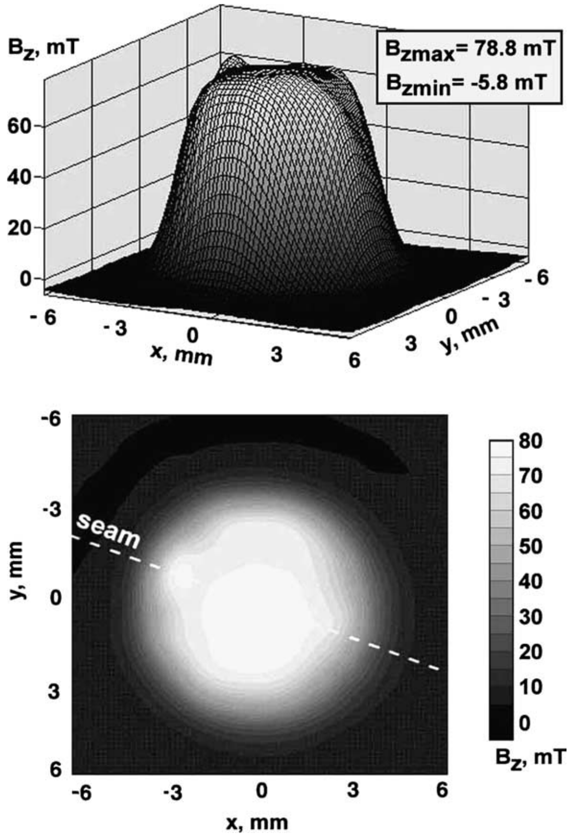

Fig. 4. Trapped-field map for the MT-YBCO soldered with Tm123 powder using optimal regime (heating up to 1010 °C). Regular shape of the truncated cone indicates that the trapped magnetic field is homogeneously distributed throughout the ring and that the critical current density in the seam is approximately the same as in the joined material.

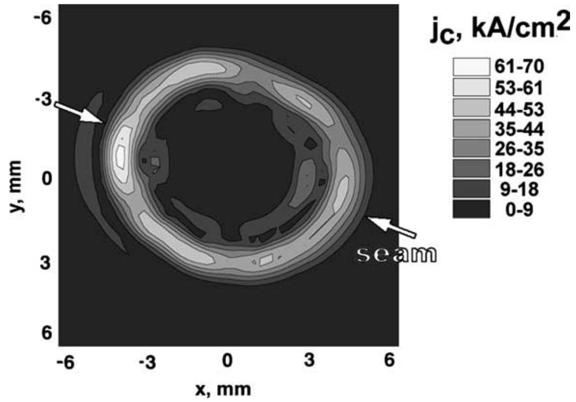

Fig. 5. The critical current density map for the superconducting ring with a seam (calculated from the FM data (Fig. 4) using the method, proposed in [20]).

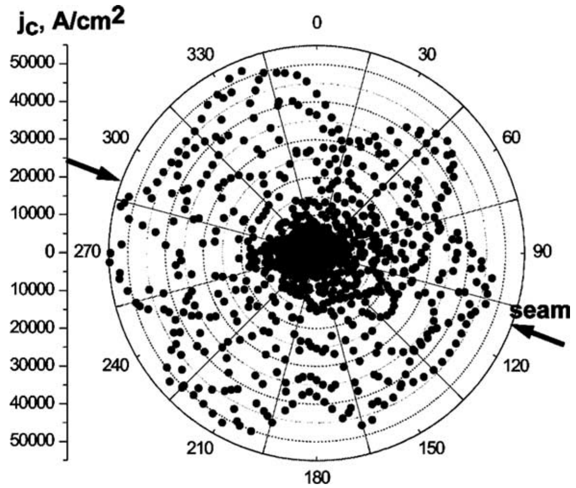

Fig. 6. The angular j_c values distribution throughout superconducting ring with a seam (calculated from the FM data (Fig. 4)).

observed up to the 2.5 T field (in zero field at 77 K it increased approximately in 1.5 times). We suppose that the increase in j_c is due to the oxygen redistribution over the MT-YBCO matrix phase during the repeated heat treatment and oxygenation. The approximately similar value of j_c in single domained ring and in the joined one support the fact that during soldering process no degradation of the joined material occurred and that the j_c in the place of junction was not lower than 3.4×10^4 A/cm^2 (at 77 K in zero field).

From the magneto-optical image of the soldered ring (Fig. 3) one could see that the reduction of the current due to the soldering is less than that due to the other weak links in the material; moreover, the current flowed through the soldering at this temperature (61 K) was comparable to the current in the bulk (compare a winding of the magneto-optical contrast near the points marked by arrows (soldered points) and others).

The field mapping (Fig. 4) and the maps of j_c calculated from the field mapping data (Figs. 5 and 6) show that a rather high current can flow in the joined ring. The critical current density in the

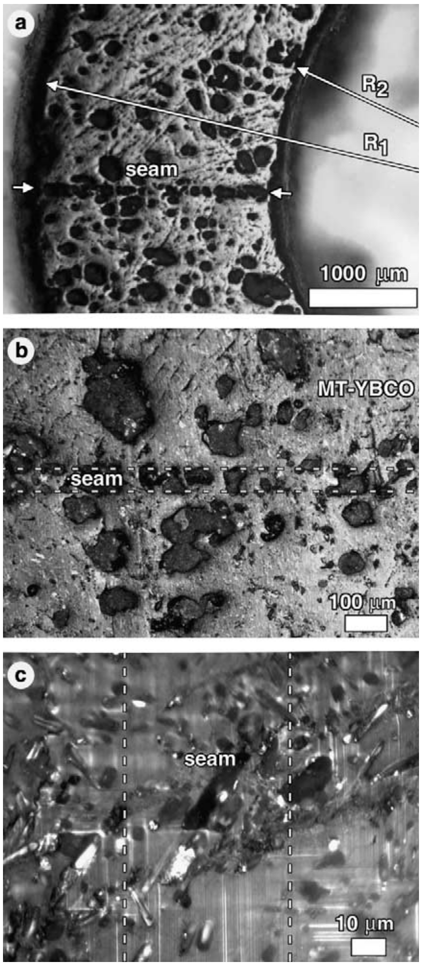

Fig. 7. The microstructure of the soldered seam in the ring in polarized light at the different magnifications. Junction was produced using Tm123 powder as a solder.

places of junctions (Figs. 5 and 6) turns out to be even higher ($4.8–4.3 \times 10^4$ A/cm^2 at 77 K) than that in the bulk (3.4×10^4 A/cm^2 at 77 K). The values of j_c in the different places of the ring (Figs. 5 and 6) are rather uniform. The structure of the seam is well accommodated to the structure of the joined material (Fig. 7c) and we suppose that this is the reason of such high critical currents in the seams.

The developed technique is rather simple and should allow us to produce junctions simultaneously in two perpendicular directions (which is necessary for joining rotor elements of HTS electromotors) or junctions with more complicated configurations.

4. Conclusions

All methods used for the j_c estimation in soldered ring (VSM, FM and calculated map of j_c distribution, magneto-optical technique) were in good agreement and confirmed the high j_c values in the joined material and seams as well as a rather good uniformity of j_c over the sample. The proposed method of joining caused no degradation of the joined material.

Acknowledgements

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