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Formation of superconducting junctions in MT-YBCO

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Abstract
The formation of superconducting junctions between MT-YBCO using $TmBa_2Cu_3O_{7-\delta}$ powder as a solder has been studied. The method proposed excludes the step of a very slow cooling (at a rate of several degrees per hour) during seam formation. The heating and cooling rate for joining parts produced from single-domain material without visible cracks (macrocracks) can be rather high (500–1000 K h^{-1}) and a holding time at the highest temperature (1010 °C) of several minutes (0.05 h) is enough to form a reliable junction. Reasonable rates of heating and cooling are however around 100 K h^{-1} if crack propagation is to be avoided in joined blocks used for practical application. Modelling experiments on rings and studies of the ring properties by vibrating sample magnetometer (VSM), field mapping with a Hall probe and magneto-optical microscopy have shown that superconducting properties of the junction were not lower than that of the joined material (j_c of about 30 kA cm^{-2} was observed in zero field at 77 K) and that the proposed process of joining did not adversely affect the properties of the material. The structure of the resulting junction was in good agreement with the structure of MT-YBCO.

1. Introduction

The developed technologies of seed-grown MT-YBCO (melt textured $YBa_2Cu_3O_{7-\delta}$-based ceramics), that is the most promising bulk HTS (high temperature superconductor) for application in electromotors, generators, flying-wheel-based energy storage devices, bearings, current limiters and maglev transport, impose limits on materials size: the dimensions of the block that can trap magnetic fields high enough for the efficient use in cryogenics are limited to 4–6 cm. A technique of superconducting (SC) joining is being developed to produce large or complex-shaped parts or elements of HTS devices.

The SC junction should provide the same level of critical current density as in the joined material and the SC characteristics of the material should not be decreased during joining.

One of the most promising methods of MT-YBCO joining is joining using Y123 structural type materials that have lower melting temperatures than the main superconductive component of MT-YBCO $YBa_2Cu_3O_{7-\delta}$ as a base for a solder. $TmBa_2Cu_3O_{7-\delta}$, $YbBa_2Cu_3O_{7-\delta}$ and $ErBa_2Cu_3O_{7-\delta}$ powders were tested as base components of a solder for MT-YBCO. Plates cut from Ag-doped MT-YBCO were also used as a solder [1–10]. To increase the viscosity of the solders, the $MeBa_2Cu_3O_{7-\delta}$ powder is usually mixed with Me_2BaCuO_5 or Me_2O_3 powders and a few per cent of CeO_2, PtO_2 or Pt is added to prevent the coarsening of Me211 inclusions. More often pastes, based on the above components of powder mixtures prepared with glycerin or toluene, or thin bulk layers (about 1 mm thick) cut from the

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Figure 1. Device for soldering of MT-YBCO parts of HTS motors at elevated pressure.
(This figure is in colour only in the electronic version)

sintered or melt-textured bulk (prepared in a separate process from the above mentioned mixtures), are used. In most cases joined MT-YBCO blocks are heated to temperatures below the melting temperature of the Y123 phase by 20°–50° and the thermal treatment contains a step of a very slow cooling: at a rate of 0.5–2 K h^{-1} (to decrease the temperature by 20°–80°), thus effectively repeating the melt-texturing process. An oxygenated (superconducting) or non-oxygenated (non-superconducting) material can be used as a starting material. The non-oxygenated material contains fewer microcracks and it is easer to handle, although it is difficult to predict its properties after soldering and oxygenation. The joining process may be conducted in air or in an oxygen atmosphere, but in both cases the low-temperature annealing under temperatures which are about half as high as those of the junction formation, in the same or a separate process is necessary for restoration of oxygen content of the joined material.

In [1, 2] we concluded that in both cases when pure $TmBa_2Cu_3O_{7-\delta}$ powder or $TmBa_2Cu_3O_{7-\delta}$ with Y_2BaCuO_5 mixture of powders was used as a solder the joined region contained $(Y, Tm)_2BaCuO_5$ inclusions and that the cooling from 980 to 950 °C at the rate of 'melt-texturing' (0.5 K h^{-1}) or at a rate of 100–130 K h^{-1} did not influence the SC properties of the join. When investigating high quality single-domain MT-YBCO without visible cracks it has been determined that the heating in the soldering process can be done at 1000 K h^{-1} and cooling can be realized at the highest possible rate for the furnace (the furnace was switched off).

To confirm the reliability of the estimation of the join quality, the SC characteristics and structure of the junction and joined material have been studied by different methods, which have produced good agreement of their results.

2. Experimental method and results

To produce MT-YBCO parts for HTS motors by soldering, a special device has been constructed and tested (figure 1). The device enables the possibility during the soldering process of applying a compressive force to the sample of about 10–20 kg from the outside of the furnace. The sample in this device can be heated up to 1100 °C and the device can be used many times.

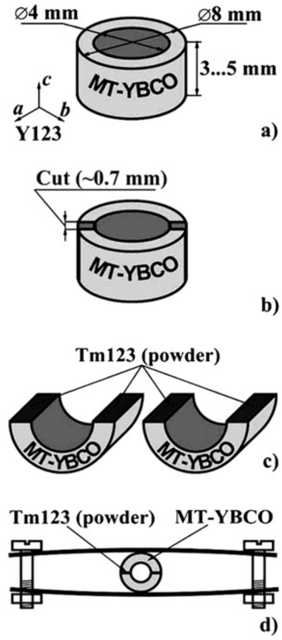

Figure 2. Experimental details of the process of soldering. (a) Initial ring machined from a single-domain material. (b) Ring cut along its diameter. (c) Regions to be soldered covered with powdered Tm123 by sieving. (d) Ring arranged for soldering.

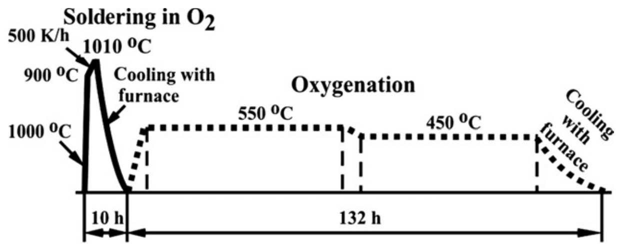

Figure 3. Regime of soldering and oxygenation used for the ring.

To estimate the critical current density through the join and how the soldered sample quality has been changed, i.e. whether the repeated heating process affected the SC characteristics of the material, model experiments on rings have been performed.

Single-domain rings were machined from MT-YBCO superconducting blocks as illustrated in figure 2(a). Then a ring was placed inside the Oxford Instrument 3001 vibrating sample magnetometer (VSM) and j_c estimated from the resulting magnetization loop using the equation $j_c = 3m/H\pi(R_2^3 - R_1^3)$, where m is the magnetic moment, R_1 and R_2 are the inner and outer radii of the ring, respectively, and H is the ring height (see curves 1 in figure 4). After this the ring was cut (figure 2(b)) by a diamond wheel into two parts along its diameter. A thin layer (<0.3 mm thick) of $TmBa_2Cu_3O_{7-\delta}$ (Tm123) powder was put onto both surfaces of the cut section by sieving or sedimentation from suspension in acetone (figure 2(c)). If the layer of the solder powder is rather thin, on arranging pieces for soldering, one can rotate the surfaces on which the powder was placed without any restriction (within 360°), i.e. without losing powder from these surfaces.

The halves of the ring were put together with the cut surfaces in close contact and fixed using screws and metallic strips (figure 2(d)). Then the ring was heated up to 1010 °C

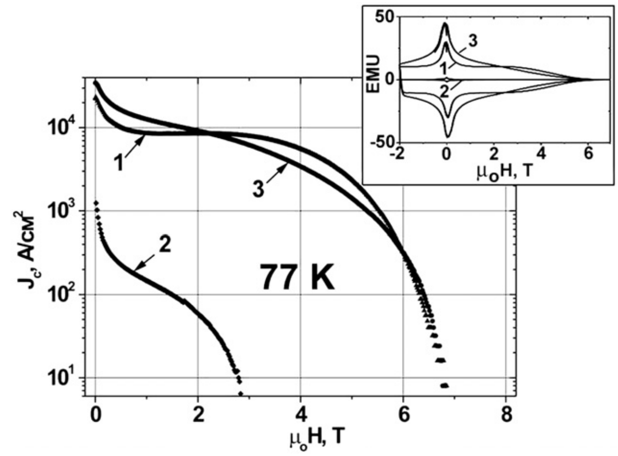

Figure 4. Critical current density j_c versus the magnetic field $\mu_0 H(T)$ of the single-domain ring before cutting (curve 1), after cutting and soldering at $T = 1010\,^\circ\mathrm{C}$ (curve 2) and after cutting, soldering and oxygenation (curve 3). In the upper right corner the initial magnetization loops used for the j_c calculation are given.

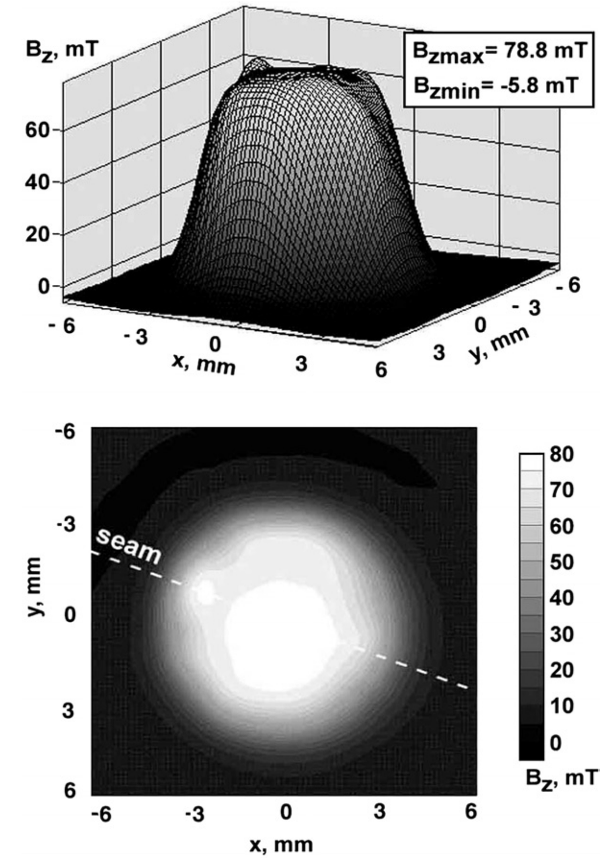

Figure 5. Trapped-field map for the MT-YBCO ring joined by Tm123 powder. The regular shape of the truncated cone indicates that the trapped magnetic field is distributed homogeneously throughout the ring and that the critical current density in the seam is approximately the same as in the joined material.

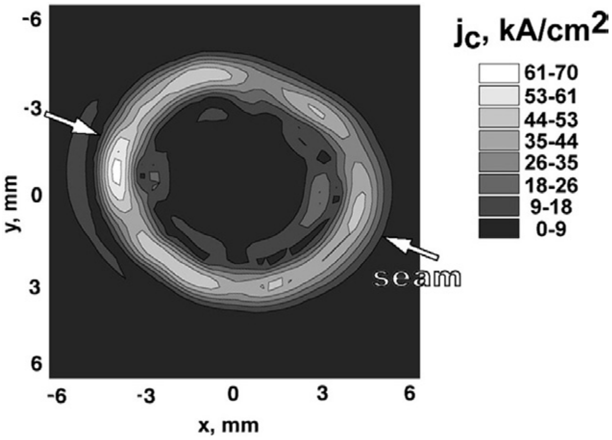

Figure 6. Critical current density map for the superconducting ring with a seam (calculated from the FM data (figure 5) using the method proposed in [11]).

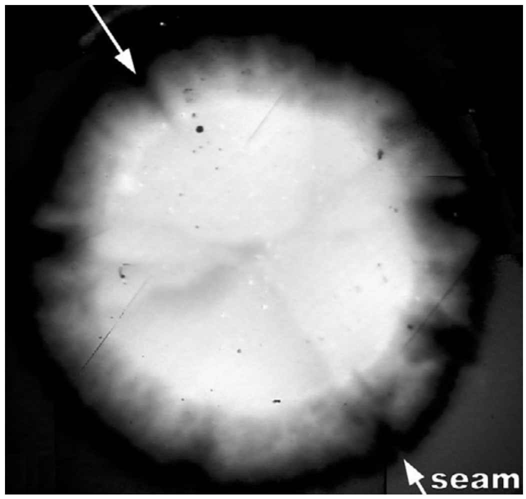

Figure 7. Magneto-optical image of the joined ring obtained at 61 K immediately after switching off the external field (0.3 T).

using the thermal profile shown in figure 3 and kept at this temperature for 6 min before the furnace was switched off. It should be noted that according to the DTA data the melting temperature of Tm123 is about 983–987 °C, while the powdered MT-YBCO started to melt at 1026 °C. Oxygen flowed through the furnace during the whole process until the temperature decreased to room temperature. The soldered ring was then oxygenated in a separate process in accordance with the profile shown by the dashed line in figure 3. The j_c values of the rings after soldering and after soldering followed by oxygenation have been estimated using a VSM (see curves 2 and 3, respectively, in figure 4).

The trapped magnetic field distribution (figure 5) over the field-cooled joined-by-Tm123 ring of MT-YBCO (the same ring for which curves 3 in figure 4 are given) was detected using a Hall probe scan (the distance from the Hall probe to the sample surface was 0.8 mm). From the field map data, the critical current density distribution over the ring has been calculated using the method proposed by Perkins *et al* [11] (figure 6).

A magneto-optical study of the same joined ring was performed by the method described in [12]. The distribution of the normal component of the trapped magnetic flux field cooled at 0.3 T is shown in figure 7. The increase of the magnetic induction is illustrated by the change in colour from black to white. The induction distribution at the distance of a

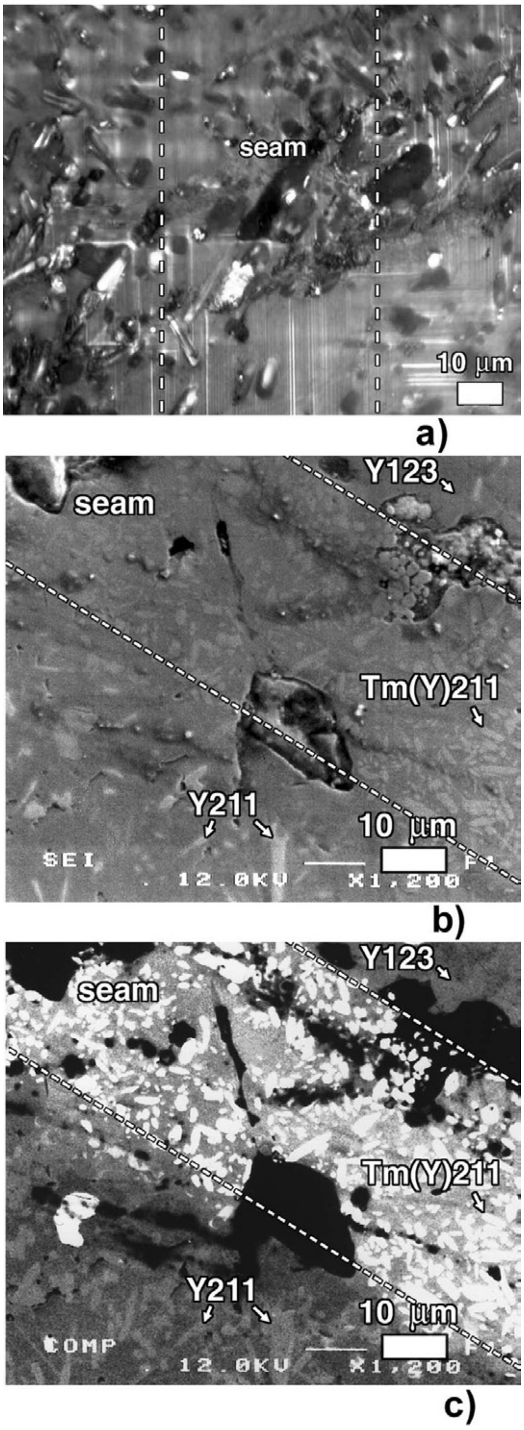

Figure 8. Microstructure of the soldered seam in the ring in polarized light (a) and obtained by SEM (b), (c): SEI (b) and COMPO (c).

few micrometres over the sample surface can be seen from the figure.

Figure 8 shows the structure of the seam observed with a polarizing microscope (figure 8(a)) and with a scanning electron microscope using a secondary electron image (SEI) (figure 8(b)) and backscattering electron image (composition) (figure 8(c)). Figures 8(b) and (c) are taken from the same region of the sample at the same magnification. Heavier elements look brighter in the backscattered electron image (figure 8(c)).

3. Discussion

The experiments on soldering under elevated pressure conducted with the purpose-built device (figure 1) have shown that, in order to avoid crack propagation in large MT-YBCO blocks used for practical purposes, the rates of heating and cooling during the seam formation should be around 100 K h^{-1}. These rates for high quality single-domain material without visible cracks (macrocracks) can be rather high 500–1000 K h^{-1}. In this process it is not necessary to introduce a step of slow cooling (at a rate of several tenths of a degree per hour) during the junction formation.

The single-domain ring cut and soldered at 1010 °C for 6 min exhibited high SC characteristics after oxygenation (figures 4–7). Some increase of j_c through the ring after soldering and oxygenation (compare to the uncut ring) in fields up to 2.5 T may be attributed to the oxygen redistribution over the Y123 matrix of MT-YBCO during the repeated heat treatment and oxygenation. Similar values of j_c in single-domain and joined rings support the conclusion that no degradation of the SC characteristics occurs during the join process and that the j_c at 77 K in zero field in the region of the join was not lower than 30 kA cm^{-2}.

The field mapping data (figure 5) and calculated j_c distribution (figure 6) as well as magneto-optical study (figure 7) confirmed the homogeneity of current flow through the material of the ring and through the formed seam. In addition, the studied indicated region of the seam is not a weak link in the joined ring.

Good agreement of the seam structure with the structure of MT-YBCO is responsible for the passage of high currents by the junction (figure 8). The formed seams were about 50 μm wide.

4. Conclusions

The method of joining investigated here caused no degradation of the MT-YBCO and allows the formation of an SC junction with a similar structure and properties to the joined material. Several methods of j_c estimation used in the present study were in good agreement and indicated a high quality of the formed join.

Acknowledgments

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