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RAPID COMMUNICATION

Simple technique for quality estimation of superconducting joints in bulk melt-processed high temperature superconductors

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Abstract
We propose an empirical approach to estimate the quality of superconducting joints (welds) between blocks of bulk high temperature superconductors (HTS). As a measuring value, we introduce a quality factor of the joint and show its natural correlation with the joint's critical current density. Being simple and non-destructive, this approach is considered to be quite important to solve the problem of the utilization of HTS in large scale applications. The approach has been applied to characterize the joint's quality of melt-processed Y-123 joined by Tm-123 solder.

1. Introduction

Bulk melt-processed high temperature superconductors (MP HTS) have appeared to be quite suitable for large scale HTS applications such as superconducting motors, contactless bearings, flywheels for energy storage and levitation transport [1, 2]. Remarkable values of critical current densities have been achieved for these quasi-single crystals. The main problem now, which is an obstacle in the way of their practical utilization, is to find a way of joining them superconductively to appropriate utilization blocks [3, 4]. Though being actively investigated [3–7], this problem is far from being completely resolved at the moment and it is vitally important to find a simple method for quantitative characterization of superconducting joints.

The most physical way to describe a superconducting joint quantitatively is to determine the density of critical current that flows through it. While the transport measurements are quite difficult to exploit here, the contactless techniques appear to be the most attractive [5, 7]. It has been shown that levitation force measurements [4], magneto-optical imaging techniques [4], and Hall-probe magnetometry [5, 6] can be successfully used to characterize the quality of the superconducting joint. At last, in a very recent paper [7], an approach to estimate the critical current density through a superconducting joint for ring samples was proposed.

In this rapid communication we propose a simple non-destructive contactless method to evaluate the quality of a superconducting joint and estimate the critical current density through it. The method is based on the technique of critical current density determination from local levitation force measurements which allows us to determine the critical current density in a thin undersurface layer. In the simplest implementation of the technique, the critical current density is inversely proportional to the shift Δz of a real levitation force versus z (the distance between a permanent magnet and the superconducting surface) dependence in respect to an ideal one. See [8] for details.

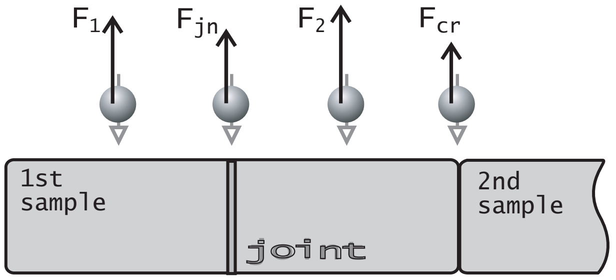

Figure 1. A schematic illustration of the 'four points procedure'. The levitation force, acting from a screening current in a small spherical permanent magnet with a vertical direction of magnetic moment, is measured in four points: above the 'uniform' parts of sample, F_1 and F_2 ($F_{un} = (F_1 + F_2)/2$), above the superconducting joint, F_{jn}, and above the 'crack' (mechanical joint of two samples), F_{cr}.

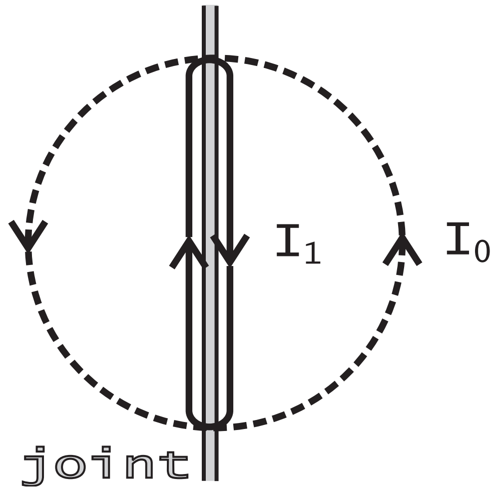

Figure 2. A schematic illustration on currents circulating in the HTS bulk which produce the levitation force.

2. Experimental details

We test the method on Y-123 MP HTS samples with superconducting joints made by a solidification technique (soldered joints) with Tm-123 as a solder. The details of the technique are described in [6]. Two types of experimental procedure were used: the 'three times procedure' and the 'four points procedure'. With the 'three times procedure' we measure the levitation force that acts on a small permanent magnet (PM) three times at one point: above the uniform sample before cutting, F_{un}, above the 'crack' (mechanical joint) after cutting, F_{cr}, and above the superconducting joint after the soldering procedure, F_{jn}. The 'four points procedure' is illustrated by figure 1. In this case, F_{un} can be estimated as $(F_1 + F_2)/2$. In the following we present the results obtained by the 'four points procedure' which does not require the measurements before soldering, although two samples were investigated by both procedures and the difference of the determined quality factors were less than 4%. We used two PMs: a spherical one of 1.5 mm in diameter with magnetic moment $\mu = 1.9$ G cm^3, and a cylindrical one of 6.3 mm in diameter and 2.3 mm in width with $\mu = 38$ G cm^3. The readout distances between the magnet centres and the HTS surface were 1.25 mm and 6 mm respectively. The basic experimental set-up and the technique for critical current density determination have been described in detail in [8].

Based on such local levitation force measurements, one can introduce a joint's quality factor

$$q = \frac{F_{jn} - F_{cr}}{F_{un} - F_{cr}}. \tag{1}$$

This formula was constructed to satisfy the natural asymptotic conditions: $q \to 0$ when $F_{jn} \to F_{cr}$ (non-superconducting joint), and $q \to 1$ when $F_{jn} \to F_{un}$ (an ideal superconducting joint). In the following we will find the physical meaning of this introduced quality factor through its relation with the joint's critical current density J_{jn}.

Let us consider the next basic picture of circular currents which are sketched in figure 2. In a uniform sample a circular current I_0 flows mainly over the top surface of the sample [8] and one can write $F_{un} = \alpha I_0$. If we crack the sample, the current (having the same value until the size of the crack is much less than sample dimensions) cannot flow though the crack and has to close over the crack walls; but one can consider this as an additional opposite ($I_1 = -I_0$) circular current flowing through the crack and over the crack walls: $F_{cr} = \alpha I_0 + \beta I_1 = (\alpha - \beta)I_0$. Next, it is quite natural to assume that for a sample with a superconducting joint one can estimate the real current through the joint as

$$I_{jn} = I_0 - I_1 = \frac{J_{jn}}{J_c} I_0, \tag{2}$$

where J_c is the bulk critical current density. Then $I_1 = (1 - (J_{jn}/J_c))I_0$ and $F_{jn} = (\alpha - \beta(1 - (J_{jn}/J_c)))I_0$. Substituting this into (1) we obtain

$$q = \frac{J_{jn}}{J_c}. \tag{3}$$

Thus, the superconducting joint's quality factor introduced by (1) represents the ratio of density of the critical current that flows through the joint to the bulk critical current density of the sample. Equation 1 shows a simple way to estimate this quality factor, but in combination with the method of J_c the determination from levitation force measurements [8] gives a simple non-destructive method for the determination of density of the critical current through the superconducting joint.

Though the given derivation of equation (3) from equation (1) is quite simple, it has some restrictions which should be considered. The first of them is the validity of consideration of the levitation forces to be proportional to the corresponding currents—we have assumed above that the introduced coefficients α and β do not depend on I_0 and I_1, correspondingly. The first assumption, $\alpha(I_0) = const$, works well when the depth δ of penetrated magnetic field at the sample surface ($\delta = cB_r/4\pi J_c$ in CGS units, c is the velocity of light and B_r is the tangential magnetic field at the HTS surface which is twice as big as the PM's field in 'zero approximation' [9]) is much less than the system's dimensions L (the distance from the centre of the magnet to the sample surface in our geometry). This is the case in the experiment being considered and can always be achieved by choosing the appropriate values of L or μ. Moreover, it was shown in [8] that the condition $\delta \ll L$ is too strong and the assumption works well even if $\delta \sim L$.

Table 1. Critical current densities and quality factors of soldered joints of MP YBCO samples.

Sample	T_{tr}, K	top plane	J_{un}, A cm^{-2}	J_{jn}, A cm^{-2}	q_I	q_{II}	q_M
1	1257	∥ ab	1.5×10^4	1.2×10^4	0.79	0.65	0.40
		⊥ ab	7.6×10^3	3.9×10^3	0.52	–	0.29
2	1257	∥ ab	1.3×10^4	3.2×10^3	0.25	0.32	0.56
		⊥ ab	7.2×10^3	5.7×10^3	0.79	–	0.67
3	1253	∥ ab	1.3×10^4	1.6×10^3	0.13	0.28	0.47
		⊥ ab	9.1×10^3	7.7×10^3	0.84	–	0.46
4	1253	∥ ab	1.6×10^4	8.5×10^3	0.53	0.49	0.33
		⊥ ab	9.3×10^3	6.7×10^3	0.72	–	0.30
5	1263	∥ ab	1.5×10^4	7.2×10^3	0.47	0.55	0.77
		⊥ ab	8.2×10^3	3.9×10^3	0.47	–	0.53
6	1263	∥ ab	2.2×10^4	9.4×10^3	0.43	0.46	0.45
		⊥ ab	7.1×10^3	6.1×10^3	0.85	–	0.57

To fulfill the assumption that $\beta(I_1) = const$ is not so easy, the penetration depth δ_{jn} of the intrajoint field must be less than the joint's width which imposes strong restrictions on the magnetic field value. For the samples that we investigated the joints were $d \sim 100$ μm in width which has motivated the readout distances we used to ensure $\delta_{jn} < d$. So, here we measure the superconducting joint's quality for magnetic field 10^2–10^3 G but the method can be extended to higher fields by replacing the levitation force measurements with the resonance oscillations technique [10, 11].

Another point, which should be mentioned, relates to sample inhomogeneity. Although every method of critical current density determination encounters the same problem, a reasonable approximation here is to assume the validity of equation (3) as an integral relation over a region where the main amount of the induced current flows ($\sim 2L$ in our case). This sets a restriction on the spatial resolution of the method but also makes it possible to vary the integrated area using different magnets. The integrated areas were about 2 mm and 10 mm in diameter respectively and 0.1 mm in depth for the two magnets used.

3. Results

The results of our measurements are summarized in table 1. The samples were treated at temperatures T_{tr} for 0.17 h in air (1, 2) and for 0.5 h in oxygen (3–6). As a solder, the powder of Tm-123 was used for even samples and Tm-123 with an addition of 10 wt% of Y-211 (green phase) for odd samples. The values q_I and q_{II} were determined with first and second magnets respectively by the 'four points procedure'. The value q_M is the joint's quality factor from the mapping technique [6]. It was estimated as $q_M = 2B_{ju}/(B_1 + B_2)$, where B_{ju}, B_1, and B_2 are the local maximum trapped magnetic fields in junction and in two pieces of cut samples. The values of J_c (determined from F_{un}, see [8]) and J_{jn} are also represented in table 1.

Although the mapping technique gives rather rough values it is possible to make some conclusions. First, the q_{II} values are closer to q_M than q_I because they are integrated over a larger volume. Second, we have compared the average values of quality factors for a different series of measurements (here $q \equiv q_I$): over all samples, $\langle q\rangle = 0.57$, $\langle q_M\rangle = 0.48$; over all in-plane surfaces (parallel to the ab-plane), $\langle q\rangle_\parallel = 0.43$, $\langle q_M\rangle_\parallel = 0.50$; and over all out-plane surfaces (perpendicular to the ab-plane), $\langle q\rangle_\perp = 0.70$, $\langle q_M\rangle_\perp = 0.47$. Assuming that the quality factors determined from the levitation force measurements give the information from a thin undersurface layer (undersurface quality) and the factors determined from mapping represent an integrated value over the whole volume (bulk quality), it is possible to say that the undersurface joint's quality is slightly better than the bulk joint's quality and that the undersurface quality is much better for out-plane surfaces in comparison to in-plane ones. In other words, this means that in the tested samples: (i) the average quality of joints is slightly better at the edges than in the middle; (ii) the critical current density of the material which fills the joints is less anisotropic than the bulk critical current density of the samples itself.

4. Conclusion

In summary, we have proposed a simple empirical approach to estimate the quality of superconducting joints between blocks of bulk high temperature superconductors. As a measuring value, we introduced a joint's quality factor and found its natural correlation with the joint's critical current density. Simultaneous use of the proposed method and the flux mapping technique has allowed us to estimate space inhomogeneity of superconducting joints and even obtain information about the anisotropy of the joint's critical current density.

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