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LETTER

On Estimating the Critical Current Density in Polycrystalline Superconductors Synthesized by Solid-State Method

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Abstract
In a recent paper, Zhang et al. [1] studied the effect of a Pb content on the superconducting properties of Bi-2223. Some earlier, Ramírez et al. [2] explored the effect of compaction pressure on the Bi-2212. In both studies, the critical current densities were estimated and compared for a series of polycrystalline superconducting samples. The synthesis conditions for the highest critical current density were claimed in both works. This comment explains that the average granule size should be used instead of the sample size in the Bean formula for the polycrystalline superconductors synthesized by solid-state, sol–gel, electrospinning, and solution blow spinning methods. The corrected estimations for the commented articles conclude that the synthesis conditions affect both the granule size and the intragranular critical current density. The synthesis parameters for the highest critical current density conditions are clarified.

Keywords Critical current density · Critical state model · Circulation scale · Two-level model · Granular superconductors · Granularity · Intragrain currents

Tuning the synthesis conditions is a popular method to modify the properties of superconductors and to improve their critical current. Such studies require the preparation and comparison of a series of superconducting samples with a gradual variation of parameters [3]. Recent articles [1, 2] in the *Journal of Superconductivity and Novel Magnetism* are also devoted to this theme. Bi-2212 samples, synthesized with applying different compact pressures, were investigated in [2]. Bi-2223 samples, having different contents of Pb, were prepared and compared in [1]. Optimal synthesis conditions were found in these works to attain the highest critical current density j_c. The values of j_c were estimated from magnetization hysteresis loops of the samples. The proportionality between ΔM, the difference between the ascending and descending magnetization hysteresis branches, and j_c results from the critical state model [4]. The highest values of the critical current density j_c were found to occur in the Bi-2212 sample compressed at 600 MPa ($j_c \approx 7.3\times10^7$ A/m^2 at 4 K) [2] and in the Bi-2223 sample ($Bi_{1-x}Pb_xSr_2Ca_2Cu_3O_{10+\delta}$) with Pb content $x = 0.4$ ($j_c \approx 4.7\times10^8$ A/m^2 at 10 K) [1]. These experimental data are valuable. However, the estimated j_c values for different samples were greatly scattered [1, 2] that is suspected to be the result of the faulty analysis. An important aspect was not accounted in the commented articles: for polycrystalline samples, ΔM depends on a granule size rather than on the sample size [5–18]. The scanning electron microscopy images demonstrated a granular structure of the investigated samples [1, 2], and the special approach for polycrystalline superconductors should be engaged for the obtained data.

Polycrystalline superconductors are considered a two-level system [5, 19–23]. One level corresponds to intergranular currents and Josephson vortices [24]. Another level relates to the intragranular currents and the granule magnetization. The two-level model is usually applicable for polycrystalline superconductors with $j_{cJ} << j_{cg}$. The intragranular critical current density j_{cg} can be in 10^3–10^4 times higher than the intergranular critical current density j_{cJ} for superconductors prepared by the solid-state synthesis, the sol–gel synthesis, the electrospinning, and the solution blow spinning [25–27]. Moreover, superconductivity of intergranular boundaries is completely suppressed by a magnetic field $\mu_0 H_{cJ} \sim 10$ mT at 4.2 K for such

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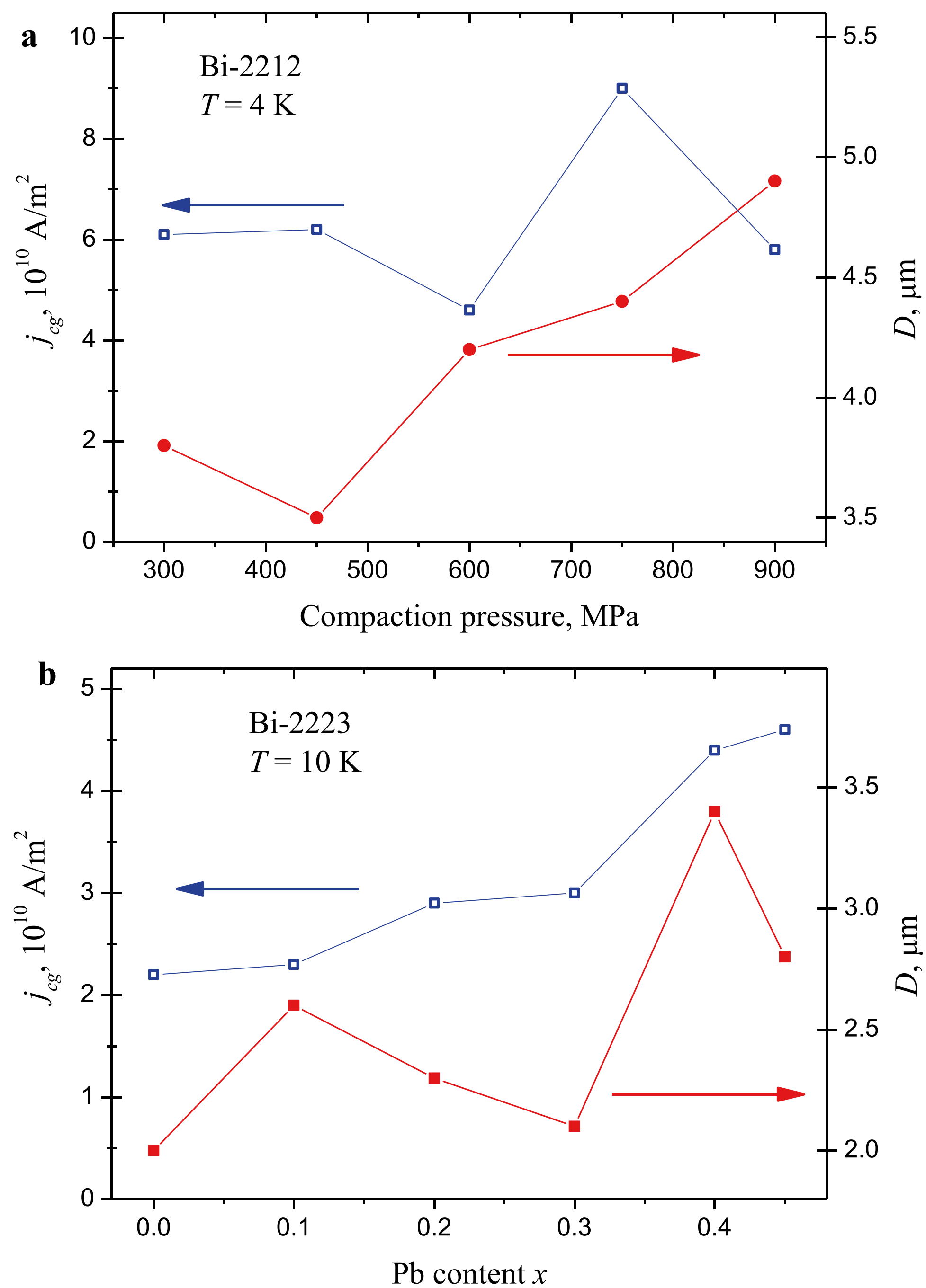
Fig. 1 Variance of estimated values of the granule size D and the intragranular critical current density j_{cg} on the synthesis parameters for Bi-2212 [3] (**a**) and Bi-2223 [2] (**b**)



samples [17, 28–30]. Therefore, the intergranular currents have a negligible contribution in high field magnetization hysteresis loops, and then the maximal field $H >> H_{cJ}$. At magnetic fields $H > H_{cJ}$, the magnetization is produced by pinning of Abrikosov vortices and currents circulating in granules. The significative scale for this second level is the average granule size D, and the magnetization hysteresis loop is mainly produced by the intragranular currents [31–33]. The Bean formula for the intragranular critical current density is conventionally expressed as

$$j_{cg} = 3\Delta M/D \quad (1)$$

Expression (1) is appropriate for irregularly shaped granules which are not aligned and vary in size [7, 12, 15, 17, 34–37]. To account porosity in (1), one should use $\Delta M = \Delta m\rho$, where m is the magnetization of the mass unit (in A m^2/kg), and ρ is the mass density of granules (ρ is about the theoretical density of the superconductor). In highly anisotropic superconductors, such as Bi-2212 and Bi-2223, D is the size of the granules in their a-b planes, because circulation of the currents occurs in these planes [38].

Synthesis conditions affect the growth rate of granules [3, 35], and different granule sizes affect the magnetization hysteresis loop. This means that the granule sizes should be traced in advance to find an effect of the synthesis parameters on the critical current density.

Adjusted estimations of D and j_{cg} from the data [1, 2] are performed and presented here (Fig. 1). A variation of D is determined using the method [33] from asymmetry of the magnetization hysteresis loops. The obtained values of D are confirmed by SEM images. The j_{cg} values at 0.15 T are determined using formula (1). It is seen that the j_{cg} values for the different samples are less scattered than in the works [1, 2] due to taking into account the diversity of D. It appears that the optimal synthesis conditions differ from those established in the commented works. The highest values of the intragranular critical current density are $j_{cg} \approx 10 \times 10^{10}$ A m^{-2} at 4 K for Bi-2212, prepared with the compaction pressure $P = 750$ MPa, and $j_{cg} \approx 5 \times 10^{10}$ A m^{-2} at 10 K for Bi-2223 with the Pb content $x = 0.45$.

In summary, the main goal of the presented comment is to prevent a frequent mistake in analysis. This mistake is disregarding of variation of the granule sizes in a series of polycrystalline samples when one attempts to estimate the critical current density from the magnetization hysteresis loops.

Declarations

Conflict of Interest The authors declare no competing interests.

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