Intra- and inter-grain critical current density in (Cu,C):1234 superconductors

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Abstract

From DC magnetization studies in fields up to 14 T and temperatures between 20 and 100 K, we estimated the intra- and inter-grain critical current density J_c of (Cu,C):1234 high-T_c superconductors, in the frame of critical state models. The inter-grain J_c was determined by comparing the magnetization loops of as-grown sample and of the ground sample. Finally, short comments on J_c resulted from AC susceptibility measurements and of the impressive increase of intra-grain J_c due to heavy-ion and neutron irradiation are presented.

Key words: $(Cu_{0.6}C_{0.4})Ba_2Ca_3Cu_4O_y$; critical current density ; magnetization ; susceptibility

1. Introduction

$(Cu_{0.6}C_{0.4})Ba_2Ca_3Cu_4O_y$ ((Cu,C):1234) is a very interesting superconducting material [1] since it has a high T_c of 117 K even in a highly over-doped state, a quite low anisotropy factor, and does not contain any toxic or volatile element. Previous estimations of intra-grain critical current density J_c^g from DC magnetization loops in fields H_{DC} up to 5 T [2] did not take into account the contribution to magnetization of inter-grain supercurrents J_c^c, which is not negligible.

In this paper we report the values of J_c^g in fields up to 14 T, the real values of J_c^g in low fields (from magnetization loops of crushed sample) and the values of J_c^c from the difference in magnetization loops of the as-grown sample and of crushed sample, respectively. Finally, the results of AC susceptibility studies as well as the impressive increase of J_c^g after neutron or heavy-ion irradiation are briefly discussed.

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2. Experimental

Polycrystalline (Cu,C):1234 was prepared by high-pressure synthesis. First, a precursor with nominal composition $Ba_2Ca_{2.7}Cu_{4.6}C_xO_y$ was prepared by solid state reaction, from a mixture of $BaCO_3$, $CaCO_3$ and CuO powders, at 900^{o}C for 24 h in flowing O_2, with one intermediate grinding. The residual carbon content x in the precursor was 0.1. One mol of precursor was mixed with 0.3 mol of $CaCO_3$ and 0.5 mol of AgO (as oxidizing agent), pressed into a pellet, sealed into a gold capsule, and treated at 1000^{o}C for 2 h under a pressure of 3.5 GPa.

XRD showed (Cu,C):1234 single phase, SEM revealed randomly-oriented plate-like grains having mean diameter $2a$=7 μm and mean thickness $2b$=1 μm. The whole sample was a cylinder with diameter $2A$=4.35 mm and thickness $2B$=2.05 mm.

DC magnetization loops of as-grown sample were measured with a SQUID MPMS (Quantum Design) up to 7 T for T between 77.3 K and 100 K and with a PPMS (Quantum Design) up to 14 T for T between 20 K and 77.3 K. At several fixed T and H_{DC} we performed also AC susceptibility studies by measuring the

AC field dependence of the out-of-phase susceptibility, $\chi''(h_{ac})$. All the measurements were repeated on isolated grains, after the sample was ground.

3. Results and discussion

DC magnetization measurements revealed a significant difference between magnetization loops of the as-grown sample and of the crushed one, at the same T ($\Delta M(H)$ being the difference in magnetization between the two branches of the magnetization loops), for fields smaller than 1-3 T (depending on temperature). While for isolated grains ΔM^{g} comes from J_c^{g} circulating the grains, in the as-grown sample there is also a contribution to magnetization due to J_c^{c} circulating the sample as a whole, $\Delta M^{g+c}=\Delta M^{g}+\Delta M^{c}$.

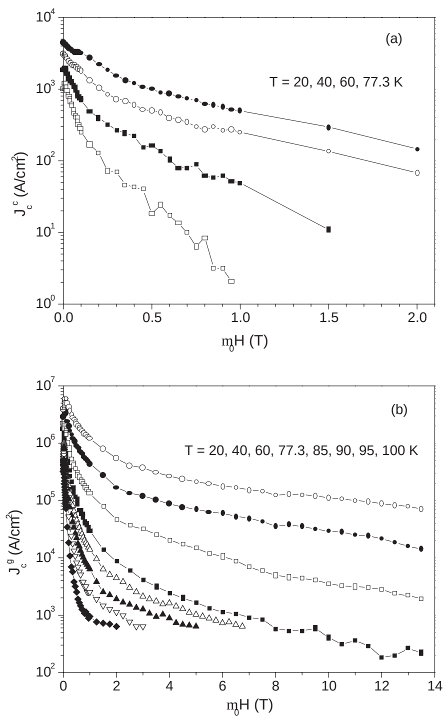

Fig. 1. Critical current density of $(Cu_{0.6}C_{0.4})Ba_2Ca_3Cu_4O_y$ at various temperatures and fields: (a) inter-grain; (b) intra-grain

J_c^{c} and J_c^{g} were estimated from critical state models. In the case of an infinite-long slab of thickness $2b$ parallel with the field, Bean's equations relate J_c to the field for full penetration, $h_p=bJ_c$, and to ΔM, $J_c=(30\Delta M)/(2b)$. Our whole sample was a cylinder with its symmetry axis parallel to the field. In this case, the field for full penetration is given by Brandt's equation [3]:

$$h_p = J_c b \ln[(a/b) + (1 + a^2/b^2)^{1/2}], \quad (1)$$

where a and b are again the radius and half-thickness of the cylinder.

Using eq. (1) with our sample's dimensions, we calculated the effective dimension for the Bean's equations and, using the resulting ΔM^{c} (the difference between magnetic hysteresis of the as grown sample and of the crushed one), we calculated J_c^{c}, shown in Fig. 1a.

For estimating J_c^{g} from ΔM^{g} we took into account not only the mean values of grains' dimensions, but also their random orientation. In the case of grains parallel to the field, the original Bean model is quite a good approximation with the dimension d_{par} being half-thickness of the grain. For our plate-like grains perpendicular to the field, the dimension d_{perp} was calculated using eq. (1) (with the grain's dimension as resulted from SEM). Finally, we have chosen as effective dimension in the Bean's equation the mean value $d_{eff}=(d_{par}/d_{perp})/2$. The resulting J_c^{g} is shown in Fig. 1b.

Regarding the AC susceptibility studies, in the critical state model, the field for full penetration corresponds to the position of the peak in the $\chi''(h_{ac})$. We performed several such measurements, at various T, H_{DC}, and with various AC frequencies, and estimated (using the same d_{eff}) the critical current density. J_c^{g} resulted to be strongly frequency-dependent (due to different time-scale for flux-creep), several times higher than the values resulted from DC magnetization, and, at the same frequency, displayed a more pronounced DC field dependence as the result of the limitations of critical state model for AC susceptibility studies. Finally, we should add that J_c^{g} of (Cu,C):1234 can be greatly increased by neutron irradiation (about 10 times) and heavy-ion irradiation (about 100 times).

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