Temperature dependence of the trapped magnetic field in MgB_2 bulk superconductors

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Based on dc magnetization measurements, the temperature dependencies of the trapped magnetic field have been calculated for two MgB_2 samples prepared by two different techniques: high-pressure sintering and hot pressing. Experimentally measured trapped field values for the first sample coincide remarkably well with calculated ones over the whole temperature range. This shows, on one hand, the validity of the introduced calculation approach, and demonstrates, on the other hand, the great prospects of the hot pressing technology for large scale superconducting applications of the MgB_2. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1629148]

Magnesium diboride is a promising superconducting material with a critical temperature of about 40 K. High T_c values and the simple chemical composition of MgB_2 have made it an interesting object for applied investigations with significant potential for use in superconducting motors, flywheels, and bearings. The key parameter for such applications is the maximum trapped field in the sample and its temperature dependence. This, in turn, is closely connected both with the critical current density and with the size of superconductor.

Since the discovery of superconductivity in MgB_2, researchers had to deal with tiny samples that were not suitable for large scale applications. Now, the situation has changed and several techniques have been developed to produce high quality MgB_2 bulk polycrystalline samples of a few centimeters in diameter and with the critical current densities up to 10^5-10^6 A/cm^2.[1,2]

It is remarkable that, in contrast to the high temperature superconductors, the grain boundaries in bulk magnesium diboride superconductors do not act as weak links.[3–5] This significantly simplifies the growth of bulk samples suitable for large scale applications.

In this letter we focus on an important property of the bulk superconductor—the trapped magnetic field. We calculate its temperature dependency from dc magnetization data using an iteration approach. We show that the trapped field values measured experimentally are in excellent agreement with the calculated ones. This enables prediction of the expected values of the trapped magnetic field in larger samples, which are presently under development.

We have studied two MgB_2 bulk samples prepared by different techniques. One of them was sintered under high pressure as described in Ref. 6. The sample has a uniform polycrystalline structure without cracks and is 28 mm in diameter and 11 mm in height. The trapped magnetic field at the center of the sintered sample was measured by a Hall probe for different temperatures from 6 to 33 K. The resulting temperature dependence of the trapped field has a negative curvature and tends to saturation at low temperatures (see Fig. 1, cross symbols). The other sample was prepared by ball milling of Mg and B powders at ambient temperatures followed by hot pressing,[7] which we call ''ball milled.'' It consists of spherical nanocrystalline grains about 40–100 nm in size that distinctly improve pinning due to the large number of grain boundaries. For this sample the trapped field could not be measured because of its small size.

To calculate the trapped field one should know the temperature and field dependencies of the critical current density $J_c(H,T)$ of the superconductors. For dc magnetization measurements small bar-shaped pieces of both samples have

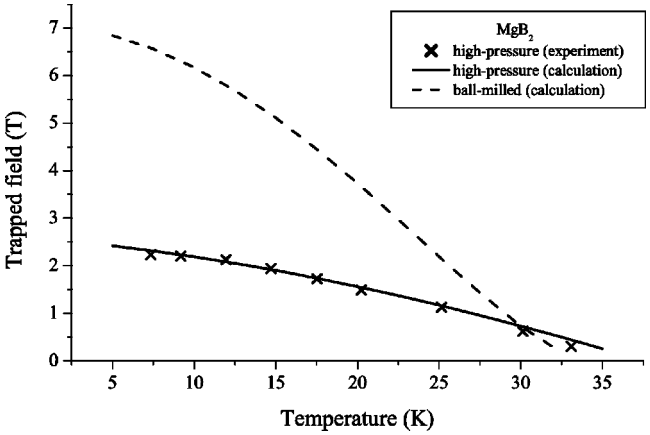

FIG. 1. Temperature dependencies of maximum trapped field in bulk MgB_2 samples prepared under high-pressure sintering (measured) and ball-milled (calculated) techniques.

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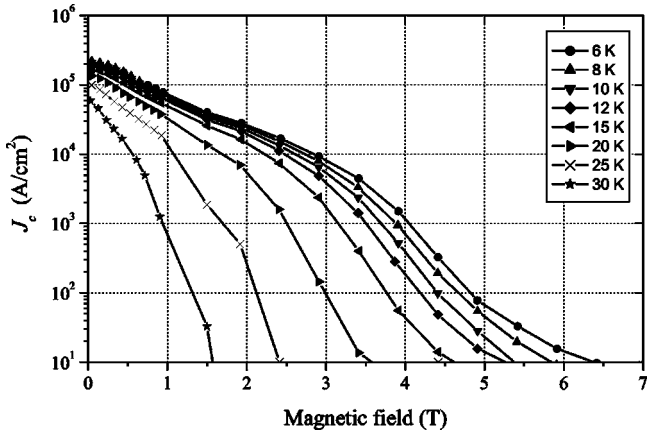

FIG. 2. Field dependencies of critical current density at different temperatures for the high-pressure sintered MgB_2 sample. $J_c(H)$ curves were obtained from dc magnetization data.

been used. Then, the $J_c(H)$ curves were obtained from the magnetization loops $M(H)$ using the conventional expression $j_c(H)=20\cdot\Delta M(b-b^2/3l)$, where ΔM is the difference in the magnetization (in emu/cm^2) measured for increasing and decreasing applied fields, b and l are the sample width and length in cm, respectively, and j_c is obtained in A/cm^2.

For the high-pressure sintered sample a set of $J_c(H)$ curves presented in Fig. 2 in logarithmical scale are practically linear for low fields up to the level of $J_c=10^4$ A/cm^2. This indicates an exponential decay of critical current density with increasing field

$$J_c(H,T)=J(T)\exp[-H/b(T)], \tag{1}$$

where $J(T)$ and $b(T)$ are temperature-dependent coefficients.

The dependencies of $J(T)$ and $b(T)$ for the sintered sample, shown in Fig. 3 by circles, can be well fitted to the expressions

$$b(T)=b_0[1-(T/T_c)^2], J(T)=J_0[1-(T/T_c)]. \tag{2}$$

Here, $T_c=37.5$ K is the critical temperature, whereas $b_0=0.9$ T and $J_0=3.1\times10^5$ A/cm^2 are fitting parameters, which characterize an effective field of supercurrent decay and a maximum critical current density at zero field and temperature, respectively.

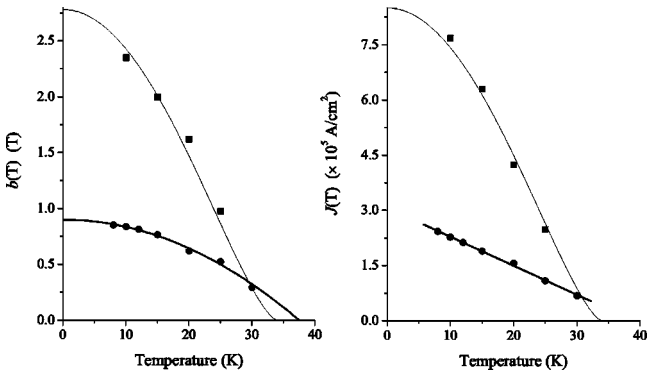

FIG. 3. $J(T)$ and $b(T)$ coefficients of $J_c(H)$ curves [see Eq. (1)] for MgB_2 bulks. Symbols represent experimental data for high-pressure sintered (circles) and ball-milled (squares) samples. Solid lines represent fitting results, which is described by formulas (2) and (3) for sintered and ball-milled samples, respectively.

For the ball-milled MgB_2 sample $J_c(H,T)$ curves can also be described by Eq. (1) (see Fig. 4 in Ref. 7), but the functions $b(T)$ and $J(T)$ are different:

$$b(T)=b_0[1-(T/T_c)^2]^{3/2}, J(T)=J_0[1-(T/T_c)^2]^{3/2}, \tag{3}$$

where the corresponding parameters are $T_c=34$ K, $b_0=2.78$ T, and $J_0=8.5\times10^5$ A/cm^2 (see Fig. 3, squares).

The results obtained show that the critical current density depends strongly on temperature. For the high-pressure sintered sample the values of $J(T)$ and $b(T)$ are about 2.5 times lower than those of for the ball-milled sample. On the other hand, the latter sample has a much stronger power dependence of $J(T)$ and $b(T)$ on temperature.

Further calculation of the trapped field from a known $J_c(H,T)$ function is a nontrivial task. According to the Biot–Savart low, the magnetic field **H** generated by the supercurrent $\mathbf{J_c}$ flowing in the volume of sample V is

$$\mathbf{H}(\mathbf{r})=\frac{1}{c}\int_V \mathbf{J_c}(\mathbf{H},\boldsymbol{\rho})\times\frac{\mathbf{r}-\boldsymbol{\rho}}{|\mathbf{r}-\boldsymbol{\rho}|^3}d^3\rho. \tag{4}$$

As $\mathbf{J_c}$ is a function of **H**, it is necessary to solve this integral equation in order to calculate the trapped field values.

To simplify the problem we assume homogeneity of the sample, i.e., (1) that the critical current density does not depend on coordinate ρ explicitly and (2) that the currents flow along concentric circles. Then, the field component normal to the sample surface, H_z, can be written in cylindrical coordinates $\mathbf{r}=(r,\phi,z)$ and $\boldsymbol{\rho}=(\rho,\psi,\zeta)$ as follows:

$$H_z(r)=\frac{1}{c}\int_V J_c(H_z)f(r,\rho,\psi,\zeta)\rho d^3\rho, \tag{5}$$

where

$$f(r,\rho,\psi,\zeta)=\frac{\rho-r\cos\psi}{[(r-\rho\cos\psi)^2+(\rho\sin\psi)^2+(z-\zeta)^2]^{3/2}},$$

$$d^3\rho=d\rho d\psi d\zeta.$$

The resulting field profile has a cylindrically symmetric form with the maximum at $r=0$.

The integral Eq. (5) can be solved for $H(r)$ numerically using an iterative procedure:[8]

$$H_{i+1}(r)=\frac{1}{c}\int_V J_c(H_i)f(r,\rho,\psi,\zeta)\rho d^3\rho, \tag{6}$$

until $|H_{i+1}-H_i|/H_i<\varepsilon$, where dimensionless quantity ε is a desired accuracy of calculation. Here, the profile obtained is used to calculate the current in the next step of iterations. We chose an initial profile $H_0(r)=$const to start the calculation.

One should note that we calculate the trapped field profile numerically in each step and cannot define the $H(r)$ function in every point. Therefore, we should discretize Eq. (5) and divide the cylindrical sample into N concentric tubes of width $\Delta=R_s/(N-1)$ and then calculate the field in each point $r_k, k=0\cdots N-1$ as a sum of fields from all tubes:

$$H(r_k)=\frac{\Delta}{c}\sum_{j=0}^{N-1}\int J_c[H(\rho_j)]f(r_k,\rho_j,\psi,\zeta)\rho_j d\psi d\zeta, \tag{7}$$

where $r_k = k\Delta$, R_s is the radius, L is the height of the cylindrical sample, and the integration here is made over ψ from 0 to 2π and over ζ from $-L$ to 0.

From Eq. (7) the field profile for a given $J_c(H)$ function is obtained using iterations (6). In the case of $J_c(H) = \text{const}$ the calculation produces a conical Bean profile with the maximum in the center of the sample. To reach an accuracy of $\varepsilon = 0.1\%$ it is sufficient to make just 16 iterations with $N = 14$ tubes. Moreover, the method of calculation has no fitting parameters and uses only experimental $J_c(H,T)$ data. The calculated temperature dependence of maximum trapped field for high-pressure sintered and ball-milled MgB_2 samples are represented in Fig. 1 by the solid and dashed lines, respectively.

We obtained very good agreement with the experimental data for the high-pressure sintered sample. Remarkably, the trapped field, which is determined by the current distribution in the whole sample volume can be calculated correctly on the base of J_c measured locally in a small piece of the sample. This provides one more evidence of the lack of granularity effect in bulk MgB_2. The ball-milled (nanocrystalline) sample was calculated to have much higher trapped fields than the sintered sample. Thus, the development of large size nanocrystalline MgB_2 samples is very attractive for future applications.

In summary, we have calculated the temperature dependence of the trapped magnetic field for two MgB_2 bulk samples prepared using different techniques. We used dc magnetization data and an iteration approach to solve the Biot–Savart equation. Experimentally measured trapped field values for the high-pressure sintered sample are in excellent agreement with the calculated ones over the whole temperature range. The correctness of the calculation allowed us to predict the expected values of the trapped field in the ball-milled sample, which revealed the great prospects of this technology for large scale applications of superconducting MgB_2.

[1] J.-S. Rhyee, C. A. Kim, B. K. Cho, and J.-T. Kim, Appl. Phys. Lett. **80**, 4407 (2002).
[2] V. Braccini, L. D. Cooley, S. Patnaik, D. C. Larbalestier, P. Manfrinetti, A. Palenzona, and A. S. Siri, Appl. Phys. Lett. **81**, 4577 (2002).
[3] M. Kambara, N. Hari Babu, E. S. Sadki, J. R. Cooper, H. Minami, D. A. Cardwell, A. M. Campbell, and I. H. Inoue, Supercond. Sci. Technol. **14**, L5 (2001).
[4] Y. Bugoslavsky, G. K. Perkins, X. Qi, L. F. Cohen, and A. D. Caplin, Nature (London) **410**, 563 (2001).
[5] K. Kawano, J. S. Abell, M. Kambara, N. Hari Babu, and D. A. Cardwell, Appl. Phys. Lett. **79**, 2216 (2001).
[6] T. A. Prikhna *et al.*, Physica C **386**, 565 (2003).
[7] A. Gümbel, J. Eckert, G. Fuchs, K. Nenkov, K.-H. Müller, and L. Schultz, Appl. Phys. Lett. **80**, 2725 (2002).
[8] T. Klupsch, T. Strasser, T. Habisreuther, W. Gawalek, S. Gruss, H. May, R. Palka, and F. J. Mora Serrano, J. Appl. Phys. **82**, 3035 (1997).