Transport behavior and critical current densities in MgB_2 wires

A. K. Pradhan,[a] Y. Feng, Y. Zhao, and N. Koshizuka
Superconductivity Research Laboratory, ISTEC, 1-10-13 Shinonome, Koto-ku, Tokyo 135-0062, Japan

L. Zhou, P. X. Zhang, X. H. Liu, P. Ji, S. J. Du, and C. F. Liu
Northwest Institute of Nonferrous Metal Research, P.O. Box 51, Xi' an 710016, People's Republic of China

(Received 17 May 2001; accepted for publication 16 July 2001)

We report on the transport and magnetization properties of MgB_2 wires fabricated by a powder-in-tube (PIT) technique. Temperature and magnetic-field-dependent resistivity displays a high conductivity and upper critical field H_{c2} generally observed in dense samples. The electronic mass anisotropy $\gamma \approx 1.3 \pm 0.15$ predicts some texturing in the wire. Our data on transition temperature T_C, H_{c2}, and both magnetic and transport critical current density J_c indicate that MgB_2 can be manufactured in a wire form using a PIT technique and required engineering J_c can be achieved on further optimization. © *2001 American Institute of Physics.*
[DOI: 10.1063/1.1403278]

The recent discovery[1] of superconductivity at 39 K in MgB_2 has generated renewed interest in intermetallic superconductivity. Various physical properties appear to be competitive with well-established A15 conductors used for magnet systems. One of the advantages with MgB_2 is its application at a higher temperature (20–30 K) region, where cryogen free cooling systems can be used in magnetic and nuclear magnetic resonance and other magnet systems. However, unlike conventional superconductors, the fabrication of an actual composite conductor of MgB_2, that shows uniform properties over a large length of a wire form remains a challenge, mainly due to the ceramic and brittle nature such as high-T_C superconductors, and high pressure synthesis method due to high reactivity with O_2. This suggests that embedding MgB_2 in a metal sheath by a powder-in-tube (PIT) technique, generally used for fabrication of Ag-sheathed Bi-2223 superconducting tapes, could be a potential solution for manufacturing long length wires for high current applications. The recent reports on fabrication of MgB_2 wires by PIT techniques[2] using either Ag or Cu sheath and MgB_2 strands[3] by directly filling Nb-lined, monel tubes with commercially available MgB_2 powders followed by drawing, rolling into tapes, and sintering[4] were the first steps to put the MgB_2 conductor into applications.

In this letter, we present a very similar technique used for fabrication of Bi-2223/Ag-sheathed tapes by the PIT method to manufacture MgB_2 round wires that are generally demanded for magnet fabrications. We show that these round wires demonstrate remarkably low resistance, moderately high critical current density J_c, and higher critical fields H_{c2} without optimization. Our results strongly suggest that high-quality MgB_2 wires can be successfully fabricated at high T.

MgB_2 composite wires were synthesized by the PIT technique. Stoichiometric composition of high purity Mg and B powders were mixed thoroughly and filled into a Ta tube of 6 mm diameter, and finally inserted into a Cu tube of 10 mm diameter to prevent reaction between Cu and Mg. The composite tube was swaged and drawn into a wire of 2.1 mm diameter with an intermediate annealing. Finally, the wires were sintered at 900 °C–950 °C for 2–5 h in Ar without high pressure. A similar technique was used to synthesize MgB_2 in a Cu tube without Ta as a buffer (named as MgB_2–Cu). X-ray diffraction reveals that the MgB_2 phase is present in the core region without any impurities, especially when Ta is used as a buffer layer. The details of the microstructure are reported elsewhere.[5] A small piece of round wire of diameter 2.1 mm and length 3 mm was used for all measurements. High-resolution transport measurements were carried out using standard four-probe ac technique ($I = 1$ mA and $f = 17$ Hz). The transport J_c was measured using a current reversal dc technique. The magnetization measurements were performed in a superconducting quantum interference device magnetometer.

Figure 1 shows the magnetic field dependence of resistivity of MgB_2–Ta wire. The midpoint value of normal-state resistivity of the superconducting transition at $H = 0$ is 38.3 K. A similar T_C value of 38.4 K (with $\Delta T_C \approx 0.6$ K) was determined from the magnetization measurements as shown in the lower inset of Fig. 1. The dense bulk extracted from the core of the wire shows sharp transition with significantly low transition width (shown as dashed lines in the inset). The normal-state resistivity curve shown in the top inset of Fig. 1 follows roughly usual T^2 temperature dependence over the entire temperature region between 300 K and the onset of T_C as obtained for dense polycrystalline samples.[6,7] We mention that the resistance due to the metallic sheath is subtracted from the wire resistance and the actual conductor resistance is normalized to the bulk sample extracted from inside the wire. No magnetoresistance was observed from 300 K to T_C in these wires and this is consistent with previous results on polycrystalline samples,[6,7] but different from the another report.[8] Although no significant broadening of the transition was observed at low fields, a considerable resistive broadening was seen at low temperatures at higher fields, which may be caused by the flux–flow effects at high magnetic fields. This becomes very clear in the Arrhenius plot of resistivity

[a]Electronic mail: pradhan@istec.or.jp

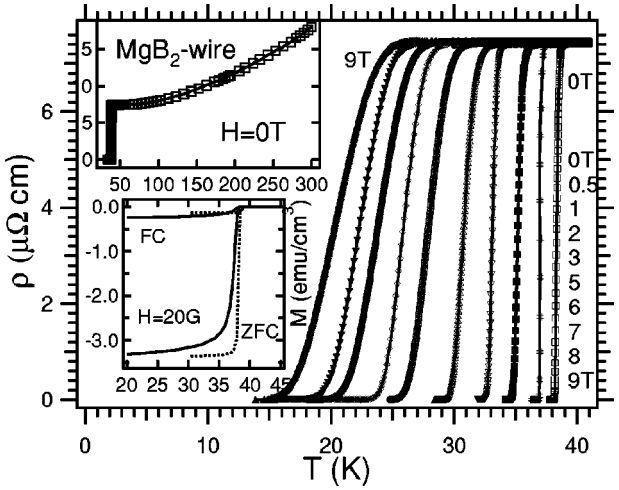

FIG. 1. Temperature-dependent electrical resistivity of MgB_2–Ta wire in applied fields $H=0$, 0.5, 1, 2, 3, 5, 6, 7, 8, and 9 T (right-hand side to left-hand side) for H parallel to the wire length is shown. The top inset shows the T dependence of the normal-state resistivity of the same wire for $H=0$ T. The bottom inset shows the T dependence of the field-cooled (FC) and zero-FC magnetization of the same wire (solid lines) and the dense bulk (dashed lines) extracted from the core of the wire.

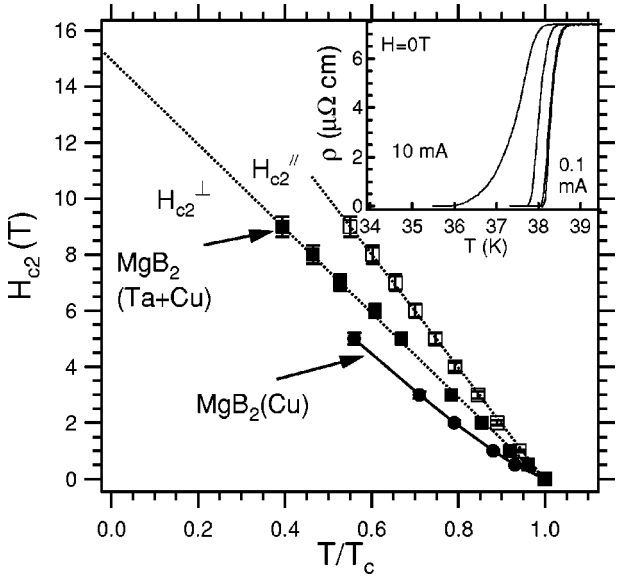

FIG. 3. The upper critical fields H_{c2} as a function of reduced temperature T/T_C for MgB_2–Ta and MgB_2–Cu wires are shown. The inset shows the resistive transition of MgB_2–Ta wire for different excitation currents $I=0.1$, 1, 3, and 10 mA in zero field.

shown in Fig. 2 that shows large slopes at higher field values indicating the thermal activation of the dissipation. However, the role of layered structure in MgB_2 in causing such dissipation is not known yet. The other option is to consider the impurity effects due to small amount of MgO in the interfaces. The resistive behavior of MgB_2 is significantly similar to that of intermetallic Borocarbide and A15 compounds.

In order to compare the resistive broadening in fields, we plot the upper critical field H_{c2} as function of reduced temperature (T/T_C) in Fig. 3 for MgB_2–Ta and MgB_2–Cu wires. We mention here that the MgB_2–Cu (without Ta as a buffer in between MgB_2 and Cu) has a $T_C \sim 38$ K with $\Delta T_C = 1.2$ K. The slope of the $H_{c2}-T$ curve yields $dH_{c2}/dT \approx -0.39$, which gives $H_{c2}(0)=15$ T and $H_{c2}(4.2\,\mathrm{K})=13.2$ T for MgB_2–Ta wire. These values are almost half the value of $H_{c2}(0)$ for Nb_3Sn. In this extrapolation method, we have considered only the linear region above 2 T in the phase diagram, because a small but definite positive curvature in H_{c2} was observed in the low-field region in both samples, similar to the borocarbides. Furthermore, it is remarkable to note that the T_C is found to be very much current-induced due to the self-field effect as shown in the inset of Fig. 3. The pronounced leg feature indicates a large dissipation that is similar to the application of a magnetic field. Hence, H_{c2} measurements were performed using a current as low as 1 mA. Using the estimation of $H_{c2}(0)=15$ T, the coherence length $\xi_0=[\phi_0/2\pi H_{c2}(0)]^{0.5}$ is found to be ~ 4.5 nm and consistent with the bulk samples.[9] In order to evaluate the electronic mass anisotropy, $\gamma = H_{c2}^{\parallel}/H_{c2}^{\perp}$, we measured both $H_{c2}^{\perp}$ (H perpendicular the wire length) and $H_{c2}^{\perp}$ (H parallel to the wire length) in MgB_2–Ta for both perpendicular and parallel fields, respectively, and shown in Fig. 3. In contrast to high-T_C layered Bi-2223/Ag multifilamentay tapes,[10] γ is $\sim 1.3 \pm 0.15$ in MgB_2–Ta wire, which is almost half of the value of Bi tapes and less than the c-axis-oriented thin film,[11] aligned MgB_2 bulk,[12] and much less than $Mg^{11}B_2$ polycrystalline sample.[13] However, this value does not reflect the actual value of γ, rather indicates that there remain some misoriented grains whose field component is closer to $H_{c2}^{\perp}$ (or $H_{c2}^{\perp c}$). This shows that the wires are textured to some extent and further optimization can yield highly textured wires for real applications, although enhancing the density of MgB_2 in the wire core remains the best option to achieve the largest J_c. However, such a low value of γ can have a serious consequence on reducing transport J_c.

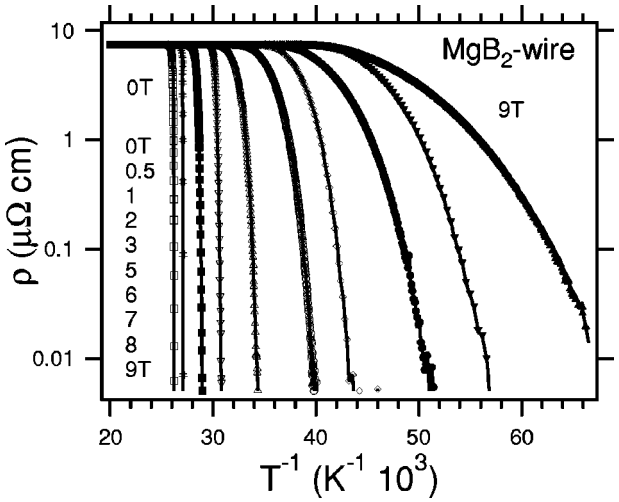

FIG. 2. The Arrhenius plot of resistivity curves at various fields 0 to 9 T (left-hand side to right-hand side) that show large broadening at higher fields is shown.

Figure 4 presents data on both magnetic and transport J_c of MgB_2–Ta wire for magnetic fields applied parallel to the wire length. The dashed lines with symbols are J_c values extracted from the direct transport measurements of the current–voltage curves at a fixed T and H. The solid lines are J_c values deduced from the magnetization loops using Bean's model. The transport J_c values (limited to only ~ 320 A/cm^2 due to local heating effects) are consistent with that of magnetization if extrapolated to the low-field region.

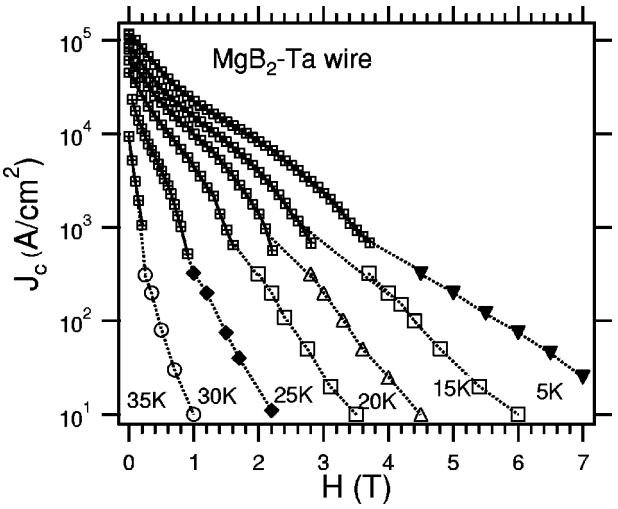

FIG. 4. The critical current density J_c as a function of applied magnetic field at $T=5$, 15, 20, 25, 30, and 35 K of MgB_2–Ta wire is shown. The symbols with solid lines are the magnetic J_c of the wire parallel to the wire length. The symbols with dashed lines are the transport J_c.

Two significant observations are recorded. First, magnetic J_c decays approximately exponentially above a characteristic plateau in field dependent J_c curve of the self-field region and may be related to the penetration field, especially at a low temperature. Second, the transport J_c is higher than the magnetic one at a fixed H and T in the high-field region and can be understood in terms of criteria fixed for two independent experiments. However, the overall J_c values both from transport and magnetization measurements are lower than that of MgB_2 strands.[3] Moreover, the wires fabricated through *in situ* reaction by a PIT technique have $\sim 25\%$ lower density than the dense bulk prepared by high pressure synthesis.[2,5] Hence, the effective radius of the wire R_{eff} is less than the actual radius R while calculating using Bean's model defined for magnetic[2] J_c as $J_c(H)=3/2(\Delta M/R)$. Consequently, J_c is reduced by 25% of the actual value for the wire. This is mainly due to lower density arising from some scattered porous MgB_2 matrix in the wire. We note that the extracted dense MgB_2 bulk from the core the wire produces comparable J_c values to strands. This suggests many scopes to enhance the flux pinning in the wire by optimizing the fabrication process. The misorientation and weak connectivity between domains seem to limit J_c although not as severe as high-T_C superconductors. We mention here that although weak-link phenomenon may not be a reason for low J_c in MgB_2 as reported,[14] the link between the domains due to poor density inside the wire remains a primary concern and needs to be addressed further.

In conclusion, our transport and magnetization results on MgB_2 suggest that embedding MgB_2 in a copper sheath with Ta as a buffer layer by the standard PIT technique could be a potential solution to attain long length flexible MgB_2 superconducting wires. Further optimization and preparation sequence of the conductor can result in required properties for applications. At present, the most important requirement for high J_c is to enhance the density of the MgB_2 matrix of the wire.

[1] J. Nagamatsu, N. Nakagawa, T. Muranaka, Y. Zenitani, and J. Akimitsu, Nature (London) **410**, 63 (2001).
[2] B. A. Glowacki, M. Majoros, M. Vickers, J. E. Evetts, Y. Shi, and I. McDougall, Semicond. Sci. Technol. **14**, 193 (2001).
[3] P. C. Canfield, D. K. Finnemore, S. L. Bud'ko, J. E. Ostenson, G. Lapertot, C. E. Cunningham, and C. Petrovic, Phys. Rev. Lett. **86**, 2423 (2001).
[4] M. D. Sumption, X. Peng, E. Lee, M. Tomsic, and E. W. Collings, cond-mat/0102441 (2001).
[5] Y. Feng, Y. Zhao, A. K. Pradhan, L. Zhou, P. X. Zhang, and N. Koshizuka (unpublished).
[6] Y. Takano, H. Takeya, H. Fujii, H. Kumakura, T. Hatano, K. Tokano, H. Kito, and H. Ihara, Appl. Phys. Lett. **78**, 2914 (2001).
[7] W. N. Kang, C. U. Jung, H. P. Kim, M. Park, S. Y. Lee, H. Kim, E. Choi, K. H. Kim, M. S. Kim, and S. I. Lee, cond-mat/0102313 (2001).
[8] D. K. Finnemore, J. E. Ostenson, S. L. Bud'ko, G. Lapertot, and P. C. Canfield, Phys. Rev. Lett. **86**, 2420 (2001).
[9] K.-H. Muller, G. Fuchs, A. Handstein, K. Nenkov, and D. Eckert (unpublished).
[10] A. K. Pradhan, Y. Feng, Y. Wu, K. Nakao, N. Koshizuka, P. X. Zhang, L. Zhou, and C. S. Li, J. Appl. Phys. **89**, 3861 (2001).
[11] S. Patnaik, L. D. Cooley, and D. C. Larbalestier, cond-mat/0104562 (2001).
[12] O. F. de Lima, R. A. Riberio, M. A. Avila, C. A. Cardoso, C. U. Jung, and S.-I. Lee, cond-mat/0103179 (2001).
[13] F. Simon, J. Janossy, T. Feher, F. Muranyi, S. Garaj, L. Forro, C. Petrov, S. L. Bud'ko, G. Lapertot, V. G. Kogan, and P. C. Canfield, cond-mat/0104557 (2001).
[14] D. C. Larbalestier, M. Rikel, L. D. Cooley, A. A. Polynskii, J. Y. Jiang, S. Patnaik, X. Y. Cai, D. M. Feldmann, A. Gurevich, C. B. Eom, E. E. Hellstrom, R. J. Cava, K. A. Regan, and M. Haas, Nature (London) **410**, 186 (2001).