High transport critical current density obtained for Powder-In-Tube-processed MgB$_2$ tapes and wires using stainless steel and Cu-Ni tubes

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MgB$_2$ tapes and wires were fabricated by the Powder-In-Tube method. Stainless steel and Cu-Ni tubes were used as sheath materials, and no heat treatment was applied. The tapes made of stainless steel showed transport critical current density $J_c$ of about 10,000A/cm$^2$ at 4.2K and 5T. A high $J_c$ of about 300,000A/cm$^2$ was obtained by extrapolating the $J_c$-B curves to zero field. Multifilamentary(7-core) MgB$_2$ wire was successfully fabricated using Cu-Ni tubes. For both tapes and wires the grain connectivity of MgB$_2$ was as good as a high-pressure sintered bulk sample. However, the $J_c$ of the Cu-Ni sheathed wire was lower than the stainless steel sheathed tape due to the lower packing density of MgB$_2$.

The recent discovery of the 39K superconductivity in MgB$_2$\cite{1} aroused much interest from researchers, not only in basic physics, but also in the field of applied superconductivity. The much higher $T_c$ of MgB$_2$ than that of conventional metallic superconductors let researchers expect that MgB$_2$ can be used at elevated temperatures as a conductor of a cryogen-free magnet. Experiments on MgB$_2$ bulks and tapes indicate no weak coupling of grains and that grain alignment is not required to obtain large current transfer across the grains\cite{2-4}. This is very advantageous compared to high-$T_c$ oxide superconductors where grain alignment is essential to improve grain coupling and to obtain high transport $J_c$ values. For high-$T_c$ oxide superconductors, researchers have developed special techniques in order to improve grain connectivity. In the case of MgB$_2$, however, we can expect high transport currents without any special technique.

For practical applications of superconductors, such as magnets and cables, we have to develop tapes or wires. Several research groups have already started the fabrication of tapes and wires using MgB$_2$. Canfield et al. first fabricated dense MgB$_2$ wires by exposing tungsten-core boron filaments to Mg vapor and obtained good superconducting properties\cite{5}. However, most MgB$_2$ tapes and wires are now fabricated by so-called Powder-In-Tube method\cite{6-9}. MgB$_2$-reacted powder or a mixture of Mg and B powder with stoichiometric composition is packed into various metal tubes. The powder/metal composite tubes are cold-worked into tapes and wires, and these tapes and wires are then heat treated at 900-1000°C for several hours. Thus, we have to use sheath materials that are not reactive with Mg and B at this temperature range. The metal tubes we can use as sheath materials are limited, as indicated by Jin et al\cite{7}. Recently, Grasso et al. fabricated tapes using MgB$_2$ powder and a Ag, Cu or Ni tube and obtained high transport currents without any heat treatment\cite{10}. This process is very attractive from the aspect of practical applications because a fabrication process including no heat treatment leads to much reduction of fabrication costs of wires and tapes. Furthermore, we can use various metals as sheath materials. Because higher $J_c$ is expected for a harder sheath material, we selected stainless steel and Cu-Ni tubes as sheath materials and fabricated MgB$_2$ tapes and wires.

Commercially available MgB$_2$ powder(Alfa-Aesar) was tightly packed into stainless steel tubes and Cu-10wt%Ni tubes of 7-10cm in length. This packing process was carried out in air. The inner and outer diameters of the tubes were 4mm and 6mm for stainless steel tubes and 10mm and 14mm for Cu-Ni tubes, respectively. These tubes were cold rolled into rectangular rods of about 2mm in size using groove rolling and then cold rolled into tapes. The final size of the tapes was about 4mm in width and about 0.5mm in thickness. The typical thickness of the MgB$_2$ layer was 0.25mm. Multifilamentary wires were fabricated using Cu-Ni tubes. Groove rolled rods made of Cu-Ni tubes were cold-drawn to wires with a diameter of 2mm, and seven wires were bundled and inserted into a Cu-Ni tube and cold-worked into wire again. The final size of this 7-core wire was 2mm. All the tapes and wires were first rolled and then cold-worked into final size without any breakage. Figure 1 shows the cross sections of stainless steel sheathed tape and Cu-Ni sheathed 7-core wire. For the scanning electron microscopy(SEM) and X-ray diffraction analysis rectangular samples were cut from the tapes and sheath materials were removed. The MgB$_2$ layer...
was rigid and the fractured cross section was shiny. Figures 2(a) and (b) show the fractured and polished cross sections respectively of the MgB$_2$ layer in the stainless steel sheathed tape. Densely stacked MgB$_2$ was observed in the fractured cross section. The grain size of MgB$_2$ after the cold rolling was sub-micron, which was comparable to the particle size of the starting powder, indicating that no fracture of MgB$_2$ grains occurred during the cold working. X-ray diffraction analysis of the MgB$_2$ layer indicates that the main phase was MgB$_2$ with random grain orientation. However, small peaks corresponding to MgO were observed.

These tapes and wires were cut into short pieces of 3-4cm in length, and critical current $I_c$ was measured. $I_c$ was measured by a four-probe resistive method at 4.2K in magnetic fields. Current leads and voltage taps were directly soldered to the sheath materials of the tapes and wires. A magnetic field was applied parallel to the tape surface. The criterion of $I_c$ definition was 1µV/cm. For current $I < I_c$ no voltage appeared. However, above $I_c$ a rapid increase of voltage was observed, indicating that the superconducting-to-normal transition was fairly sharp. Critical current density $J_c$ was obtained by dividing $I_c$ by the cross sectional area of the MgB$_2$ core. Figure 3 shows $J_c$ vs. magnetic field curves of the mono-core MgB$_2$/stainless steel) tape, mono-core MgB$_2$/(Cu-Ni) tape and 7-core MgB$_2$/(Cu-Ni) wire at 4.2K. For comparison the $J_c$-B curve of the MgB$_2$ bulk prepared by the high pressure sintering and measured by the magnetization method is also shown in the figure[4]. All the tapes and wire show the same field dependence of $J_c$, and this field dependence of $J_c$ is exactly the same as that of the high-pressure sintered bulk. This suggests that the connectivity of MgB$_2$ grains in all the tapes and wire is as good as the grain connectivity in the high-pressure sintered sample. The $J_c$ of 7-core MgB$_2$/(Cu-Ni) wire was somewhat lower than that of the MgB$_2$/(Cu-Ni) tape. This should be attributed to the irregular cross section and sausaging of the MgB$_2$ filaments in the 7-core wire. High $J_c$ values were obtained for MgB$_2$/stainless steel) tape. $J_c$ values of MgB$_2$/stainless steel) were much higher than those of the MgB$_2$/(Cu-Ni) tape and wire although the cross sectional area reduction of MgB$_2$/stainless steel) tape by the cold working is smaller than that of the MgB$_2$/(Cu-Ni) tape and wire. This can be explained by the difference of packing density of MgB$_2$ between the two samples. Because of the higher hardness of the stainless steel, stress applied to the MgB$_2$ in the stainless steel sheath during the cold rolling was higher than that in the Cu-Ni sheath. Thus, higher packing density of MgB$_2$ was obtained for MgB$_2$/stainless steel) tape. $J_c$ in 5T of MgB$_2$/stainless steel) tape was about 10,000A/cm$^2$ which was one of the highest transport $J_c$ values ever reported for MgB$_2$ tapes and wires. This $J_c$ is equal to or higher than that of the high-pressure sintered bulk. Below 5T precise $J_c$ measurement was difficult for MgB$_2$/(stainless steel) tape because the heat generation at the current contacts increased the temperature of the sample and the tape was sometimes burned out immediately after the applied current exceeded $I_c$. Therefore we extrapolated the $J_c$-B curve of the MgB$_2$/(stainless steel) tape to a lower field, referring to the $J_c$-B curves of the high-pressure sintered bulk sample. The extrapolation of the $J_c$-B curve suggests that $J_c$ at 0T was as high as 300,000A/cm$^2$. However, due to the poor $J_c$ tolerance against magnetic field, the $J_c$ values in magnetic fields of our MgB$_2$/stainless steel) tapes are still below the practical level. Because the packing density of MgB$_2$ layer is already high as shown in Fig. 1. $J_c$ enhancement by increasing the packing density is limited for our sample. Thus, introduction of pinning centers is required to obtain substantial increase of $J_c$. The introduction of pinning centers is also effective in reducing the sensitivity of $J_c$ to a magnetic field.

In summary, we fabricated MgB$_2$/stainless steel) and MgB$_2$/(Cu-Ni) tapes by the PIT method without any heat treatment. MgB$_2$ grain connectivity for both tapes was as good as that of the high-pressure sintered bulk. $J_c$ of 10,000A/cm$^2$ at 4.2K and 5T was obtained for the MgB$_2$/(stainless steel) tape. Extrapolation of the $J_c$-B curve suggests the high $J_c$ of ~30,000A/cm$^2$ at 4.2K and zero field. Such high $J_c$ values can be explained by the high packing density of MgB$_2$ associated with the hard sheath material. MgB$_2$/(Cu-Ni) multifilamentary wires were also successfully fabricated by the PIT method without any heat treatment.

References
1. J. Nagamatsu, N. Nakagawa, Y. Zenitani and J. Akimitsu, Nature 410(2001)63.
2. D.C. Larbalestier, M.O. Rikel, L.D. Cooley, A.A. Polyanskii, J.Y. Jiang, S. Patnaik, X.Y. Cai, D.M. Feldmann, A. Gurevichi, A.A. Squitieri, M.T. Naus, C.B. Ecom, E.E. Hellstrom, R.J. Cava, K.A. Regan, N. Rogado, M.A. Hayward, T.He, J.S. Slusky, P. Khalifah, K. Inumaru and M. Haas, Nature 410(2001)186.
3. M. Kambara, N. HariBabu, E.S. Sadki, J.R. Cooper, H. Minami, D.A. Cardwell, A.M. Campbell and I.H. Inoue, Supercond. Sci. Technol. 14(2001)L5.
4. H. Kumakura, Y. Takano, H. Fujii and K. Togano, submitted to Physica C.
5. P.C. Canfield, D.K. Finnemore, S.L. Bud’ko, J.E.
Figure captions

Fig. 1. Cross sectional view of mono-core MgB$_2$ tape (stainless steel sheath) and 7-core MgB$_2$ wire (Cu-Ni sheath).

Fig. 2. Scanning electron micrographs of (a) fractured and (b) polished MgB$_2$ layers in stainless-steel-sheathed MgB$_2$ tape.

Fig. 3. Transport $J_c$ vs. field curves at 4.2K of Ni-Cu sheathed mono-core tape, Cu-Ni sheathed 7-core wire and stainless-steel-sheathed mono-core tape. $J_c$ values of high-pressure sintered bulk sample estimated by the magnetization method are also shown in the figure. Extrapolated $J_c$ for the stainless steel sheathed tape is indicated by the dotted line.
Fig. 3