Direct jointing of Ba–Sr–Ca–Cu–O superconducting glass-ceramics by welding

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Superconducting glass-ceramics in the Bi–Sr–Ca–Cu–O (BSCCO) system were found to be successfully joined together by welding with an LNG-O_2 flame. Two edge portions of the glass-ceramics to be joined were set in close contact to each other and melted by the high-temperature flame. After the welding, the joined portion was annealed with a soft flame, so that no crack formed in the product. The directly joined product was converted into a superconductor with $T_c \simeq 90$ K by a postheating at ~830 °C. Its critical current density J_c, was almost the same as the of the original glass-ceramic. This technique is very important for fabrication of large-sized superconducting apparatus such as current leads or magnetic shields. © *1995 American Institute of Physics.*

Electrical current power leads are expected to be one of the most important applications of high-T_c superconductors (HTS).[1–5] We have been studying a superconducting bushing apparatus which is composed of long and slender HTS rods or pipes for the current leads and for the external magnetic shielding.[4,5] Abe *et al.* in our group developed a simple fabricating method of fine HTS rods[6] or pipes[7] in the Bi–Sr–Ca–Cu–O (BSCCO) system by using a glass-ceramic processing, which involves casting of the melt in low viscosity and reheating the forming product.

For a practical use, large-sized HTS-bushing apparatus is required. To fabricate the large-sized leads or shields, joining between one HTS and another HTS is one of the most important technologies. Mechanical joining of HTS is far from technical use for shielding the external flux. A welding process using a flame is one of the most promising candidates for the simple joining because it is expected to have high forming ability into desired shapes. Li *et al.*[8] reported the difficulty of the direct joining of two Bi-based superconducting pillars by welding with an O_2 flame. Their method has a serious problem in the mechanical strength: some cracks tend to appear around the welded region.[9] The present work is the first successful demonstration of direct welding of BSCCO superconducting glass-ceramics by melting annealing using a liquid natural gas (LNG)-O_2 flame.

Commercial powders of guaranteed reagents such as Bi_2O_3, $SrCO_3$, $CaCO_3$, and CuO were mixed to obtain the nominal composition of $Bi_2Sr_2Ca_1Cu_2O_x$. The mixture of the given powders was melted in a platinum crucible at 1150 °C for 15 min. By following the technique in a previous paper,[6] the melt was cast and quenched into a silica glass tube of an inner diameter of 2 mm. After the outer glass tubes were removed, the resultant as-cast precursor rod specimens were reheated at 830 °C for 50 h in air, and subsequently the specimens were taken out from the furnace to be rapidly cooled to room temperature, resulting in the formation of rod-shaped BSCCO glass-ceramics.

The resultant glass-ceramic was cut into two rod specimens. The cut surface of each specimen was heated simultaneously by using a LNG-O_2 flame. When the cut surfaces were partially melted, two specimens were joined by quickly putting the molten faces against each other. Subsequently, the welded portion in the unified specimen was annealed sufficiently (for ~5 min) with the soft flame of 900–950 °C, and then it was slowly cooled. The successfully joined specimen was reheated at 830 °C for 50 h in air. After the heat treatment, the specimen was taken out of the furnace and was rapidly cooled to room temperature.

Figure 1 shows powder XRD (Cu *Kα*; 40 kV, 20 mA) patterns for the original BSCCO glass-ceramic and for the

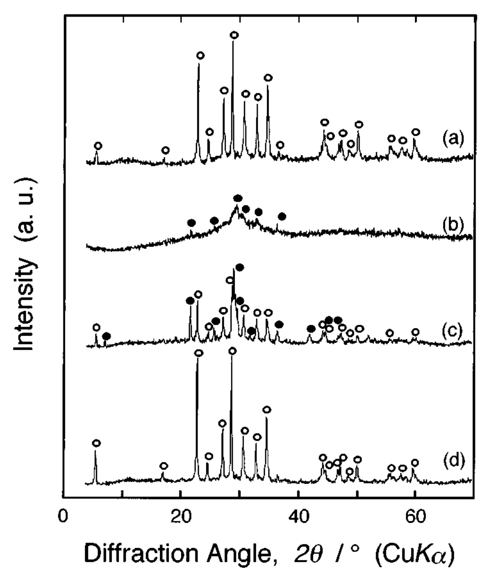

FIG. 1. Powder XRD (Cu *Kα*) patterns for the original BSCCO glass-ceramic and for the welded regions in the joined specimens. (a) the original BSCCO glass ceramic, (b) the as-welded portion, which was allowed to cool down to ambient temperature after joining, (c) the welded portion in the specimen annealed by using a soft flame after joining and (d); the welded portion in the specimen postheated at 830 °C for 50 h. (○); $Bi_2Sr_2Ca_1Cu_2O_x$ (2212 phase), (●); $Bi_2Sr_2CuO_x$ (2201 phase).

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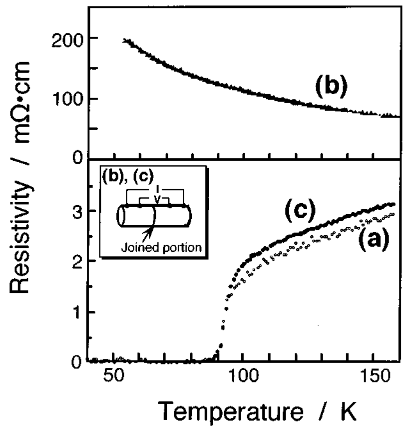

FIG. 2. Temperature dependence of resistivities of (a) the original BSCCO glass-ceramic before joining, (b) the as-joined specimen, and (c) the specimen postheated at 830 °C after joining. The inset shows the portions of the electrodes attached to the joined specimens, (b) and (c).

welded regions, which may include their environs, of the joined specimens. When the joined specimen was not annealed over the flame, some cracks tended to appear around the interface between the welded portion and the original one, as reported by Li *et al.*[8] The as-welded portion was comprised of glassy phase with a small amount of $Bi_2Sr_2CuO_x$ (2201) crystals as shown in Fig. 1(b). In this case, the cracks tend to form in the glassy phase during the cooling. On the other hand, the specimen annealed sufficiently with the soft flame after the welding consists of a large amount of the crystalline phases such as 2201 and $Bi_2Sr_2Ca_1Cu_2O_x$ (2212) and a very small amount of the glassy phase [Fig. 1(c)]. No serious gaps and/or cracks were seen around the joined portion. The flame annealing is an important process for fabrication of joined products. As seen in Fig. 1(d), the specimen when postheated at 830 °C contains a large amount of the 2212 phase in the welded region.

Figure 2 shows resistivity versus temperature curves: (a) for the original BSCCO glass ceramic before joining, (b) for the as-joined specimen, and (c) for the annealed specimen postheated at 830 °C after joining. The electrodes were attached to the specimens at the portions as shown by the inset in Fig. 2. The as-joined product did not show superconductivity as shown in Fig. 2(b). On the other hand, the postheated specimen showed $T_{c(0)}=89$ K [Fig. 2(c)], which is almost the same as that of the original BSCCO glass-ceramic [Fig. 2(a)]. The specimen (c) in Fig. 2 showed a critical current density (J_c) of $155\ \mathrm{A\,cm^{-2}}$ at zero magnetic field. This value is almost the same as that of the original glass ceramic, specimen (a) in Fig. 2 ($150\ \mathrm{A\,cm^{-2}}$).

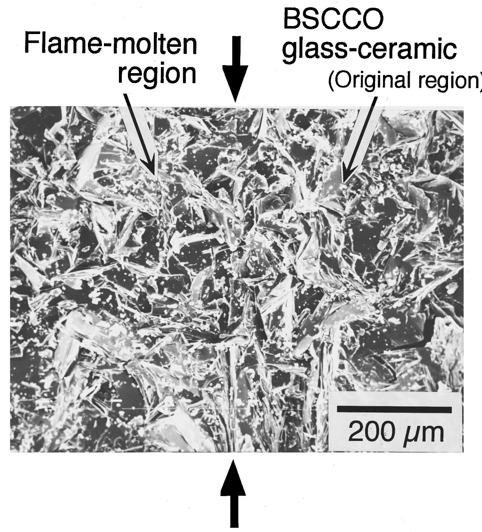

FIG. 3. A SEM photo of the fracture face around the joined boundary of the postheated specimen.

Figure 3 shows a SEM photo of the fracture face around the joined boundary of the postheated specimen. It is difficult to find the joined boundary because two specimens were unified completely by melting. No serious cracks or other defects are seen around the joined boundary. The irregular face shows that a large amount of platelike crystals with large sizes ($\simeq 100\ \mu$m) were precipitated in the welded region by the postheating. With this morphology it is not surprising that a J_c value of the joined specimen is as high as that of the original one.

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[1] J. R. Hull, Cryogenics **29**, 1116 (1989).
[2] J. L. Wu, J. T. Dederer, P. W. Eckels, S. K. Singh, J. R. Hull, P. B. Poeppel, C. A. Youngdahl, J. P. Singh, M. T. Lanagan, and U. Balachanran, IEEE Trans. Magn. **27**, 1861 (1991).
[3] K. Ueda, T. Bohno, K. Takita, K. Mukae, T. Uede, L. Itoh, M. Mimura, N. Uno, and T. Tanaka, IEEE Trans. Appl. Supercond. **3**, 400 (1993).
[4] K. Nakamura, Y. Abe, E. Inukai, and M. Sone, IEEE Trans. Appl. Supercond. **3**, 413 (1993).
[5] K. Nakamura, Y. Abe, E. Inukai, and M. Sone, Appl. Phys. Lett. **64**, 2019 (1994).
[6] Y. Abe, H. Hosono, M. Hosoe, J. Iwase, and Y. Kubo, Appl. Phys. Lett. **53**, 1341 (1988).
[7] Y. Abe, H. Hosono, W.-H. Lee, M. Hosoe, K. Nakamura, and E. Inukai, J. Mater. Res. **8**, 1 (1993).
[8] B. Li, X. Gao, and W. Chen, J. Less-Common Met. **164&165**, 660 (1990).
[9] J. Cai, X. M. Xie, L. Baoshun, X. X. Huang, T. G. Chen, and J. K. Guo, Supercond. Sci. Technol. **5**, 599 (1992).