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High Magnetic Field Properties of Critical Current Density in $Y_1Ba_2Cu_3O_{7-\delta}$ Coated Conductor Fabricated by Improved TFA-MOD Process

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***Abstract*—Current transport characteristics in a $Y_1Ba_2Cu_3O_{7-\delta}$ (YBCO) coated conductor fabricated by a trifluoroacetates-metal organic deposition (TFA-MOD) process were investigated over a wide range of temperature and magnetic field up to 25 T. Improved TFA-MOD process was successfully introduced for the better property of critical current density, J_c, at high magnetic fields. The J_c and critical current, I_c, values of multi-coated film with 1.2 μm thickness and 1 cm width were 2.1 MA/cm^2 and 251 A at 77 K in self-field. Additionally, the superior J_c properties remained even at high magnetic fields over 20 T and lower temperature, e.g. J_c value at 30 K in 25 T was 1.0 MA/cm^2. The J_c value was about 2.5 times higher than those of previous TFA-MOD process at wide range of magnetic field. Moreover, the statistical distribution of J_c in the conductor was also estimated within a framework of the percolation model. The uniformity in the YBCO coated conductor was improved by optimizing the TFA-MOD process.**

***Index Terms*—High-temperature superconductors, magnetic field effects, superconducting filaments and wires, superconducting materials measurements.**

I. Introduction

YBCO coated conductor has been extensively researched and developed for electric power applications. Several fabrication processes for each layer of metallic substrate, buffer layer, cap layer, YBCO layer and stabilizing layer were proposed for commercial manufacturing [1]–[4]. The metal-organic deposition process using trifluoroacetate (TFA-MOD process) is one of the most promising processes [5], [6], because the solution processing has the advantage of nonvacuum process. Additionally, it is confirmed that critical current density, J_c, over 1 MA/cm^2 at 77.3 K in self-field can be easily obtained by this process reproducibly [5]. However, in order to obtain higher value of J_c, especially at high magnetic fields, further improvement of the fabrication process is required. Moreover, it is important to investigate magnetic field dependence of J_c over wide range of magnetic field and temperature for practical applications such as high field magnets and magnetic energy storage devices [7].

In this work, we experimentally investigated high magnetic field properties of J_c in YBCO coated conductor fabricated by improved TFA-MOD process and estimated the pinning properties based on the percolation model [8] along with the scaling characteristics of pinning force density. Furthermore, we compared the transport characteristics and the pinning properties in the improved TFA-MOD process with those obtained in previous process.

II. Experiment

A. Fabrication of TFA-MOD YBCO Coated Conductor

The specimen is composed of four functional layers, Hastelloy substrate, $Gd_2Zr_2O_7$ buffer layer made by ion beam assisted deposition (IBAD) process, CeO_2 cap layer deposited by RF magnetron sputtering, and YBCO layer made by the TFA-MOD process. The precursor solution for the YBCO film was prepared by dissolving the TFA salts of Y, Ba and fluorine-free Cu. Using the fluorine-free Cu in TFA-MOD process is one of the most effective progresses in high speed process. Moreover, for the improvement of J_c, some conditions of heat treatment such as flow rate of the inlet gas, and water partial pressures were also optimized [9]. In order to make a thicker YBCO film, we applied the multi-coating technique [5]. Using this technique, we obtained a 1.2 μm thick YBCO film. J_c and I_c at 77 K in self-field were 2.1 MA/cm^2 and 251 A/cm-w, respectively.

B. Measurement of $E-J$ Characteristics

In order to measure electric field vs. current density $(E-J)$ characteristics in detail, we made a 360 μm long and 48 μm wide micro-bridge using a laser cutter. An external magnetic field was applied perpendicularly to the conductor surface by use of a superconducting magnet. A hybrid magnet system was used to apply higher magnetic field up to 25 T. The bias temperature was controlled by adjusting both heater power and flow rate of cooling helium gas, and the stability of the temperature was about ± 1 K during the measurement. From the measured

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$E-J$ characteristics, J_c is defined by the electric field criterion of 10 $\mu\mathrm{V/cm}$.

III. Formulation of Transport Characteristics

In our previous work [8], [10], we showed that transport characteristics at arbitrary conditions of temperature, T, and magnetic field, B, can be formulated based on the percolation model along with scaling of pinning. The $E-J$ characteristic is described by using statistical distribution of J_c, as follows:

$$E(J) = \frac{\rho_{FF}}{m+1} J \left(\frac{J}{J_0}\right)^m \left(1 - \frac{J_{cm}}{J}\right)^{m+1}, \quad \text{for } J_{cm} \le J \text{ and } B \le B_{GL} \qquad (1.a)$$

$$= \frac{\rho_{FF}}{m+1} |J_{cm}| \left(\frac{|J_{cm}|}{J_0}\right)^m \left\{\left(1 + \frac{J}{|J_{cm}|}\right)^{m+1} - 1\right\}, \quad \text{for } 0 < J \text{ and } B > B_{GL} \qquad (1.b)$$

$$= 0, \quad \text{for } J < J_{cm} \qquad (1.c)$$

where, J_{cm} is the threshold value of J_c distribution and J_0 corresponds to half value of the distribution width. The power index m is also a numerical parameter characterizing the shape of J_c distribution, ρ_{FF} is the flux flow resistivity, and B_{GL} is the vortex glass-liquid transition field.

It is known that the minimum strength of pinning force density, $F_{pm} \equiv J_{cm} \cdot B$, is scaled on a master curve at wide range of T and B given as follows [10]:

$$F_{pm} = A B_{GL}{}^{\zeta} \left(\frac{B}{B_{GL}(T)}\right)^{\gamma} \left(1 - \frac{B}{B_{GL}(T)}\right)^{\delta}, \qquad (2)$$

where A, ζ, γ and δ are related to the pinning parameters. Critical field B_{GL} is defined when J_{cm} becomes zero.

From the scaling law, the temperature dependence of J_{cm} can be attributed to that of B_{GL}. The temperature dependence is described by the following function [8], [11]:

$$B_{GL}(T) = \frac{b}{1-\nu_p}\left(1 - \frac{T}{T_c}\right) \cdot \left\{1 - \frac{a}{1-\frac{T}{T_c}} + \sqrt{\left(1 + \frac{a}{1-\frac{T}{T_c}}\right)^2 - 4\nu_p \cdot \frac{a}{1-\frac{T}{T_c}}}\right\} \qquad (3)$$

where a, b and ν_p are numerical parameters, and T_c is the critical temperature.

Applying the above mentioned formulae to measured $E-J$ characteristics, J_c distribution and pinning parameters can be determined. Furthermore, transport characteristics at arbitrary conditions of T and B can be predicted by using the numerical parameters [8], [10].

IV. Results and Discussions

Fig. 1 shows measured $E-J$ characteristics at various magnetic fields at (a) 50 K and (b) 30 K. Applying high magnetic field over 20 T, the vortex grass-liquid transition of $E-J$ characteristics is observed at 50 K. Additionally, even at high magnetic fields around 20 T, $E-J$ characteristics behave as vortex glass state at 30 K. These results indicate that the TFA-MOD YBCO coated conductor has a high potential for practical applications in high magnetic field use [7].

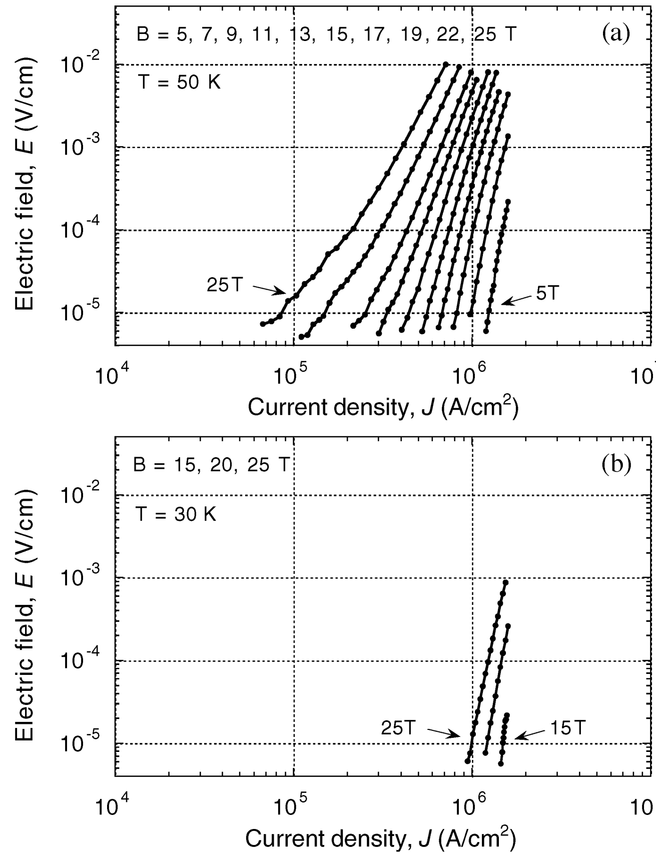

Fig. 1. Magnetic field dependent $E-J$ characteristics at (a) 50 K and (b) 30 K.

Figs. 2(a) and 2(b) show the magnetic field dependence of J_c in both improved- and previous-TFA-MOD process, respectively. The closed symbols denote the experimental results. From the comparison between Fig. 2(a) and Fig. 2(b), it can be seen that J_c obtained by the improved TFA-MOD process is about 2.5 times superior to the previous one in a wide range of magnetic field. For example, J_c over 1 $\mathrm{MA/cm^2}$ is obtained up to 7 T, and 0.1 $\mathrm{MA/cm^2}$ of J_c is remained up to 25 T, at 50 K. Additionally, at lower temperature, 20 K, 60 A/cm-w of I_c is obtained even in 25 T. However, the magnetic field dependence itself is not varied drastically if we compare the properties normalized by the self-field J_c at each temperature.

In order to clarify the difference between the improved- and previous-TFA-MOD YBCO coated conductor, the pinning properties were analyzed from measured $E-J$ characteristics within the framework of the percolation model. Solid lines in Fig. 2 are predicted $J_c - B$ curves for the electric field criterion of 10 $\mu\mathrm{V/cm}$ using (1)to (3). From the quantitative agreements between measured and predicted value, it is confirmed that the prediction based on the present model is useful for the basic design of practical applications.

Fig. 3 shows magnetic field dependence of F_{pm}. The closed symbols are extracted value from measured $E-J$ characteristics, and the lines are predicted properties based on the scaling law of pinning force density. From Fig. 3, the peak height of F_{pm}

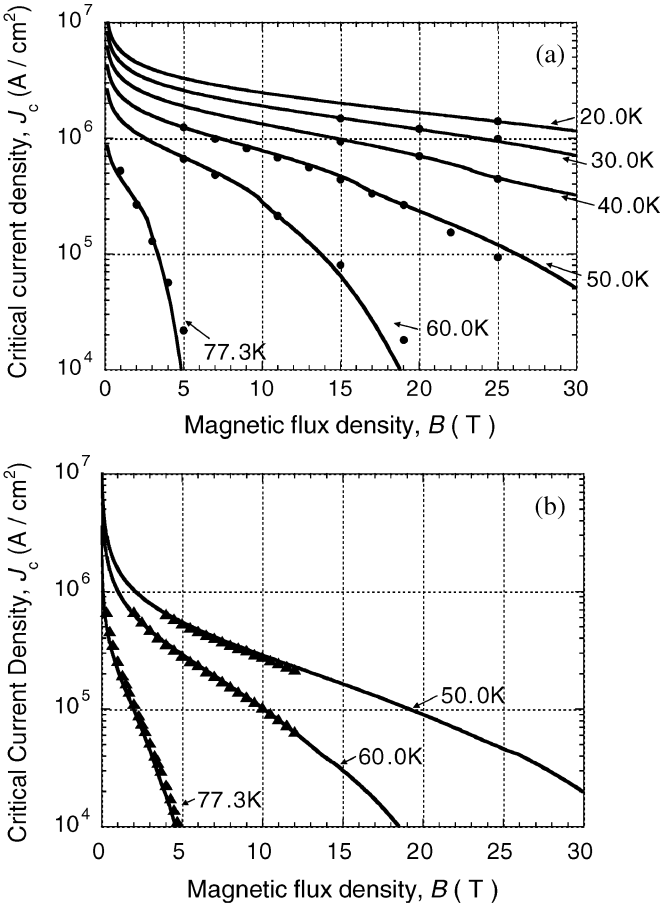

Fig. 2. Magnetic field dependence of J_c at various temperatures in (a) improved- and (b) previous-TFA-MOD process. J_c is defined by $10\,\mu\mathrm{V/cm}$ of electric field criterion. The closed symbols denote the experimental results, whereas the solid lines show predicted curves based on the percolation model.

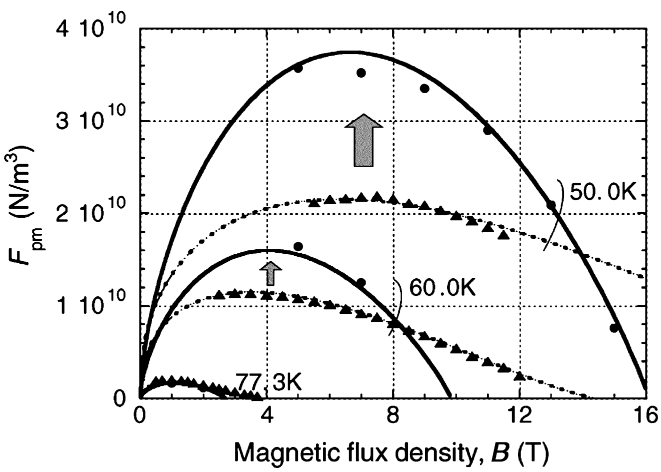

Fig. 3. Magnetic field dependences of the minimum strength of pinning force density, F_{pm}. Solid lines are the predicted properties based on scaling law of F_{pm} in improved TFA-MOD process and dashed lines are those of previous process.

in improved process is higher than those of previous process. On the other hand, it seems that the B_{GL} and the shape of the F_{pm} are also different. However, it is not clear the difference is significant or not, because the experimental results are limited for high field region at this moment.

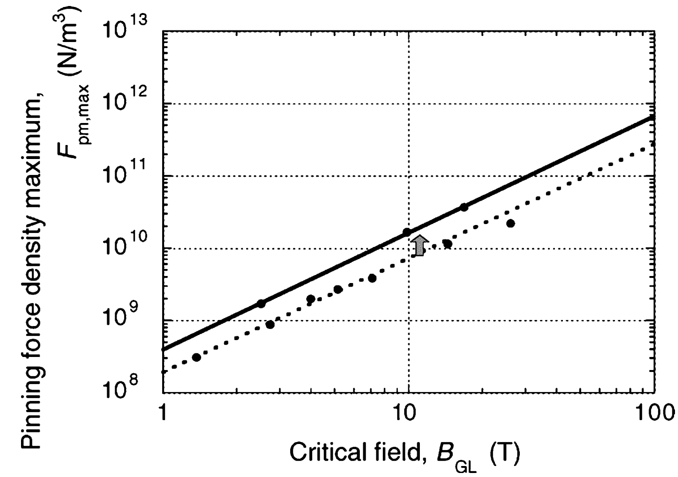

Fig. 4. Critical field dependence of pinning force density maximum, $F_{pm,max}$. Solid line and dashed line stand for the approximated properties in improved- and previous-TFA-MOD process, respectively.

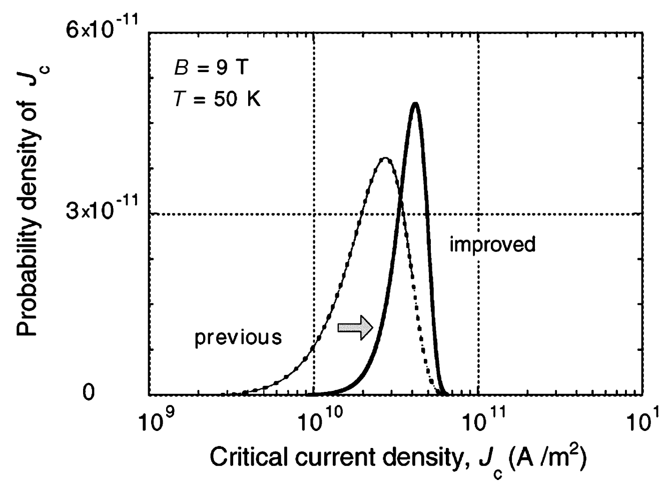

Fig. 5. Statistic distribution of J_c in YBCO coated conductor fabricated by improved (solid line) and previous (dashed line) TFA-MOD process.

The critical field, B_{GL}, dependences of the peak height value of F_{pm} denoted by $F_{pm,max}$, is shown in Fig. 4. The closed symbols are estimated values from the magnetic field dependences of F_{pm} as shown in Fig. 3, and lines are approximate properties. $F_{pm,max}$ increases in the improved process, although the slope is almost same. This result suggests that the effective cross-sectional area, i.e., uniformity in the YBCO layer is improved.

Fig. 5 shows the comparison of statistical distribution of J_c obtained from the analysis. The minimum J_c value in the J_c distribution obtained by the improved TFA-MOD process is about 2.5 times higher than that in previous process. This result corresponds to the enhancement of $J_c - B$ characteristics as shown in Fig. 2. It can be also seen that the distribution becomes sharper in the improved process. This result indicates that the uniformity in the YBCO film by the improved TFA-MOD process is superior to the previous one. From another work [12], this improvement of the uniformity mainly comes from the difference of water partial pressures, P_{H2O}. Figs. 6(a) and 6(b) are cross-sectional TEM images for the TFA-MOD processed conductor obtained at 13.5% and 2.1% of P_{H2O}, respectively [12]. The size of pore shown by dashed line is drastically reduced in

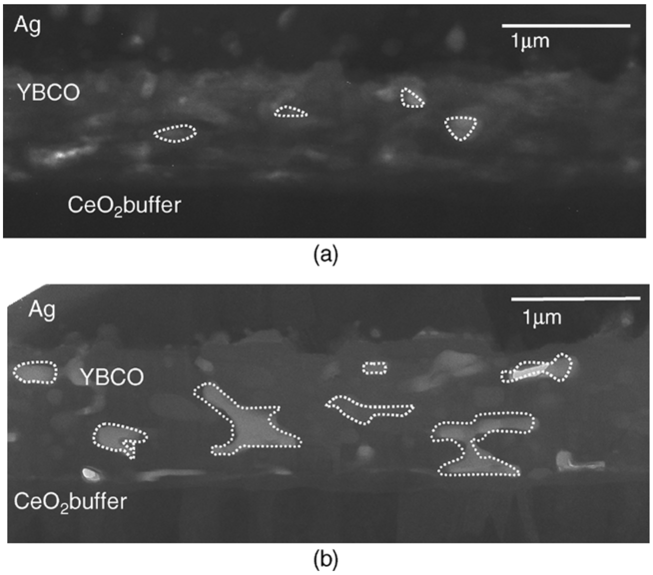

Fig. 6. Cross-sectional TEM images. The water partial pressures, $P_{\rm H2O}$ are (a) 13.5% and (b) 2.1%.

the case of higher $P_{\rm H2O}$. The $P_{\rm H2O}$ conditions both improved- and previous-TFA-MOD process in this paper approximately the same to the case of Figs. 6(a) and 6(b), respectively.

Since the magnetic field dependence itself is not varied drastically in the new process, it can be concluded that the improvement of the J_c mainly comes from the improvement of the uniformity. Namely, improvement of grain connectivity is the main contribution to higher J_c properties in the present case rather than the pinning which may be controlled by crystallographic structure in the smaller length scale in the matrix.

V. Conclusion

Current transport characteristics in a YBCO coated conductor fabricated by improved TFA-MOD process were investigated in detail including at high magnetic fields up to 25 T. J_c of 2.1 $\rm MA/cm^2$ and I_c of 251 A/cm-w were obtained at 77 K in self-field. The J_c properties are about 2.5 times superior than those of previous one. However, the magnetic field dependence itself is not varied drastically. From the experimental results and pinning analysis within a framework of the percolation model, it is considered that the high performances of J_c mainly come from the improvement of uniformity in the YBCO film.

References

[1] A. Goyal, M. P. Paranthaman, and U. Schoop, "The RABiTS approach: using rolling-assisted biaxially textured substrates for high-performance YBCO superconductors," *MRS Bull.*, vol. 29, no. 8, pp. 552–561, Aug. 2004.

[2] Y. Iijima, K. Kakimoto, Y. Yamada, T. Izumi, T. Saitoh, and Y. Shiohara, "Research and development of biaxially textured IBAD-GZO templates for coated superconductors," *MRS Bull.*, vol. 29, no. 8, pp. 564–571, Aug. 2004.

[3] U. Balachandran, B. Ma, M. Li, B. L. Fisher, R. E. Koritala, D. J. Miller, and S. E. Dorris, "Development of coated conductors by inclined substrate deposition," *Phys. C–Superconductivity and Its Applications*, vol. 392, pp. 806–814, Oct. 2003.

[4] P. N. Arendt, S. R. Foltyn, L. Civale, R. F. DePaula, P. C. Dowden, J. R. Groves, T. G. Holesinger, Q. X. Jia, S. Kreiskott, L. Stan, I. Usov, H. Wang, and J. Y. Coulter, "High critical current YBCO coated conductors based on IBAD MgO," *Phys. C–Superconductivity and Its Applications*, vol. 412–414, pp. 795–800, Oct. 2004.

[5] T. Honjo, Y. Nakamura, R. Teranishi, Y. Tokunaga, H. Fuji, J. Shibata, S. Asada, T. Izumi, Y. Shiohara, Y. Iijima, T. Saitoh, A. Kaneko, and K. Murata, "Fabrication and growth mechanism of YBCO coated conductors by TFA-MOD process," *Phys. C–Superconductivity and Its Applications*, vol. 392, pp. 873–881, Oct. 2003.

[6] R. Teranishi, H. Fuji, T. Honjo, Y. Nakamura, T. Izumi, Y. Shiohara, J. Shibata, T. Yamamoto, Y. Ikuhara, and M. Yoshimura, "Growth mechanism of Y123 film by MOD-TFA process," *Phys. C–Superconductivity and Its Applications*, vol. 378, pp. 1033–1038, Oct. 2002.

[7] K. Watanabe, S. Awaji, G. Nishijima, K. Takahashi, K. Koyama, M. Motokawa, and N. Kobayashi, "Magnet technology and materials research at the high-field laboratory for superconducting materials," *Phys. B: Condensed Matter*, vol. 346–347, Apr. 2004.

[8] T. Kiss, M. Inoue, S. Egashira, T. Kuga, M. Ishimaru, M. Takeo, T. Matsushita, Y. Iijima, K. Kakimoto, T. Saitoh, S. Awaji, K. Watanabe, and Y. Shiohara, "Percolative transition and scaling of transport $E-J$ characteristics in YBCO coated IBAD tape," *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, pp. 2607–2610, Jun. 2003.

[9] Y. Tokunaga, T. Honjo, T. Izumi, Y. Shiohara, Y. Iijima, T. Saitoh, T. Goto, A. Yoshinaka, and A. Yajima, "Advanced TFA-MOD process of high critical current YBCO films for coated conductors," *Cryogen.*, vol. 44, no. 11, pp. 817–822, Nov. 2004.

[10] M. Inoue, T. Kiss, T. Kuga, M. Ishimaru, M. Takeo, T. Matsushita, Y. Iijima, K. Kakimoto, T. Saitoh, S. Awaji, K. Watanabe, and Y. Shiohara, "Estimation of $E-J$ characteristics in a YBCO coated conductor at low temperature and very high magnetic field," *Phys. C–Superconductivity and Its Applications*, vol. 392, pp. 1078–1082, Oct. 2003.

[11] T. Koyama and M. Tachiki, "The effect of internal orbital motion in 2D d-wave superconductors," *Phys. C–Superconductivity and Its Applications*, vol. 263, pp. 25–29, May 1996.

[12] Y. Tokunaga, H. Fuji, R. Teranishi, J. Matsuda, S. Asada, A. Kaneko, T. Honjo, T. Izumi, Y. Shiohara, Y. Yamada, K. Murata, Y. Iijima, T. Saitoh, T. Goto, A. Yoshinak, and A. Yajima, "High critical current YBCO films using advanced TFA-MOD process," *Phys. CC–Superconductivity and Its Applications*, vol. 412–414, pp. 910–915, Oct. 2004.