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Flux Pinning Properties of REBCO coated conductors for High Field Magnets

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***Abstract*-- From the viewpoint of high field application, the mechanical and critical current properties of recently developed $REBa_2Cu_3O_y$ (RE123, RE: rare-earth) coated conductors are summarized. In addition, effective flux pinning mechanisms in RE123 are also introduced. As one of the examples for high field application, the upgrading of the 18 T cryogen-free superconducting magnet is shown. The large anisotropy of J_c is a problem at low temperature and high magnetic field. The nanorod is considered as the useful methods to improve the anisotropy of J_c, although its efficiency becomes small at low temperature.**

1. INTRODUCTION

$REBa_2Cu_3O_y$(RE123, RE=rare earth) coated conductors are developed aggressively. Those show not only high in-field critical current density J_c but also high mechanical tolerance. The external stress dependences of critical current density J_c for various practical superconducting wires are summarized in Fig. 1 [1-5]. It is clear that the RE123 coated conductors show the excellent mechanical properties among the practical superconducting wires due to elastic constant and a high yield stress of the Hastelloy substrate. Therefore, RE123 coated conductors on the Hastelloy tape are the promising superconducting wires for high field application. Nowadays, some companies commercially supply the coated conductors produced by their own techniques.

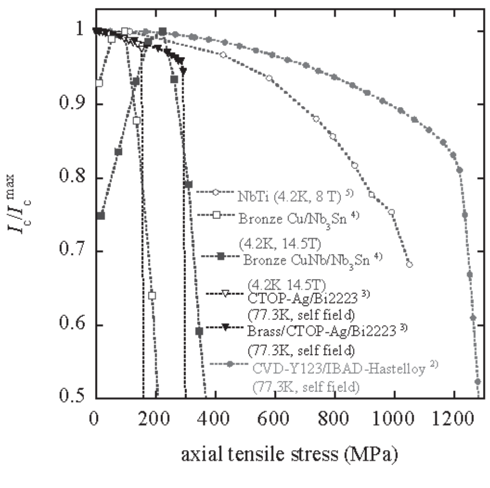

Fig. 1. Stress dependence of J_c for various practical superconducting wires [1-5].

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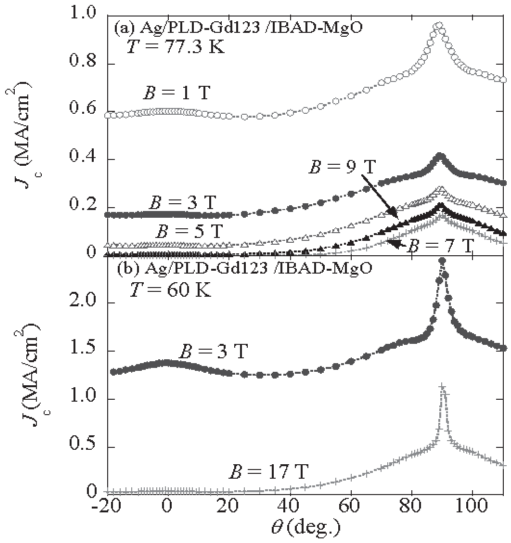

Fig. 2. Angular dependence of J_c at 77.3 K and 60 K for PLD-Gd123 coated conductors.

However, the characterizations of J_c on the basis of the flux pinning mechanism are still going on in application-oriented research. In this review, the recent understandings on the flux pinning mechanism in RE123 coated conductors and of high field magnets are introduced.

2. FLUX PINNING PROPERTY OF COATED CONDUTORS

2.1. Intrinsic pinning

The angular dependence of J_c at 77.3 and 60 K for PLD-Gd123 coated conductors are shown in Fig. 2. The angular-dependent J_c represents a large sharp peak at $\theta = 90^\circ$ ($B \perp c$) and a small broad peak at $\theta = 0$ ($B // c$). This is a typical behavior for the RE123 films without any artificial pinning centers [6]. In addition, the angular dependence of the n-value is qualitatively similar to that of J_c at 77.3 K as shown in Fig. 3. When the temperature decreases to 60K, the large $J_c(\theta)$ peak for $B \perp c$ becomes sharper in comparison with that at 77.3 K. However, the angular dependence of the n-value near $B \perp c$ at 60 K shows an

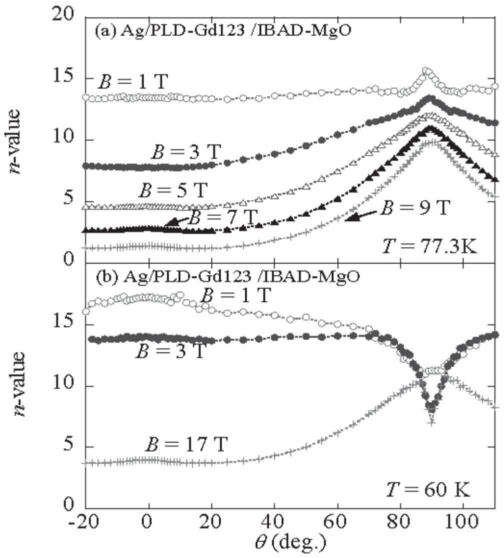

Fig. 3. Angular dependence of n-values at 77.3 K and 60 K for the PLD-Gd123 coated conductors.

inverse correlation to that of J_c. In addition, the n-value is as small as about 8 and is independent of the magnetic Fields despite of the large J_c. It is reported that this behavior is due to the double-kink excitation of the pinned vortices in the periodic correlated pinning centers like the intrinsic pinning [6-8]. If we assume that the inverse angular dependence between J_c and n-value is related with the intrinsic pinning, the intrinsic pinning is not effective at 77.3K but effective at 60 K. This is quite reasonable because the coherence length along the c-axis becomes large when the temperature is close to the critical temperature [9]. When the intrinsic pinning is effective, however, the small n-value for $B\perp$c, which can be seen in Fig. 3, is a problem for the application of the superconducting magnets. These behaviors were observed in other RE123 coated conductors [6, 7]. Figure 4 shows the temperature dependence of n-value of the CVD-Y123 coated conductors at 17 T. The n-value for B//c at 17 T increase monotonically with decreasing temperature. However, there exists a plateau region on the temperature dependence of n-value between 70 and 40K for $B\perp$c at 17 T, but the n-value increase rapidly below 20 K. It is considered that the increase of n-values at low temperature associates from the reduction of the thermally induced double kink excitations of the vortices at low temperatures.

At low temperatures, the quite high in-field J_c can be achieved for $B\perp$c because of the strong intrinsic pinning. On the other hand, J_c determined by the random pinning for B//c is small in comparison with that for $B\perp$c. In particular, J_c for the intrinsic pinning increases rapidly in comparison with that for the random pinning. Therefore, the anisotropy of J_c becomes larger in higher magnetic field and lower temperatures [7]. In order to overcome the problem of the large anisotropy of J_c, the introduction of the nanorod as the c-axis correlated pining is effective as shown in the next section.

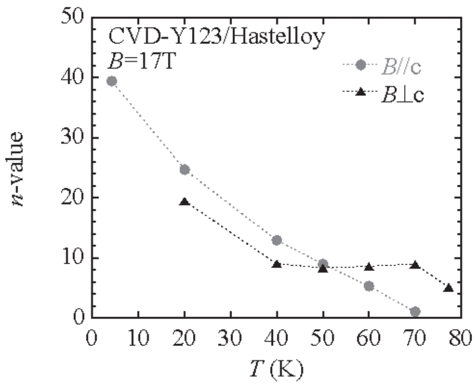

Fig. 4. Temperature dependence of n-values at 17 T.

Fig. 5. TEM cross-sectional image of the Zr-doped PLD-Gd123 coated conductors.

2.2. Nanorod as an artificial pinning center

Figure 5 shows the TEM cross-sectional image of the Zr-doped Gd123 coated conductor. The nano-scaled rod-shape precipitates can be observed. The nanorods typically align along the c-axis of Gd123 matrix. However those nanorods tend to tilt from the direction of the c-axis of the RE123 matrix with increasing a thickness.

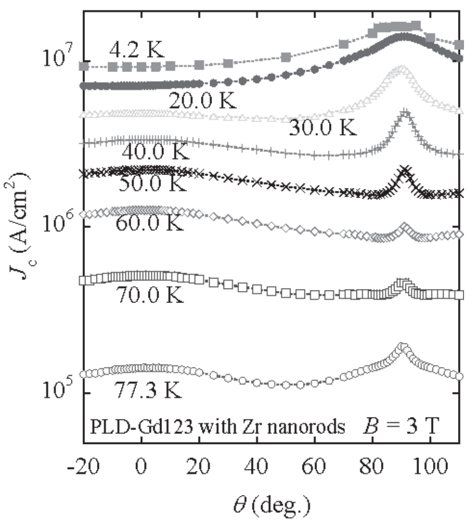

Fig. 6. Angular dependence of J_c for the Zr-doped PLD-Gd123 coated conductors.

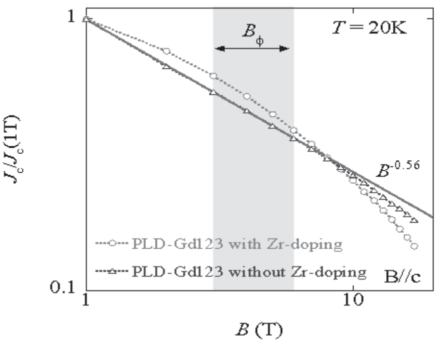

Fig. 7. Field dependence of J_c for the Zr-doped and non-doped PLD-Gd123 coated conductors at low temperatures.

It is reported that the nanorods work well as the c-axis correlated pinning center and improve J_c for B//c at high temperatures [10]. Figure 6 represents the angular dependence of J_c for the Zr-doped PLD-Gd123 coated conductors at 3 T and at various temperatures. At high temperatures, the large peak of $J_c(\theta)$ for B//c appears. This is related to the existence of the $BaZrO_3$ nanorods as shown in Fig. 5. This $J_c(\theta)$ peak along the nanorods increases with decreasing temperature. With further decreasing temperature, however, it decreases after the maximum around 60 K and disappears at 20 K at 3 T. The field dependences of J_c for the Zr-doped and undoped Gd123 coated conductors at 20 K, where no peak of $J_c(\theta)$ for B//c is observed, are compared each other in Fig. 7. The $J_c \propto B^{-0.5}$ relation can be seen in the low field region below 8 T for the non-doped Gd123 coated conductor. This means that the random pinning is dominant in the non-doped Gd123. On the other hand, the J_c of the Zr-doped Gd123 coated conductor shows weaker field dependence in the low field region but more steeper field dependence in the high field region. The boundary of the different field dependences of J_c is in agreement with the matching field $B_\phi \approx$ 3-6 T, where B_ϕ is the magnetic field, at which the density of the magnetic quantum flux is the same as that of the nanorods. Therefore, the flux pinning by the nanorods are still effective at low temperatures, although the contribution of the c-axis correlated pinning against the random pinning becomes small [11]. The cooperation model of the random and correlated pinning centers can explain these phenomena. The detailed discussion is explained in the references [13].

3. APPLICATION OF COATED CONDUTORS FOR HIGH FIELD MAGVET

The progress of the superconducting magnets are shown in Fig. 8. The materials used for the innermost coil are also shown in the figure. The magnetic field generated by both of the liquid helium cooled and cryogen-free superconducting magnets increased gradually. The materials for the innermost coil changed with a time and recently high temperature superconducting wires (HTS) are utilized to generate high magnetic field. By the

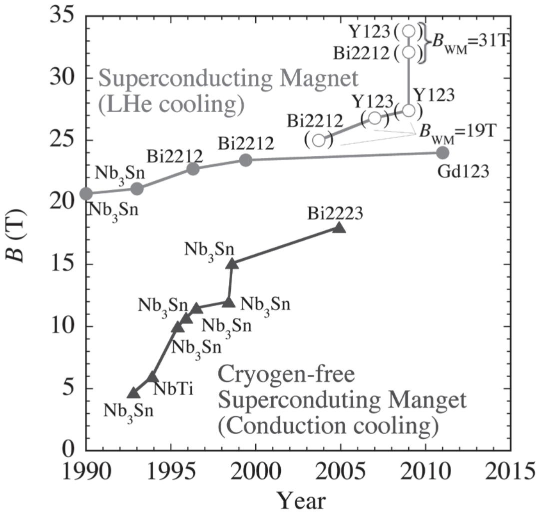

Fig. 8. Progress of liquid He cooled and cryogen-free superconducting magnets.

developments of the long RE123 coated conductors, especially, the very recently in the combination magnet system[14]. The brackets in the figure mean that those are not all superconducting magnets but the small HTS insert coils in the back ground field generated by the resistive or the hybrid magnets. Those test results suggest that the RE123 coils have a capacity of high field generation more than 30 T [1, 14, 15]. Very recently, the Tsukuba Magnet Laboratory succeeded in the generation of 24 T by the Gd123 test coil combined with the low temperature superconductor background magnet [15].

The 18T cryogen-free superconducting magnet (18T-CSM) at the HFLSM, IMR, Tohoku University consists of an outer NbTi, a middle Nb_3Sn and an inner $Bi_2Sr_2Ca_2Cu_3O_y$ (Bi2223) coils as shown in Fig. 9. The Bi2223 insert coil generates 2.52 T in a background field of 15.6 T by the Nb_3Sn and NbTi coils [16]. The Ag-alloy sheathed Bi2223 tapes for the inner most coil was reinforced by the co-winding with 0.3 mm thick stainless

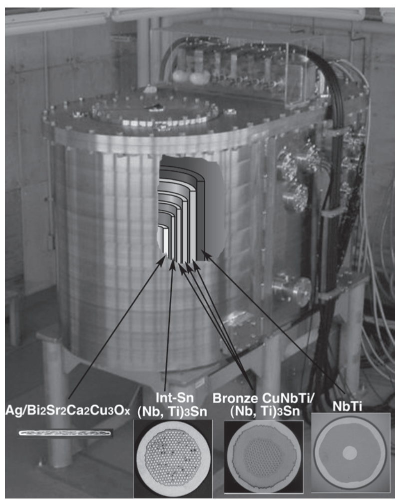

Fig. 9. Picture of the 18 T cryogen-free superconducting magnet. The cross-sectional images of the wires used in the magnet are demonstrated.

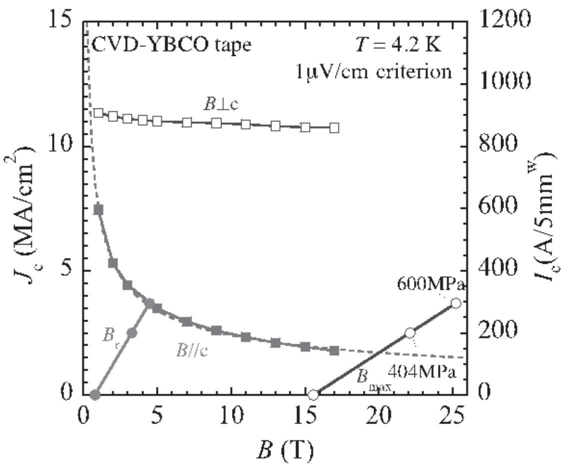

Fig. 10. I_c of the CVD-Y123 coated conductor at 4.2 K and load lines.

steel tape. If we use the Y123 CC tapes for inner coil, it is expected to achieve higher magnetic field over 20T because of the high mechanical tolerance as show in Fig.1 [17, 18].

We design the size of the Y123 coil similarly to the present Bi2223 insert of the 18T-CSM, in order to replace it. However, the number of turns is increased and the large hoop stress up to 600 MPa is permitted. We found that the central field of 21.9T at I_{op} = 200 A for the stress limit of 400 MPa and 25.0 T at I_{op} = 295 A for the stress limit of 600 MPa can be achieved in the back up field of 15.6 T generated by the Nb_3Sn middle and the NbTi outer coils [17]. Figure 10 represents a load line of the maximum field, B_{max}, together with the I_c-B properties of the CVD-Y123 coated conductors at 4.2 K. The operating current of 295 A is much smaller than that for B⊥c. In the case of the insert coil, which puts into the large background field, the most magnetic field contribution is parallel to the tape surface, i.e., perpendicular to the c-axis of the Y123 tape. However, we have to care the effects of magnetic field direction, because Y123 has large anisotropy of J_c. The radial component of the magnetic field B_r, which corresponds to the field parallel to the c-axis, should be compared with I_c for B//c. In this case, I_{op} = 295 A is just on the I_c-B curve for B//c as shown in Fig. 10. This means that the 25 T at I_{op} = 295 A is quench point when we use the CVD-Y123 coated conductor [17]. Therefore, the performance of the coated conductor coil is limited by the I_c for B//c in this case. The improvement of the anisotropy of I_c (J_c) is necessary for the development of the high field magnet using the coated conductors. The introduction of the nanorod is one of the good techniques for the improvement of J_c anisotropy as mentioned above.

4. SUMMARY

The J_c properties of the RE123 coated conductors are explained on the basis of the flux pinning mechanism. By using J_c properties for the present RE123 coated conductors, the design of the RE123 insert coil is introduced, although the J_c properties of the RE123 coated conductors is still in progress. It is expected that the introduction of the nanorods improves the anisotropy of J_c even at low temperatures and high magnetic fields. The high field superconducting magnets beyond 30 T will be realize in near future by using the high performance RE123 coated conductors.

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