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M3Or4O-02: [Invited] Numerical evaluation on angular dependence of Jc in REBCO coated conductors due to spherical pins and columnar pins

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In addition to naturally induced pinning centers in $RE\mathrm{Ba_2Cu_3O_{7-\delta}}$ coated conductors (REBCO-CCs), such as blocking layers and stacking faults act as planer pins, minor-phase precipitates and oxygen defects act as coarse and fine spherical pins, an introduction of fine pinning centers plays a crucial role for improving the critical current density Jc characteristics of REBCO-CCs. Regarding fine spherical pins, RE_2O_3 nano-particles with a PLD technique [1] and Ba(Hf/Zr)O_3 (BHO/BZO) nano-particles with TFA-MOD [2] and F-free MOD [3] methods have been introduced, and an anomalous depression of $J_c(\theta \sim B \parallel ab)$ at low fields and a crossover to an usual effective mass like $J_c(\theta)$ at high fields, have been observed in some cases [2, 4]. As for columnar defects, Fujikura successfully introduced short BHO nano-rods via their Hot-wall PLD with a fast growth rate and reported $J_c(T, B, \theta)$ with a smaller anisotropy, namely with a less remarkable $J_c(B \parallel c)$ peak, compared with $J_c(T, B, \theta)$ caused by well-aligned nano-rods [5].
For further improving the $J_c(T, B, \theta)$ characteristics of REBCO-CCs, it is important and beneficial to understand such novel $J_c(T, B, \theta)$ characteristics due to artificial pinning centers. In this study, we calculated the angular dependence of the elementary pinning force $f_p(T, \theta)$ due to spherical pins imitating BHO nano-particles and inclined short columnar pins imitating BHO nano-rods by evaluating the dimensions of pinning centers and vortex cores rigorously within a normal-core approximation. We found that $f_p(T, \theta)$ tends to decrease with θ approaching the $B \parallel ab$ direction in some conditions and confirmed that the combination of the angular dependence of $f_p(T, \theta)$ and $B_{c2}(\theta)$ leads the anomalous $J_c(\theta)$ depression at low B and its crossover to the usual effective mass like $J_c(\theta)$ at high B. As for columnar pins, we confirmed that the $f_{cp}(\theta \simeq B \parallel c)$ peak becomes broad with shorter columns and successfully reproduced experimentally observed broader $J_c(\theta)$ by taking account of the distribution of the inclination and azimuth of short BHO nano-rods.
These results suggest that experimentally observed $J_c(T, B, \theta)$ can be basically explained by numerically evaluated $f_p(T, \theta)$ and that a prediction of $J_c(T, B, \theta)$ based on $f_p(T, \theta)$ due pinning centers may be helpful for tailoring the pinning properties of REBCO-CCs depending on applications.
At the conference, we would like to explain our calculations and discuss vortex pinning properties of REBCO-CCs due to spherical pins and columnar pins.

[1] A. Molodyk *et al.*, Sci. Rep., **11** (2022) 2084.
[2] For example, K. Nakaoka *et al.*, SuST, **30** (2017) 055008., M. Miura *et al.*, NPG Asia Mat., **9** (2017) 197.
[3] T. Yoshihara *et al.*, IEEE-TAS, **33** (2023) 6600205.
[4] T. Okada *et al.*, IEEE-TAS, **29** (2019) 8002705., T. Okada and S. Awaji, *to be submitted.*
[5] S. Fujita *et al.*, IEEE-TAS, **28** (2020) 6600604.

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