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Simulation studies of mechanical stresses and trapped field in annular REBaCuO superconducting bulk magnet for NMR spectrometer during field-cooled magnetization

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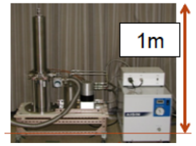
200MHz SCBM



1. Introduction

Recently, a compact and cryogen-free NMR spectrometer with a medium resolution of 200 MHz (4.7 T) has been developed using annular REBaCuO superconducting bulks, in which the NMR spectra of ethanol with a full width at half of the maximum (FWHM) of 0.1 ppm (21 Hz) have been achieved [1]. In the apparatus, the annular REBaCuO bulks are magnetized by field-cooled magnetization (FCM), in which large hoop and radial stresses are experienced and the bulks are sometimes fractured for higher applied field. The metal ring support must be considered to avoid the bulk fracture. We have investigated numerically and experimentally the hoop stress, σ_θ in the REBaCuO annular bulk reinforced by metal ring during FCM [2, 3]. The thermal hoop stress, σ_θ^{cool}, was also studied, which is applied to the bulk when cooling down to operating temperature due to the difference of thermal expansion coefficient between bulk and metal ring. It was found that the compressive σ_θ^{cool} was reduced comparatively at the uppermost surface of the finite bulk because of the larger thermal expansion of the metal ring along the axial direction. The total hoop stress during FCM under cooling, σ_θ (= σ_θ^{cool} + σ_θ^{FCM}), was estimated for the finite ring bulk reinforced by the metal ring with the same height, which was larger than the results for the infinite ring bulk reinforced by the metal ring with infinite height [3]. These analytical results are valuable to judge the bulk fracture during FCM.

[1] T. Nakamura *et al.*, *J. Magn. Reson.*, vol. 259, pp. 68-75, 2015
[2] H. Mochizuki *et al.*, *IEEE Trans. Appl. Supercond.*, vol. 26, 2016, Art. ID 6800205.
[3] H. Fujishiro *et al.*, *Supercond. Sci. Technol.*, vol. 30, 2017, Art. ID 085008.

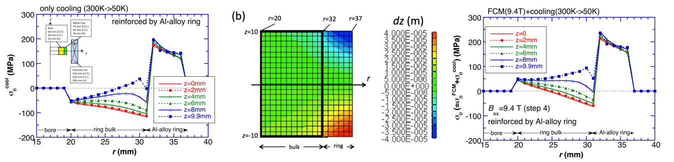


Fig. 1. (a) The radius (r) dependence of the thermal hoop stress, σ_θ^{cool}, for the finite ring bulk reinforced by an aluminum alloy ring for each z-position under cooling from 300 to 50 K. (b) The contour maps of the displacement, *dz*, along *z*-direction. (c) The total hoop stress, σ_θ (=σ_θ^{FCM}+σ_θ^{cool}) furing FCM from 9.4 T under cooling.

2. Motivation

In this study, we performed the numerical simulation of the hoop stress, σ_θ, and the electromagnetic properties (trapped field, B_z, and induced persistent supercurrent density, J_θ, in the actual annular REBaCuO bulks reinforced by three types of aluminum alloy rings during FCM from B_{ex} = 9.4 T at 50 K using the finite element method (FEM) to realize the 400 MHz (9.4 T) NMR spectrometer safely.

3. Modelling of numerical simulation

Electromagnetic properties (Bean model)

$$\frac{\partial}{\partial r}\left[\frac{v}{r}\frac{\partial}{\partial r}(r\mathbf{A})\right]+\frac{\partial}{\partial z}\left(v\frac{\partial \mathbf{A}}{\partial z}\right)=J_0+J$$

$$E=E_c\left(\frac{J}{J_c}\right)^n \qquad n=100$$

• J_c=4.8 x 10^8 (A/m^2)

mechanical properties (Hooke's law)

$$\sigma_{ij}=\lambda\cdot e_{kk}\cdot\delta_{ij}+2G\cdot e_{ij}$$

$$\lambda=\frac{E\cdot v}{(1+v)(1-2v)}$$

$$G=\frac{E}{2(1+v)}$$

TABLE I. MECHANICAL PARAMETERS USED IN THE NUMERICAL SIMULATION.

	E (GPa)	ν	α (K^{-1})
REBaCuO bulk	100	0.33	5.2e-6
Al alloy ring	78	0.34	1.66e-5
Indium	110	0.44	3.25e-5

(*E*: Young's modulus, *ν*: Poisson ratio, *α*: thermal expansion coefficient)

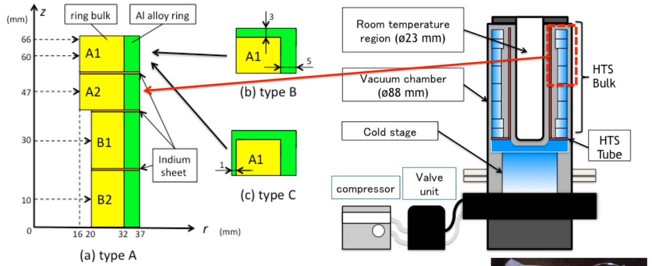


Fig. 2. Schematic view of three types of numerical models.

4. Results & Discussion

A. Trapped field, B_z, and induced current density, J_θ

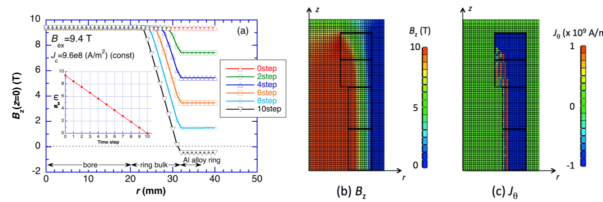


Fig. 3. (a) Time step dependence of the cross-sectional plots of the trapped field, $B_z(r)$, for the annular REBaCuO bulks during FCM from B_{ex} = 9.4 T. Contour maps of the (b) trapped field, B_z, and (c) persistent current density, J_θ, at the final (10th) step are shown.

B. Thermal hoop stress, σ_θ^{cool}, under cooling from 300 K to 50 K

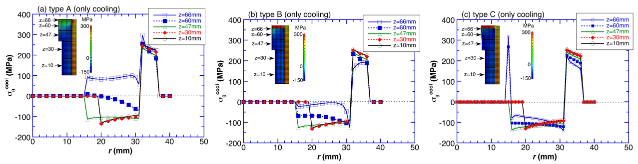


Fig. 4. The radius (r) dependence of the thermal hoop stress, σ_θ^{cool}, for the annular REBaCuO bulks reinforced by three types of aluminum alloy rings for each *z*-position under cooling from 300 K to 50 K. Inset of each figure shows the contour map of the σ_θ^{cool}.

C. Electromagnetic hoop stress, σ_θ^{FCM} during FCM

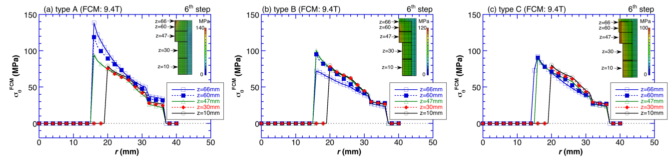


Fig. 5. Cross-sectional plots of the electromagnetic hoop stress, σ_θ^{FCM}, for the annular bulks with the (a) "type A", (b) "type B" and (c) "type C" reinforcements at the 6th step of FCM from B_{ex} = 9.4 T, without cooling.

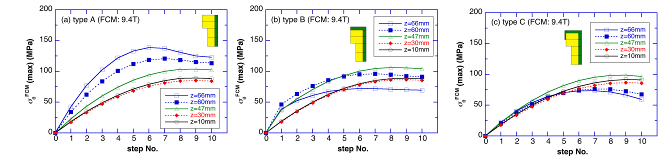
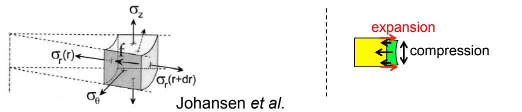


Fig. 6. Time step dependence of the maximum electromagnetic hoop stress, σ_θ^{FCM}(max), in each annular bulk with the three types of aluminum alloy ring reinforcements ((a) "type A", (b) "type B" and (c) "type C") during FCM from B_{ex} = 9.4 T.



D. Total hoop stress, σ_θ during FCM under cooling

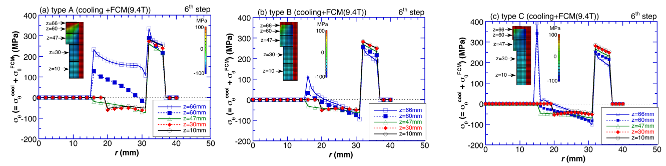


Fig. 7. The radius (r) dependence of the total hoop stress, σ_θ (=σ_θ^{cool} + σ_θ^{FCM}), value at the 6th step at various z-positions in the finite ring bulk reinforced by three types of the reinforcements ((a) "type A", (b) "type B", and (c) "type C"), under both the cooling process (σ_θ^{cool}) from 300 K to 50 K and the FCM process (σ_θ^{FCM}) of B_{ex} = 9.4 T.

5. Summary

(1) **The thermal hoop stress, σ_θ^{cool}, which was applied to the annular bulks during cooling, changed depending on the shape of the aluminum alloy reinforcement. For the simple metal ring reinforcement ("type A"), a large tensile stress was applied at the surface of the end bulk. The "type B" reinforcement with a ring plate to the end bulk of "type A" is effective to reduce the tensile stress. Furthermore, the "type C" reinforcement with an inner ring to the end bulk of "type B" is more effective.**

(2) The electromagnetic hoop stress, σ_θ^{FCM}, also changed depending on the shape of the aluminum alloy reinforcement and became the maximum at the innermost edge of the uppermost ring bulk at intermediate step in FCM.

(3) The actual total hoop stress, σ_θ (= σ_θ^{cool} + σ_θ^{FCM}), due to both cooling and FCM processes was analyzed for three types of aluminum alloy reinforcements. As a result, the "type C" reinforcement was confirmed to be fairly effective to reduce the total hoop stress and to have a possibility to avoid the mechanical fracture of the annular bulks.