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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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, $\sigma_{\theta}$, in the REBaCuO annular bulk reinforced by metal ring during FCM [2, 3]. The thermal hoop stress, $\sigma_{\theta,cool}$, 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 $\sigma_{\theta,cool}$ was reduced comparatively at the uppermost surface of the finite bulks because of the larger thermal expansion of the metal ring along the axial direction. The total hoop stress during FCM under cooling, $\sigma_{\theta} = \sigma_{\theta,cool} + \sigma_{\theta,FCM}$, 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 bulks reinforced by the metal ring with infinite height [3]. These analytical results are valuable to judge the bulk fracture during FCM.

2. Motivation
In this study, we performed the numerical simulation of the hoop stress, $\sigma_{\theta}$, and the electromagnetic properties (trapped field, $B_z$, and induced current density, $J_z$) for the annular REBaCuO bulks reinforced by three types of aluminum alloy rings during FCM from $B_0 = 9.4$ 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

3.1. Electromagnetic properties (Beam model)

\[ E = \frac{V}{\sqrt{L}} \]
\[ J = \frac{E}{(1+y)(1-2y)} \]
\[ \sigma_{\theta} = \lambda + \mu \varepsilon + 2G \varepsilon_z \]

3.2. Mechanical properties (Hooke’s law)

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

3.3. Numerical simulation parameters

- $V$: Volume (m$^3$)
- $L$: Length (m)
- $E$: Young’s modulus (Pa)
- $\mu$: Poisson ratio
- $\lambda$: Thermal expansion coefficient

4. Results & Discussion

4.1. Trapped field, $B_z$, and induced current density, $J_z$

Fig. 1. (a) The radius ($r$) dependence of the thermal hoop stress, $\sigma_{\theta,cool}$, for the finite ring bulk reinforced by an aluminum alloy ring for each $z$-position under cooling from 300 K to 50 K. (b) The contour maps of the trapped field, $B_z$, and (c) persistent current density, $J_z$, at the final (10th) step between are shown.

4.2. Thermal hoop stress, $\sigma_{\theta,cool}$, under cooling from 300 K to 50 K

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

4.3. Cross-sectional plots of the trapped field, $B_z$, for the annular REBaCuO bulks during FCM from $B_0 = 9.4$ T. Contour maps of the trapped field, $B_z$, and (c) persistent current density, $J_z$, at the final (10th) step are shown.

5. Summary

(1) The thermal hoop stress, $\sigma_{\theta,cool}$, 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 at the end of the bulk "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, $\sigma_{\theta,FCM}$, 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, $\sigma_{\theta} = \sigma_{\theta,cool} + \sigma_{\theta,FCM}$, 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 thermal hoop stress and to have a possibility to avoid the mechanical fracture of the annular bulks.