Numerical simulation of electromagnetic and thermal stress in REBaCuO superconducting ring and disk bulks reinforced by stainless steel ring with various widths during field-cooled magnetization

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I. Introduction

REBaCuO bulk superconductor (RE: rare earth element or Y) is a promising material to be used as trapped field magnet (TFM), which has ever realized the trapped field of over 10 T by field-cooled magnetization (FCM). Contrary to the superiority, TFM shows the fracture behavior in the higher magnetic field during FCM by Lorentz force due to the current-field interaction, in which the principal hoop stress exceeds the fracture strength, and cracks propagate along the radial direction of the bulk [1]. We reported the fracture strength of the ring bulk, which was estimated using the numerical simulation combined with an actual experimental results in previous study [2]. As a typical technique to reinforce the bulk, the metal ring has been used commonly, but the reinforcement effect has not been investigated extensively, except for a conventional setup.

[1] T. Miyamoto *et al. Physica C*, vol.**340**, 2000, pp. 41-50.

- In this study, the reinforcement effect using the wider stainless steel (SUS) ring has been investigated for the disk and ring bulks magnetized by FCM from 20 T at 50 K.

IV. Conclusion

We have compared the numerical results of the mechanical stress of the electromagnetic hoop stress, σ_θ^{FCM}, during FCM from 20 T at 50 K, and the thermal hoop stress, σ_θ^{cool}, under cooling from 300 K to 50 K in REBaCuO disk and ring bulks reinforced by SUS ring with various widths. The important numerical results are summarized as below.

- Numerical results showed that the stress concentration of σ_θ^{FCM} in the ring bulk could be alleviated by the wider SUS ring.
- The width of SUS ring needs to be at least 10 mm to prevent the fracture behavior of the bulk in this simulation.
- The optimal design of the reinforcement ring should be constructed so that the total hoop stress, σ_θ^{total} (= $\sigma_\theta^{FCM} + \sigma_\theta^{cool}$), could be less than the fracture strength of the bulk during FCM.

II. Numerical Simulation Framework

Modelling

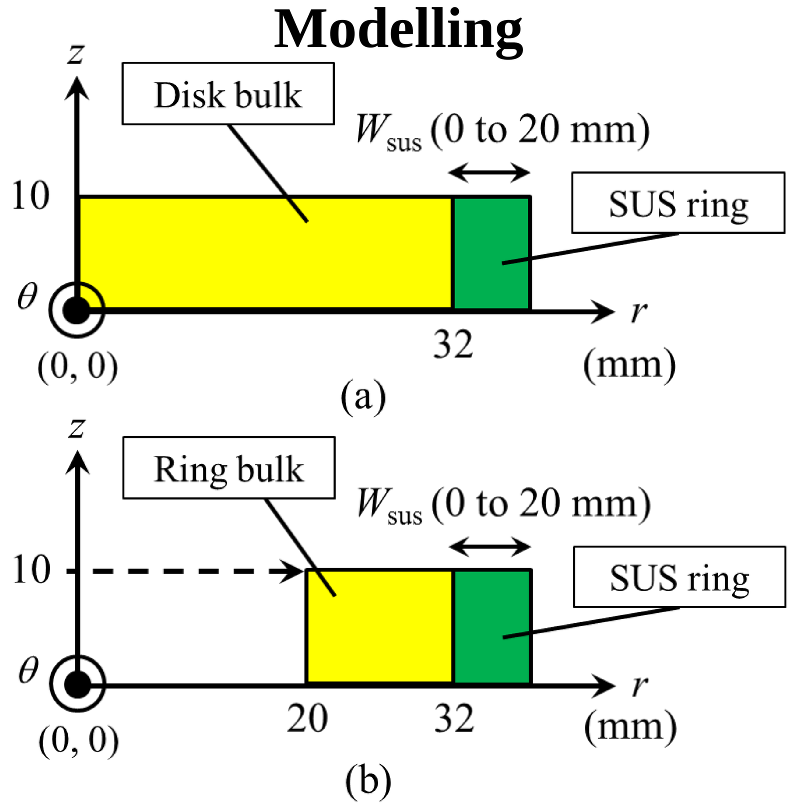

Fig. 1 Schematic view of numerical models for (a) the disk bulk and (b)the ring bulk.

Electromagnetic characteristics

- ***n*-power law (*n* = 20)** $$E = E_c\left(\frac{J}{J_c}\right)^n \quad (1)$$

The magnetic field dependence of critical current density, J_c, of the bulk was described with the following equation [2], where $J_{c1} = 8.0 \times 10^8$ A/m^2.

$$J_c(B) = J_{c1}\exp\left(-\frac{B}{B_L}\right) + J_{c2}\frac{B}{B_{max}}\exp\left[\frac{1}{k}\left(1-\left(\frac{B}{B_{max}}\right)^k\right)\right] \quad (2)$$

[2] K. Takahashi et al. accepted in *Supercond. Sci. Technol*., 2017.

Elastic equations

- **Hooke's law** $$\sigma_{ij} = \lambda \cdot e_{kk} \cdot \delta_{ij} + 2G \cdot e_{ij} \quad (3)$$

$$\lambda = \frac{E \cdot \nu}{(1+\nu)(1-2\nu)}, \qquad G = \frac{E}{2(1+\nu)}$$

TABLE. 1 Mechanical parameters used in the numerical simulation.

	E (GPa)	ν	α (K^{-1})
Ring bulk	1.0e11	0.33	5.2e-6
SUS316 L	1.93e11	0.28	1.27e-5

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

III. Numerical Results and Discussion

Trapped field, B_z

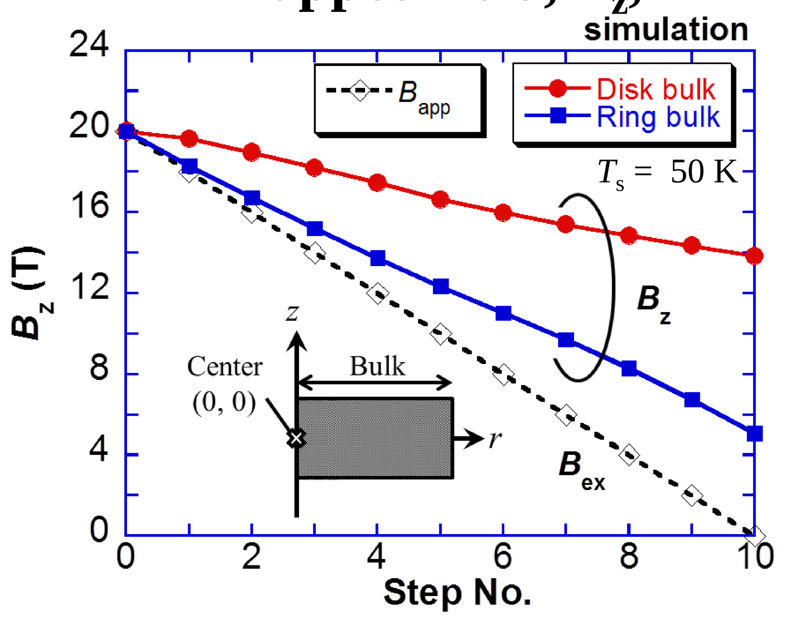

Fig. 2 Time step dependence of the trapped field, B_z, at the center of each bulk for the disk bulk and the ring bulk during FCM from B_{app} = 20 T.

At the final step after FCM from 20 T;

Disk bulk: B_z = 13.8 T
Ring bulk: B_z = 5.1 T

Each bulk was magnetized fully.

Electromagnetic hoop stress, σ_θ^{FCM}, without SUS ring reinforcement

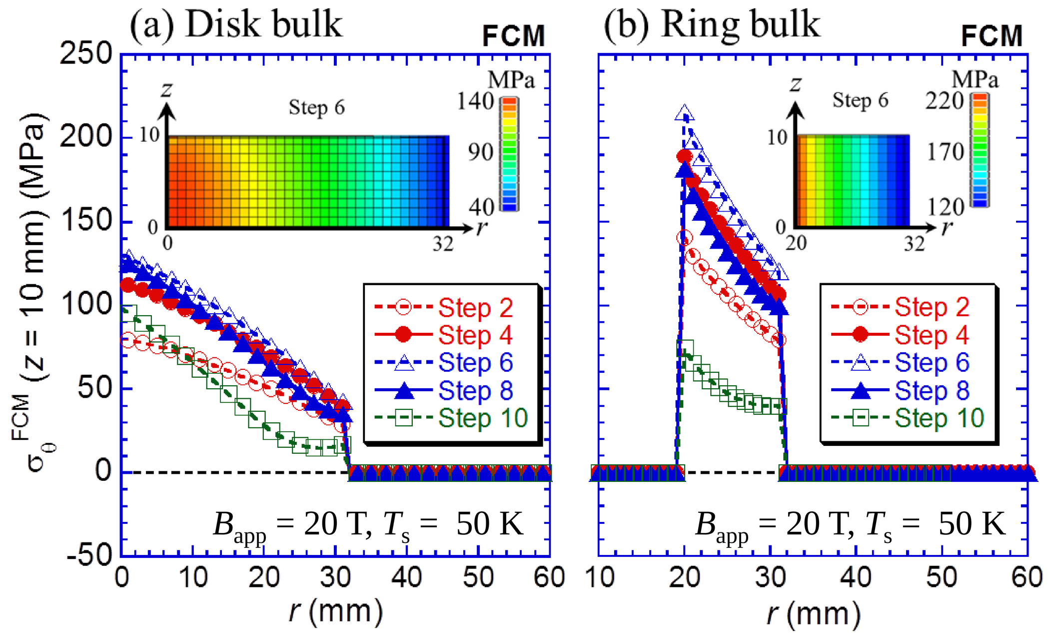

Fig. 3 Time step dependence of the electromagnetic hoop stress, σ_θ^{FCM}, profile along r-direction on the top surface of the bulk (z = 10 mm) without SUS ring reinforcement during FCM for (a) the disk bulk and (b) the ring bulk. The contour maps of σ_θ^{FCM} at the 6th step are also shown in each panel.

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

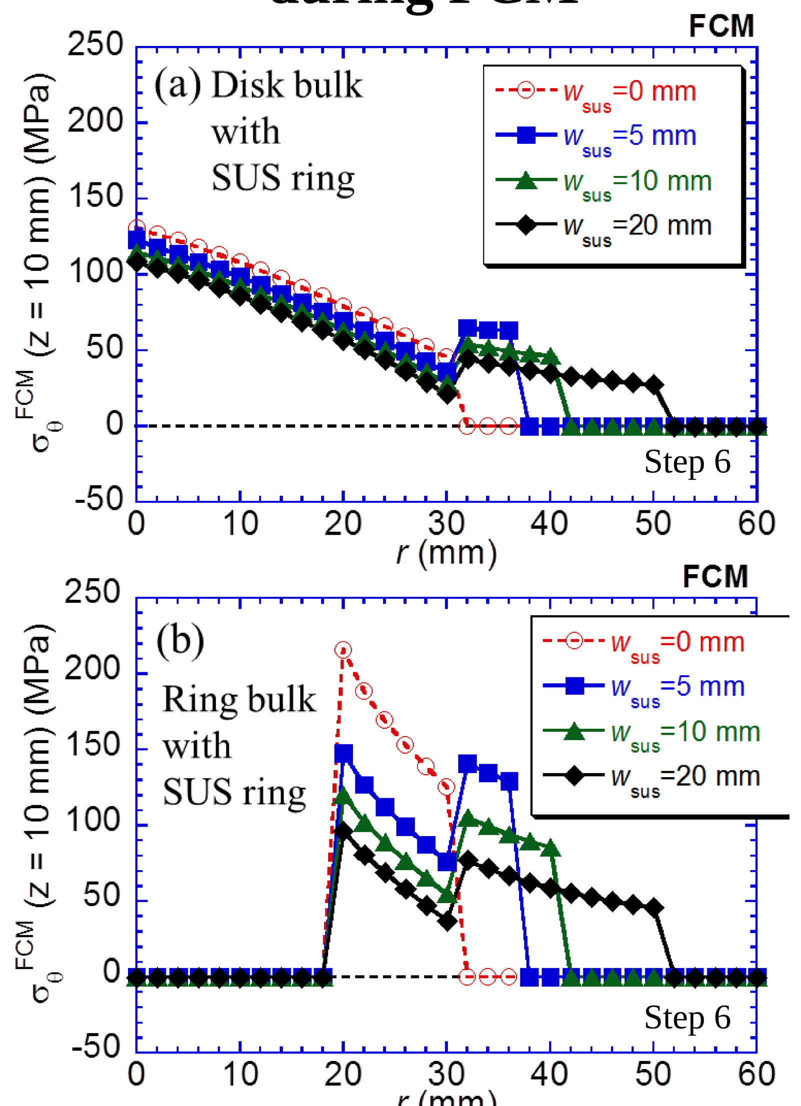

Fig. 4 Electromagnetic hoop stress, σ_θ^{FCM}, profile along r-direction on the top surface of the bulk reinforced by SUS ring with various widths at the 6th step during FCM for each bulk.

In Fig. 3 for the case without the SUS ring, σ_θ^{FCM} had a peak value at the 6th step during FCM.

Disk bulk: Max σ_θ^{FCM} = 130 MPa
Ring bulk: Max σ_θ^{FCM} = 216 MPa

Contour maps show that σ_θ^{FCM} profile is relatively homogeneous along z-direction of the bulk.

In Fig. 4, Maximum σ_θ^{FCM} was reduced with increasing the SUS ring width. For W_{SUS} = 20 mm,

Disk bulk: Max σ_θ^{FCM} = 108 MPa
Ring bulk: Max σ_θ^{FCM} = 97 MPa

The stress concentration in the ring bulk could be alleviated by the wider SUS ring.

Thermal hoop stress, σ_θ^{cool}, under cooling process

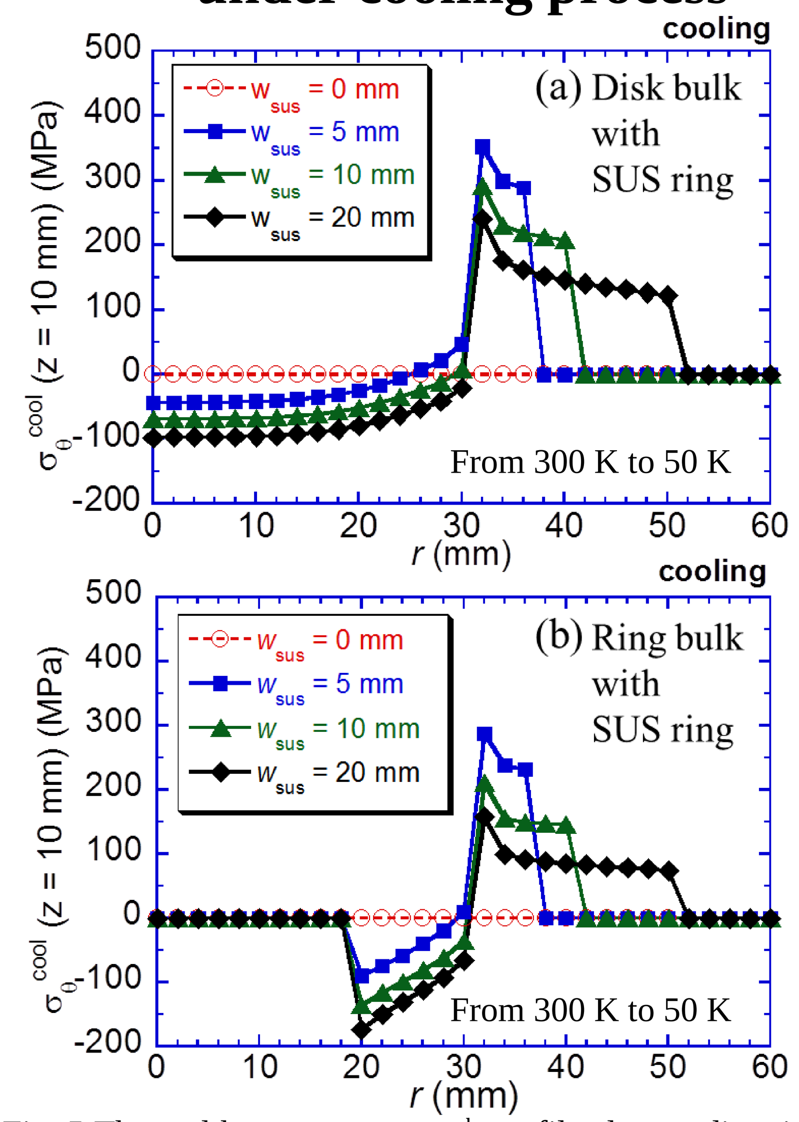

Fig. 5 Thermal hoop stress, σ_θ^{cool}, profile along r-direction on the top surface of the bulk reinforced by SUS ring with various widths under cooling from 300 K to 50 K for each bulk.

In Fig. 5, under cooling, maximum σ_θ^{cool} was also reduced with increasing W_{SUS}. The reinforcement using wider SUS ring was effective for each bulk.

$$\sigma_\theta^{FCM} + \sigma_\theta^{cool} = \sigma_\theta^{total}$$

(Fig. 4) (Fig. 5) (Fig. 6)

When the SUS ring with W_{SUS} = 5 mm was used for both cases, tensile σ_θ^{total} higher than +50 MPa is applied, which is as high as the fracture strength (≅ 59 MPa) of the REBaCuO bulk [2].

We suggest that the width of SUS ring needs to be at least 10 mm to prevent the fracture of the bulk.

Total hoop stress, σ_θ^{total}, during FCM under cooling

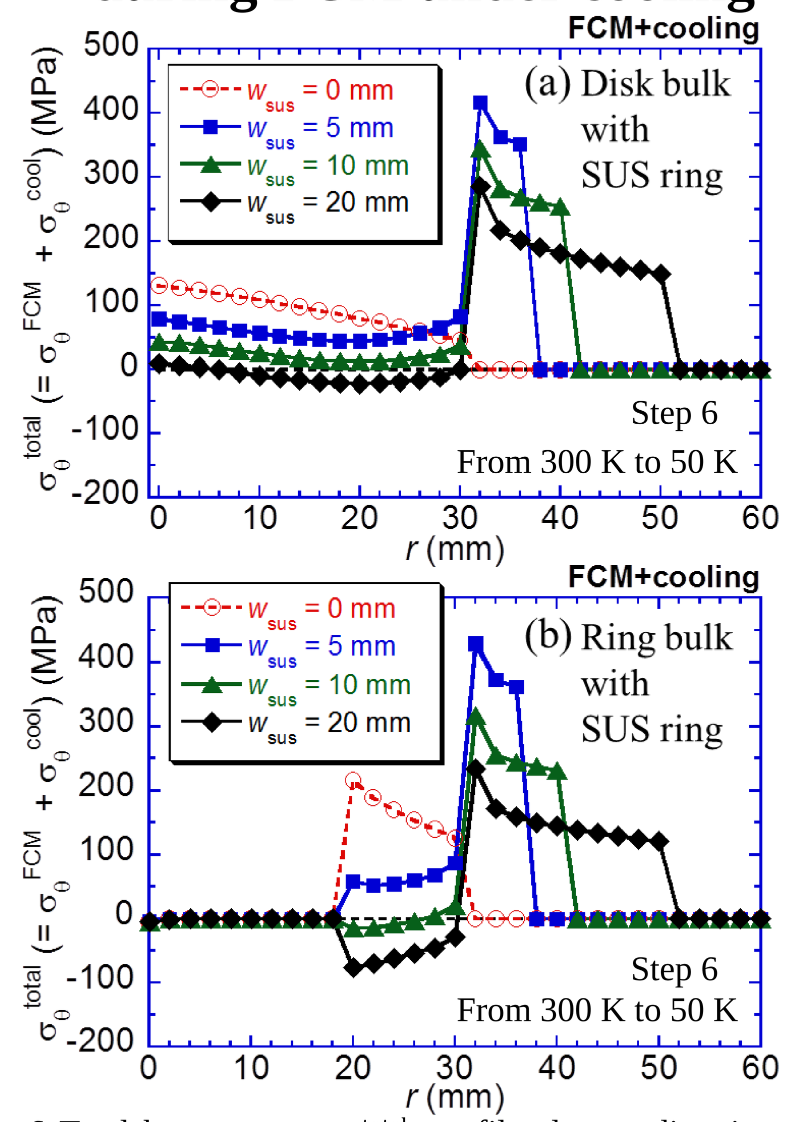

Fig. 6 Total hoop stress, σ_θ^{total}, profile along r-direction on the top surface of the bulk reinforced by SUS ring with various widths for each bulk.

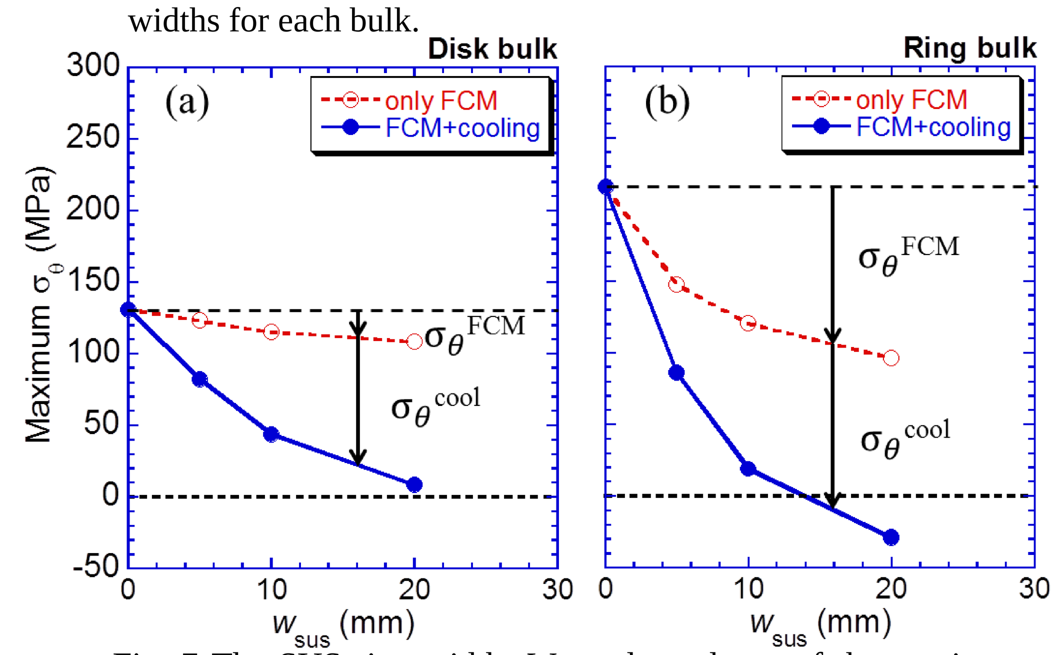

Fig. 7 The SUS ring width, W_{SUS}, dependence of the maximum σ_θ^{FCM} and σ_θ^{total} for (a) the disk bulk and (b) the ring bulk, which were extracted from Fig. 4 and Fig. 6, respectively.

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