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.

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

II. Numerical Simulation Framework

Electromagnetic characteristics

\[ E = J \times B \]  

The magnetic field dependence of critical current density, \( J_c \), of the bulk was described with the following equation [2], where \( J_{c0} = 2 \times 10^5 \text{A/m}^2 \), and \( B_{m} = 3 \times 10^4 \text{mT} \).

\[ J_c(B) = J_{c0} \exp \left( \frac{B - B_m}{B_{m1}} \right) \exp \left( \frac{1}{1 + (B - B_m) / B_{m2}} \right) \]


Elastic equations

\[ \lambda = E \cdot \nu \cdot \frac{1 + \nu}{(1 - 2\nu)\cdot K} \]

TABLE I. Mechanical parameters used in the numerical simulation.

<table>
<thead>
<tr>
<th>Material</th>
<th>E (GPa)</th>
<th>ν</th>
<th>α (K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring bulk</td>
<td>1.0311</td>
<td>0.33</td>
<td>5.25 \times 10⁻⁵</td>
</tr>
<tr>
<td>SUS316L</td>
<td>1.9611</td>
<td>0.28</td>
<td>1.27 \times 10⁻⁵</td>
</tr>
</tbody>
</table>

Young’s modulus, Poisson ratio, α: thermal expansion coefficients

III. Numerical Results and Discussion

Electromagnetic hoop stress, \( \sigma_{FCM} \), without SUS ring reinforcement

\[ \sigma_{FCM} = E \cdot \frac{\partial J_c}{\partial B} \cdot \frac{\partial B}{\partial \theta} \]

Fig. 3. Step dependence of the electromagnetic hoop stress, \( \sigma_{FCM} \), profile along \( \theta \)-direction on the top surface of the bulk without SUS ring reinforcement during FCM for (a) the disk bulk and (b) the ring bulk. The contour maps of \( \sigma_{FCM} \) at the 6th step are also shown in each panel.

Electromagnetic hoop stress, \( \sigma_{FCM} \), during FCM

\[ \sigma_{FCM} = E \cdot \frac{\partial J_c}{\partial B} \cdot \frac{\partial B}{\partial \theta} \]

Fig. 4. Electromagnetic hoop stress, \( \sigma_{FCM} \), profile along \( \theta \)-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, \( \sigma_{FCM} \) had a peak value at the step 6th during FCM. In Fig. 3, for the case without the SUS ring, \( \sigma_{FCM} \) had a peak value at the step 6th during FCM.

Disk bulk: Max \( \sigma_{FCM} \) = 150 MPa

Ring bulk: Max \( \sigma_{FCM} \) = 205 MPa

Continuous maps show that \( \sigma_{FCM} \) profile is relatively homogeneous along \( \theta \)-direction of the bulk.

In Fig. 4, Maximum \( \sigma_{FCM} \) was reduced with increasing the SUS ring width. For \( R_{W20} = 20 \text{mm} \), the disk bulk: Max \( \sigma_{FCM} \) = 150 MPa

Ring bulk: Max \( \sigma_{FCM} \) = 150 MPa

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

IV. Conclusion

We have compared the numerical results of the electromagnetic hoop stress, \( \sigma_{FCM} \), during FCM from 20 T at 50 K, and the thermal hoop stress, \( \sigma_{thermal} \), 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 \( \sigma_{FCM} \) in the ring bulk could be alleviated by the wider SUS ring.

- The optimal design of the reinforcement ring should be constructed so that the total hoop stress, \( \sigma_{FCM} + \sigma_{thermal} \), could be less than the fracture strength of the bulk during FCM.

Total hoop stress, \( \sigma_{total} \), during FCM under cooling

\[ \sigma_{total} = \sigma_{FCM} + \sigma_{thermal} \]

Fig. 5. Thermal hoop stress, \( \sigma_{FCM} + \sigma_{thermal} \), profile along \( \theta \)-direction on the top surface of the bulk reinforced by SUS ring with various widths during cooling from 300 K to 50 K for each bulk.

In Fig. 5, under cooling, maximum \( \sigma_{FCM} \) was also reduced with increasing \( R_{W20} \). The reinforcement using wider SUS ring was effective for each bulk.

When the SUS ring with \( R_{W20} = 5 \text{mm} \) was used for both cases, tensile \( \sigma_{FCM} \) higher than 450 MPa is applied, which is as high as the fracture stress (\( \approx 59 \text{MPa} \)) 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.