Modelling of the pulsed field magnetization of a (RE)BaCuO bulk with a superconducting weld

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***Abstract*— The Pulsed Field Magnetization (PFM) is a compact and fast method to magnetize superconducting bulks compared to the field cooling method. However, the heat generation induced by the strong applied variable magnetic field during the PFM makes high trapped magnetic field harder to achieve. In order to make the REBaCuO bulks easier to magnetize by PFM, superconducting bulks including a superconducting weld are studied taking into account the thermal and electromagnetic properties of the weld different from those of the bulk body. This artificial grain boundary obtained by superconducting welding method might increase the trapped magnetic flux without increasing the applied magnetic field. In this paper, we are modelling the superconducting weld behavior during PFM using a 3D finite element model with the software COMSOL Multiphysics. The simulations are based on an H-formulation from Maxwell's equations and the heat diffusion equation. We analyse the impact of the critical current J_c of the weld on the trapped magnetic field.**

Keywords—Superconducting weld, (RE)BaCuO, Pulsed field magnetization

I. Introduction

The superconducting welding process for (RE)BaCuO bulks consist of the use of a superconducting material with a low peritectic temperature to make an artificial grain boundary between two single grain bulks. Superconducting welded bulks have shown good trapped field in field cooling at 77 K [1]–[3] and the crystallization process is well known [4].

The pulsed field magnetization (PFM) appears to be a more compact way to magnetize superconducting bulk compared to the field cooling method. However, the applied magnetic field during PFM must be very large for the flux to reach the sample centre and completely magnetize the bulk. Consequently, the heat generation induced by fast flux motion during the pulse decrease the maximum achievable trapped field [5]. In order to increase the trapped flux obtained by PFM, a superconducting weld placed at the middle of the bulk is considered with a critical current J_c weaker than that of the bulk body. By doing so, we are expecting the magnetic field to penetrate the bulk through the weld, thus reducing the required applied field to fully magnetize the sample.

In this paper, we are simulating by Finite Element Method (FEM) the PFM of a superconducting bulk including a junction with a different J_c on a 3D model implemented on the software COMSOL Multiphysics.

II. Numerical model description

A. Applied magnetic field

During the PFM process, a capacitor is discharged into a coil placed around the bulk. The applied variable magnetic field $B_a(t)$ is supposed to be uniform, on the z direction and have the following expression:

$$B_a(t) = B_{max}\frac{t}{\tau}\exp\left(1-\frac{t}{\tau}\right) \quad (1)$$

with τ the time constant of the magnetization circuit set at 10 ms in our model and B_{max} the maximal applied magnetic field.

B. Bulk description

Fig. 1 shows the studied welded bulk, which is 30 mm in diameter and 15 mm in height. The weld is a 1 mm wide superconducting slice located in the centre of the bulk.

The E-J power law gives the relation between the electric field E and the current density J inside the bulk and the weld in the superconductive state:

$$E(J,\mathbf{B},T) = E_c\left(\frac{J}{J_c(\mathbf{B},T)}\right)^{n(\mathbf{B},T)} \quad (2)$$

where J_c is the critical current density, E_c the critical electrical field of 1 μV/cm and n the exponent of the power law. The expression of J_c is a function of the temperature T and the flux density $\mathbf{B}$ given by the Kim's model [6] and by assuming a linear relation between J_c and T as in [7]:

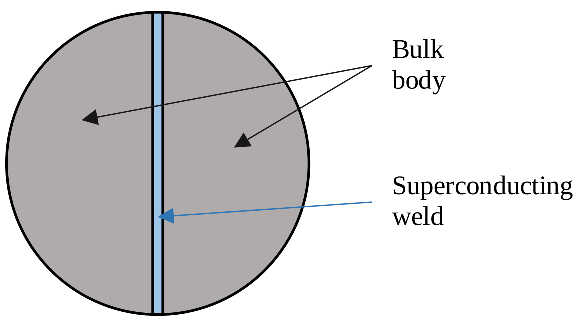

Fig.1. The superconducting weld separates the bulk body into two parts.

$$J_c(\mathbf{B},T) = \frac{J_{c0}}{\left(1+\|\mathbf{B}\|/B_0\right)^{\beta}} \times \frac{1-T/T_c}{1-T_0/T_c} \quad (3)$$

where β and B_0 are constants, T_0 the initial bulk temperature before the pulse, T_c the critical temperature of the superconductor and J_{c0} is the critical current for $\|\mathbf{B}\| = 0$ and $T = T_0$. The variation of the n exponent over $\mathbf{B}$ ant T is expressed as:

$$n(\mathbf{B},T) = \left(n_1 + \frac{n_0 - n_1}{1+\|\mathbf{B}\|/B_0}\right) \times \frac{T_0}{T} \quad (4)$$

where n_0 and n_1 are the n values for $T = T_0$ when, respectively, $\|\mathbf{B}\| = 0$ and $\|\mathbf{B}\| >> B_0$.

The welded part having a lower J_c, the magnetic field would penetrate the bulk through it, thus generating a large temperature rise in this region. Since this temperature rise might exceed T_c, the model have to take into account a possible transition between the superconductive state and the normal state. For this purpose, we define two resistivity, the normal state resistivity ρ_n, which is assumed constant, and the superconducting resistivity ρ_s, which comes from the E-J law:

$$\rho_s(J,\mathbf{B},T) = \frac{E_c}{J_c(\mathbf{B},T)}\left(\frac{J}{J_c(\mathbf{B},T)}\right)^{n(\mathbf{B},T)-1} \quad (5)$$

The transition between both resistivity is modelled using transition functions. The resulting expression of the material resistivity ρ is:

$$\rho = \left(1-\tan\left(\frac{T_c - T}{0.2}\right)\right)\frac{\rho_s}{2} + \left(1-\tan\left(\frac{T-T_c}{0.2}\right)\right)\frac{\rho_n}{2} \quad (6)$$

The behaviour laws presented in the previous part are coupled with an H-formulation of the Maxwell's equations.

C. Thermal model

As shown in Fig. 2, during the PFM process at temperature below 77 K, the bulk is set on the cold head of a cryocooler in a vacuum chamber. The thermal insulation is assumed perfect, thus the only thermal exchange happen at the surface between the bulk and the cold head.

In the thermal model, only the superconducting bulk is simulated and the cryocooler cold head is modelled by a constant heat exchange power P_{cryo} on the bottom side of the bulk. The temperature distribution over the bulk is determined by solving the heat equation.

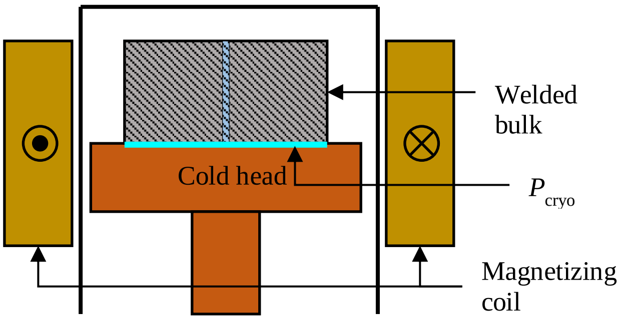

Fig.2. Schematic illustration of the PFM setup. Only the hatched parts are considered in the thermal model. The electromagnetic model simulate the hatched part and the surrounding space is considered as vacuum.

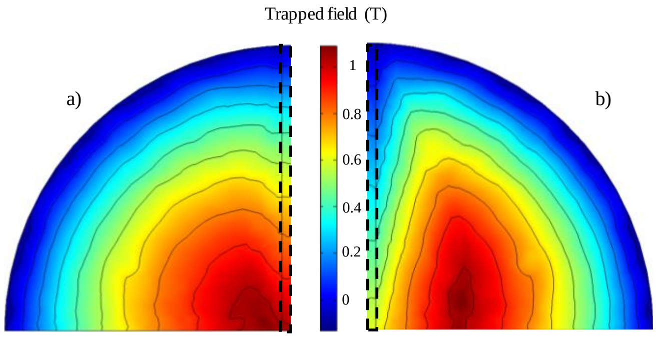

Fig.3. Examples of trapped magnetic field map after a 4 T pulse for different weld critical current to body critical current ratios. a) The weld critical current is 75 % of the bulk critical current. b) The weld critical current is 25 % of the bulk critical current.

III. Numerical results

We are investigating the influence of the applied field amplitude and the weld critical current on the trapped magnetic flux in the welded bulk one minute after the pulse. We compare the welded bulks performances during PFM with a normal bulk, i.e. without weld, by observing the total trapped magnetic flux and the optimal applied field. We also analyse the trapped field maps on the bulk surface after the pulse. As an example, the trapped field maps after a pulse of 4 T for different weld J_c to bulk body J_c ratios are shown in Fig. 3. Finally, by analysing the electromagnetic and thermal behaviour of the welded bulk, we conclude on the optimal weld critical current.

References

[1] K. Iida *et al.*, « Joining of Y–Ba–Cu–O/Ag bulk superconductors using Er–Ba–Cu–O/Ag solder », *Supercond. Sci. Technol.*, vol. 17, nº 2, p. S46–S50, janv. 2004, doi: 10.1088/0953-2048/17/2/060.

[2] K. Iida *et al.*, « Joining of different Y–Ba–Cu–O blocks », *Phys. C Supercond.*, vol. 402, nº 1, p. 119-126, févr. 2004, doi: 10.1016/j.physc.2003.09.083.

[3] X. Chai *et al.*, « Fast joining of melt textured Y–Ba–Cu–O bulks with high quality », *Phys. C Supercond.*, vol. 470, nº 13, p. 598-601, juill. 2010, doi: 10.1016/j.physc.2010.05.236.

[4] J. Yoshioka, K. Iida, N. Sakai, et M. Murakami, « The crystallization in the welding region for Y–Ba–Cu–O bulk superconductors », *Phys. C Supercond.*, vol. 386, p. 495-499, avr. 2003, doi: 10.1016/S0921-4534(02)02109-3.

[5] M. D. Ainslie et H. Fujishiro, « Modelling of bulk superconductor magnetization », *Supercond. Sci. Technol.*, vol. 28, nº 5, p. 053002, mars 2015, doi: 10.1088/0953-2048/28/5/053002.

[6] Y. B. Kim, C. F. Hempstead, et A. R. Strnad, « Critical Persistent Currents in Hard Superconductors », *Phys. Rev. Lett.*, vol. 9, nº 7, p. 306-309, oct. 1962, doi: 10.1103/PhysRevLett.9.306.

[7] K. Berger, J. Leveque, D. Netter, B. Douine, et A. Rezzoug, « Influence of Temperature and/or Field Dependences of the $E-J$ Power Law on Trapped Magnetic Field in Bulk YBaCuO », *IEEE Trans. Appl. Supercond.*, vol. 17, nº 2, p. 3028-3031, juin 2007, doi: 10.1109/TASC.2007.902095.