Structural Modeling and Optimization for REBCO Ring Magnet Using Coupled Electromagnetic-Thermal-Mechanical T-A Formulation

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***Abstract*—(RE)BCO high-temperature superconducting tape(HTS) can be stacked into a compact ring magnet along parallel magnetic field direction, with huge potential to trap strong magnetic fields. However, large mechanical deformation will be introduced in the process of making HTS ring magnets, which may lead to the degradation of the critical current density. This paper simulates the plastic deformation of HTS ring tape during the machining stage based on an elastoplastic bilinear isotropic hardening model. After that, a 3D coupled electromagnetic-thermal-mechanical T-A formulation was used to analyze the field cooling and pulse field magnetization trapping field, and the length and radius of the ring magnet are optimized. It is found that plastic strain will significantly reduce the critical current density resulting in a decrease of trapping fields. The influence of length and radius on the trapping field is restricted by each other. and the relationship between them needs to be reasonably matched.**

Keywords—REBCO Ring Magnet, elastoplastic model, coupled T-A formulation, structural optimization

I. INTRODUCTION

In recent years, superconducting permanent magnet stacked by the second generation high-temperature superconducting (2GHTS) tapes has been able to trap magnetic fields up to 17.89 T[1], and have great potential in high-field applications such as electric airplanes, nuclear magnetic resonance instrument(MRI), and magnetic levitation. Benefiting from the high critical current density and high transition temperature of superconducting tapes, trapped field magnets can be made more compact and with lower cooling costs.

The REBCO ring magnet is a jointless magnet separated by laser along the midline of superconducting tape and expanding by machining. Compared with the HTS bulk, the ring magnet has the advantages of flexible size and independent current loop, which can be made into a superconducting magnet with a diameter of more than 50 mm [2]. Moreover, it can also be magnetized along the parallel direction of the magnetic field, which means a higher critical current density than the stack. The reason is the a-b plane of the REBCO crystal and the loop current are parallel to the magnetic field, leading to the Lorentz force helping the flux vortex overcome the pinning forces are close to 0, and effectively reducing the influence of the magnetic field on the critical current density. At present, the trapped field of the ring magnet at 25 K has already reached 4.6 T [3].

The structural deformation of superconducting tapes will significantly reduce the critical current density. According to different practical applications, structural deformation including tensile, shear, torsion, bending, and delamination may occur in the production, processing, and operation of superconducting tape [4][5]. In the above deformation mode, the superconducting tape will have a certain critical current recession. In general, the irreversible strain of the REBCO layer can only reach 0.45 %. Since the residual strain of the REBCO super-conducting layer can reach -0.237% when cooling it to 77K, the strain of recession point can reach 0.7 %. Moreover, the critical current density of the superconducting tape will quickly decay to 0 after the plastic yield happens [6]

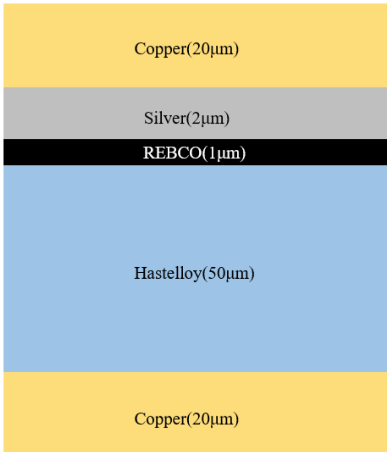


Fig. 1. Cross-section of REBCO HTS tape

T-A formulation is currently used for electromagnetic field simulation of superconducting tapes, and its calculation speed has been greatly improved compared with the traditional H-formulation [7]. Its advantage is that the superconducting tape is regarded as an infinitely thin shell, ignoring the thin layer structure in the thickness direction, which effectively reduces the meshing and greatly improves the calculation speed. The main idea of this method is to apply the T formulation to the superconducting thin shell to calculate the current density, and the A formulation to the non-superconducting region to calculate the magnetic field. The two are coupled by applying the boundary conditions of magnetic field and current density. Today, in the three-dimensional magnet structure, such as CORC cables and Roebel cables, the calculation advantage of the T-A formulation is obvious [8].

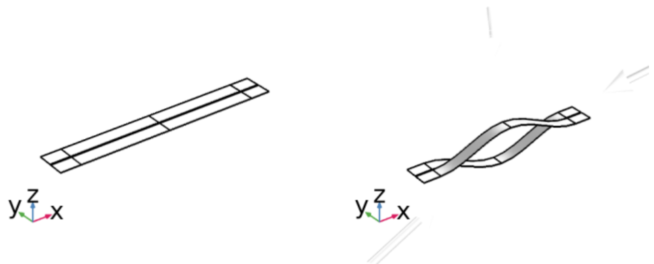
This work focuses on the construction of a 3D elastoplastic model of the mechanical expansion stage of the

REBCO ring magnet. The key is to evaluate whether the strain of the REBCO layer exceeds its irreversible strain during the expansion of the superconducting tapes, resulting in a decline in the critical current density. Based on the three-dimensional structure of the superconducting ring after deformation, the thermodynamic parameters and mechanical parameters are equivalent in one dimension, and the electromagnetic-thermal-mechanical coupled T-A formulation is constructed. Finally, based on the above multi-field calculation results, the length and expansion radius of the REBCO ring magnet is optimized and analyzed with the maximum capture field as the optimization objective.

II. NUMERICAL MODELING

A. Elastoplastic model

The superconducting tape is a kind of multi-layer composite structure material. The materials include copper, Hastelloy alloy, silver, REBCO, etc. the cross-section diagram is shown in Fig. 1. When the superconducting tape is expanded into a ring, it will inevitably produce large deformation. In this process, metal materials such as copper bear a large amount of plastic deformation, which reduces the bending stress of the REBCO layer. With the increase of deformation, the stress in the REBCO layer reaches the fracture strength, and the critical current density of the superconducting tape is irreversible degradation. The 3D deformation diagrams of the ring tape at the expansion and non-expansion stage are shown in Fig. 2.



(a) non-expansion (b) expansion

Fig. 2. 3D deformation diagrams of REBCO ring tape

The elastic-plastic model used in this paper is the linear hardening model, and the mechanical constitutive relation is :

$$\begin{cases} \sigma_i = E_i \varepsilon_i & if \ \ \varepsilon_i \ll \dfrac{\sigma_{si}}{E_i} \\ \sigma_i = \sigma_{si} + \left(\varepsilon_i - \dfrac{\sigma_{si}}{E_i} \right) E_{Ti} & if \ \ \varepsilon_i > \dfrac{\sigma_{si}}{E_i} \end{cases} \tag{1}$$

σ_i, ε_i are the stress and strain of each layer of the superconducting tape, σ_{si} is the yield strength of the metal materials of each layer of the superconducting tape, E_i is the elastic modulus of each layer, and E_{Ti} is the tangent modulus of the metal materials of each layer after yield. The above parameters are isotropic. At the same time, the isotropic hardening model is adopted, and the kinematic hardening is ignored [9]. Since REBCO is a brittle material, yield strength and tangent modulus are not set. i denotes layers of superconducting tape

The 3D model of superconducting tape is a thin shell, which is modeled by the Layerwise theory (LWT). In this method, the elements and integral points are constructed by the thickness of the shell and different layers. This means that only translational degrees of freedom are solved at each node, thus providing more accurate full-thickness stress and strain results than the equivalent single-layer method (ESL). The cost is that the simulation time is longer (the total number of degrees of freedom is more).

B. T-A formulation

The REBCO ring tape has no symmetrical structure in space. In order to accurately simulate the electromagnetic field of the REBCO ring magnet, the 3D configuration of the ring superconducting tape after the elastoplastic simulation is adopted. On the basis of the configuration, the T-A formulation is used to model the electromagnetic-thermal-mechanical coupling characteristics of the REBCO ring magnet during magnetization.

C. Multi-field coupling model

Since the T-A formulation does not consider the thickness direction of the superconducting tape, it cannot directly couple the solid heat transfer module as the H formulation[10]. In this paper, the thermodynamic parameters of each layer of the superconducting tape along the thickness direction are equivalent, and the heat transfer formulation the width direction is obtained :

$$\rho_{\text{eff}} C_{\text{eff}} h_{\text{tape}} \frac{\partial T}{\partial t} - k_{\tau\text{-eff}} \nabla_\tau \cdot \left(\nabla_\tau T \right) \text{-} k_{l\text{-eff}} \nabla_l \cdot \left(\nabla_l T \right) = Q_{sc} \tag{2}$$

Where τ, l are the transverse and longitudinal components of the superconducting tape, and ρ_{eff}, C_{eff}, $k_{\tau\text{-eff}}$, $k_{\text{l-eff}}$ respectively, are the equivalent density, equivalent specific heat capacity, equivalent transverse thermal conductivity and longitudinal thermal conductivity of the superconducting tape. T is the temperature of superconducting tape, Q_{sc} representing the heat source of the superconducting tape, which is generated by the thermal effect of current, and its value is Q_{sc}=E×J.

In order to couple the mechanics in the T-A formulation, the influence of the deformation of superconducting tape on the critical current density needs to be considered. Here, the empirical model is used to fit the influence of strain on the critical current density:

$$J_{c,\,\varepsilon} = k\left(\varepsilon\right) J_c\left(B,T\right) \tag{3}$$

Here, $k(\varepsilon)$ denotes the influence factor of strain on the critical current density, and its specific form is referred to Yan[11]

The calculation of stress and strain needs to consider the effect of Lorentz force $\mathbf{F}_{\text{L}}$=$\mathbf{J}\times\mathbf{B}$, which is brought into the elastic equation to obtain :

$$\nabla \cdot \boldsymbol{\sigma} + \mathbf{F}_{\text{L}} = 0 \tag{4}$$

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