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Dynamic fracture behavior of a crack in the bulk superconductor under electromagnetic force

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ABSTRACT

As the high temperature superconductors are under the electromagnetic field, large Lorentz body force can lead to the cracking of the superconductors. In the present paper, the dynamic fracture behavior of the crack in the bulk superconductor is investigated. We consider the central crack case and edge crack case. It is assumed that bulk superconductor is long enough and the demagnetization effect is neglected. By using the nonlinear constitutive relation in superconductor, the time-dependent Lorentz body force can be obtained. Then, the dynamic strain energy release rates are presented as the superconductor is under the magnetic field or with transport current. The results show that the dynamic strain energy release rates are also the periodic functions of time. The variations of dynamic strain energy release rate with edge crack length are different for the magnetic field and transport current cases.

1. Introduction

High temperature superconductors (HTSs) with zero resistance at low temperature can be used in many areas, such as permanent magnet and superconducting bearing [1,2]. HTSs have the ability of trapping high magnetic field. With the enhancing of the critical current density, higher trapped field has been achieved. Recently, a trapped filed of 17.6 T was reported in bulk GdBCO which is fabricated with top-seeded melt growth [3]. However, it is well known that the performance of superconductor is limited by the electromagnetic and mechanical stability. The mechanical stability also plays an important role in the applications of superconductors, which have attracted much attention in the past decades. As the magnetic flux penetrates into the superconductor, the current will be induced to shield the magnetic field. Then, Lorentz body force is generated by the magnetic field and induced current [2]. During the magnetization process, the mechanical damage or cracking caused by the Lorentz force in the superconductors will occur for unreinforced superconductors in high field [4,5]. Since the nature of bulk superconductor is brittle [6], in order to achieve high trapped field, stainless steel or carbon fiber was used to reinforce the mechanical strength of the superconductors [7–9]. It was pointed out that the required tensile strength is about 91 MPa for field of 18 T in a GdBCO superconductor bulk [3].

There are many theoretical studies on the mechanical behaviors in the superconductors. Based on critical state model, the magnetostriction in superconductors was studied extensively with linear elastic theory [10–12]. The magnetostriction curve is a closed loop and the shape of loop is dependent on the critical state model. Then, the stresses in some special structures

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Nomenclature

a	crack length
L	half length of superconductor
d	half width of superconductor
n	parameter of E–J relation
E_0	parameter of E–J relation
t	time
J_c	critical current density
J_0	normalized critical current density
f	frequency
q_x, q_y	body force components
q_0	normalized body force
H_a	applied external magnetic field
H_0	amplitude of external magnetic field
σ_x, σ_y, τ_{xy}	stress components
ρ	density
G	strain energy release rate
G_0	normalized strain energy release rate
I_t	transport current
I_p	normalized transport current
$\mathbf{E}$	electric field vector
$\mathbf{H}$	magnetic field vector

(disk, cylinder and slab) under magnetic field were investigated, and the results show that the stress will become tensile during the decreasing field [13–15]. It is to be noted that higher magnetic field can increase the maximum tensile stress which are dangerous for the superconductors. Then, the stress distributions in various samples were investigated under magnetic field [16–18]. In addition, some works were related to the magneto-elastic behaviors in the functionally graded superconductors [19,20], and the graded distribution of material property will affect the mechanical deformation in the superconductors.

During the process of fabrication of bulk superconductor, there are many defects and cracks in the superconductors [21]. The effect of cracks or defects on the electromagnetic behaviors of bulk superconductor was considered by Xia and Zhou [22]. They pointed out that current density is enhanced in the vicinity of the flaw tip. Moreover, some researchers also paid attention to the fracture behaviors of superconductors under magnetic field. Using the linear elastic fracture mechanics, the stress intensity factors in bulk superconductor for zero field cooling and field cooling were presented [23]. The stress intensity factor for field cooling is larger than that for zero field cooling in the same magnetic field. Then, different crack problems in long cylinder and slab under magnetic field were also studied by accounting for the effect of crack on the current distributions [24–27]. It was found that the stress intensity factor is not a monotonic function of the crack length. In order to consider the effect of the inhomogeneity and geometry structure on the fracture behavior, the crack problems in nonhomogeneous superconductors [28–30] and superconducting strips with different thicknesses were studied [31,32].

The above investigations mainly considered the crack problems in the superconductors under the static magnetic field. However, the superconductors are often subjected to the dynamic magnetic field or transport current. The dynamic stress intensity factor was considered for the superconducting strip in the transverse magnetic field [33]. There are a few researches on the dynamic behavior of a crack in the bulk superconductors. In this paper, we will investigate the dynamic response of a crack in bulk superconductor under the axial magnetic field or with transport current. Based on the nonlinear relationship between the electric field and current density, the time-dependent Lorentz body forces are obtained. After that, the dynamic strain energy release rates will be determined for the central crack case and edge crack case. The results show that frequency and magnetic field have obvious effects on the dynamic strain energy release rate. For the edge crack problem, the variations of dynamic strain energy release rate with crack length for magnetic field and transport current are different.

2. Central crack in the bulk superconductor

Firstly, we consider a large slab with a central crack and the slab is infinitely long, as shown in Fig. 1. The crack orientation is parallel to the x direction with reference to the Cartesian coordinate system (x, y, z). The slab occupies the region $(-L < x < L,\ -d < y < d,\ -\infty < z < \infty)$. The magnetic field H_a along z direction is applied and the length of through crack is $2a$. Since the slab is thick enough along z direction, the demagnetization effect can be neglected.

As the bulk superconductor is under the magnetic field which is larger than the lower critical magnetic field, the magnetic flux will penetrate into the sample. There are several methods which can calculate the electromagnetic field of