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Review

Evaluation of mechanical properties of high-temperature superconducting bulks fabricated by a melt-processing ☆

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Abstract

High-temperature superconducting bulks with highly oriented crystallographic structures are expected to be applied for high field quasi-permanent magnets, current leads and so on. However, the bulks sometimes fracture due to the thermal stress on the cooling process or the electromagnetic force during the magnetization. Thus, it has been recognized that improvement and understanding of the mechanical properties of bulks are indispensable for practical application. In this review, we summarize the present status of evaluation process of the mechanical properties for various bulks. The Young's modulus, Poisson's ratio, fracture strength, fracture toughness and hardness are evaluated by tensile, bending, compression and hardness tests. The mechanical properties are anisotropic, mainly due to the crystallographic structure and pre-existing micro-cracks associated with it. Data obtained are summarized and the influential parameters associated with the microstructure and testing condition for the mechanical properties are explained.

Keywords: Elastic modulus; Hardness; Fracture strength; Fatigue strength; Fracture toughness

Contents

1. Introduction

Due to their high flux pinning capability, researches have been widely conducted on R123 ($RBa_2Cu_3O_x$, where R is yttrium or rare-earth elements) high-temperature superconducting bulks with highly oriented crystallographic structures for application to high-field quasi-permanent magnets, large capacity current leads and current

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limiters [1]. However, the bulks have been reported to be fractured due to the thermal stress during cooling or electromagnetic force during the magnetization process at cryogenic temperatures or mechanical vibrations [2–4]. There is a wide scattering in the mechanical property data of bulks which have many pores and pre-existing micro-cracks associated with the fabrication process, and the data available for practical application has not been accumulated sufficiently. The standard evaluation method of the mechanical properties has not been established yet. Although there are many problems in the bulks, it is expected that they contribute in the field mentioned above and will be leading materials for superconducting devices if we overcome them. Thus, it is now recognized that improvement and understanding of the mechanical properties are indispensable for assurance of reliability of devices using bulks.

In this review, we summarize testing methods that have been carried out for bulks, such as tensile, bending, compression, fracture toughness, fatigue and hardness tests at room temperature (RT) and cryogenic temperatures. The mechanical properties evaluated for various bulks are the elastic parameters used for thermal stress and stress analyses in the bulk of various geometries such as the Young's modulus and Poisson's ratio, fracture strength for many loading mode, fracture toughness and hardness. The relationship among the parameters of the mechanical properties obtained by the different evaluation methods is explained and the effects of the micro-structures of bulks are described.

2. Evaluation method of mechanical properties

Although it has been reported that the fatal crack for whole a bulk was initiated in the <100> direction during the magnetization process [2–4], the mechanical properties of disc shaped bulks are commonly evaluated by bending tests on specimens cut from them [4–29] or by hardness tests [30–36]. INSTRON-type or servo-hydraulic-type testing machines are used for bending tests, and Vickers, Berkovich and Knoop indenters are used for hardness tests. Fig. 1 shows a bending test specimen mounted on a three-point bending jig. Although evaluation of mechanical properties have been conveniently carried out at RT, bending tests at 77 K are also carried out immersing the specimen, together with the jig, into a liquid nitrogen bath [12,14,16,19,21,22,24–27]. Recently, bending tests at 7 K using a testing machine equipped with a cryostat [23] and Vickers hardness tests at cryogenic temperatures using a tester equipped with a GM-cryocooler [34–36] have been also carried out. Since the distributions of pores, pre-existing micro-cracks, Ag particles and the R211 (R_2BaCuO_5) or R422 ($R_4Ba_2Cu_2O_{10}$) secondary phase particles in bulks are not uniform, tensile tests on small specimens are carried out so as to elucidate their distributions [15,18,20,37–53]. In this case, the tensile test specimen is glued to aluminum alloy rods by using epoxy resin, and an increasing load is applied through the universal joints. Since many micro-cracks perpendicular to the *c*-axis (direction of thickness of the bulk) are inevitably formed in bulks by a phase transformation during the fabrication process, all the tests mentioned above are carried out taking the directions of loading and crack propagation into account.

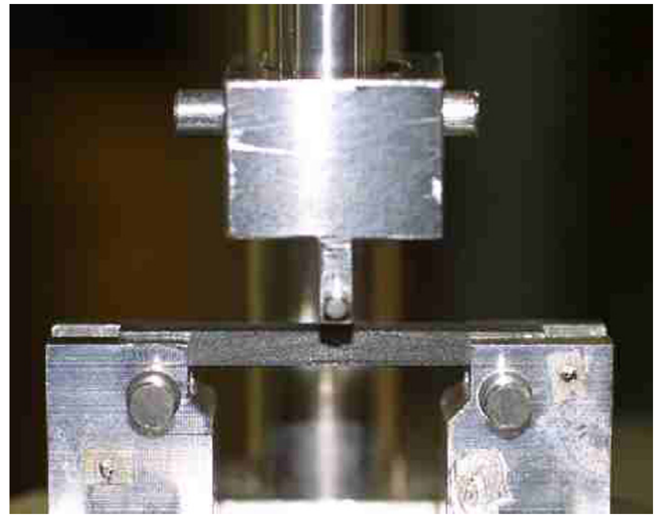

Fig. 1. A bending test specimen mounted on a three-point bending jig.

The Young's modulus and the Poisson's ratio of the bulk are evaluated from the slope of the stress–strain curve and the ratio of the transverse strain to the longitudinal strain in tensile or bending tests. The shear modulus can be calculated from these elastic parameters. The strains in any directions are measured by using strain gages glued to the specimen. Evaluation of the Young's modulus based on the relationship between the bending load and the deflection of the specimen has been also carried out [25]. In the evaluation of the elastic parameters by tensile and compressive loadings, the dimensions of the specimen should be carefully determined because the strain is underestimated in the short specimens such as $3 \times 3 \times 4\ mm^3$, frequently used. It has been clarified that length of 8 mm is required to obtain valid Poisson's ratio. This is due to the constraint of the deformation associated with crack opening near the interfaces between the specimen and the jig [42,54]. An anisotropy of the elastic parameters appears depending on the dimensions of the specimen to be mentioned below [42,54]. Evaluations of the elastic parameters by the Berkovich indentation load and depth [30] and by the ultrasonic velocity measurement [55] have been also carried out.

The tensile, bending and compressive strengths, which are the maximum stresses until the fracture, have been properly evaluated at RT. The tensile strength at 77 K, however, is sometimes underestimated due to the thermal stress induced by the difference in the coefficient of thermal expansion between the tensile test specimen of bulks and the rods of an aluminum alloy [52]. Although the thermal stress can be reduced by substituting to a titanium alloy