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Impact of fatigue loading on the critical current of Bi-2223 tapes under background magnetic field

Wei Chen[a], Haiyang Zhang[a], Yong Chen[a], Xinsheng Yang[a,*], Yong Zhang[a], Yong Zhao[a,b]

[a] Key Laboratory of Magnetic Levitation Technologies and Maglev Trains (Ministry of Education), Superconductivity and New Energy R&D Center, Southwest Jiaotong University, Chengdu 610031, China

[b] College of Physics and Energy, Fujian Normal University, Fuzhou, Fujian 350117, China

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ABSTRACT

In practical applications, such as superconducting magnetic energy storage (SMES) magnets or alternate current applications of superconducting power cables, high temperature superconducting (HTS) tapes are subject to cyclical loads caused by repeated thermal cycles and periodic electromagnetic forces. These repeated loads will affect electromechanical properties of the tapes. Previous electromechanical properties studies have provided useful information on the performance of multifilament Bi-2223 tapes under different forms of fatigue loading. The impact of axial tensile fatigue loading on the critical current (I_c) under external magnetic field, however, has not been reported. In this work, we studied the variation of I_c of the Bi-2223 tapes with the background magnetic field after different cycles of fatigue at 77 K. It was found that the effect of stress amplitude on the degradation of I_c for Bi-2223 tapes was more significant than the maximum stress. When the maximum fatigue stress approached the irreversible stress limit, the copper alloy reinforced Bi-2223 tapes still had good current-carrying properties after 10^5 fatigue loadings. I_c became less sensitive to the external magnetic field with the increase of the number of fatigue cycle.

1. Introduction

Bi-2223 HTS tape was the first cuprate superconductor fabricated into kilometer length, its electromechanical properties can be dramatically improved by the controlled over-pressure (CT-OP) sintering process and laminating tape with high-strength reinforcement materials such as copper alloy, stainless steel and Ni alloy [1–3]. Thus, Bi-2223 tape has been widely used in superconducting machines, such as power cables, transformers, high field magnet, motors and generators [4–9]. In application, such as superconducting magnetic energy storage (SMES) magnets or alternate current (AC) applications of superconducting power cables, the Bi-2223 tapes will be subject to periodic stress resulting in degradation of their current carrying properties [10–13]. Therefore, it is of great significance to study the current carrying characteristics of Bi-2223 tapes under different fatigue strength for the reliability evaluation of superconducting devices.

In the past few years, some scholars have studied the influence of different forms of fatigue loadings on the current carrying characteristics of Bi-2223 tapes. Ryan et al. [10] researched the fatigue behavior of I_c with Bi-2223 HTS tapes under tensile and compressive loads. They found that Bi-2223 tapes had a critical current decay of less than 5% when the tensile strain was 0–0.35 or the compressive strain was 0–0.2 after 100 cycles. In addition, when the tensile strain was 0–0.21 or the compressive strain was 0–0.15 after 1000 cycles, the critical current decay was also less than 5%. Shin et al. [12] studied the effect of different reinforcing materials on the fatigue properties and critical current attenuation behavior of Bi-2223 tapes. They found that when the stress ratio was equal to 0.1, the fatigue cycle reached 10^6 times and the critical current was only attenuated by 5%. The maximum fatigue stress of Bi-2223 tapes for Ag-Mn alloy sheath was 115 MPa, and the maximum fatigue stress for external reinforced Bi-2223 tapes was 320 MPa. Hojo et al. [13] found that when the static irreversible stress was equal to the maximum fatigue stress, the critical current of the stainless steel reinforced Bi-2223 tape was only attenuated by 2% after 10^6 fatigue loads. In practical application, superconducting tapes are used in a variety of complex magnetic field environments. However, the change of critical current of Bi-2223 tapes with background magnetic field under different fatigue strength has not been reported. Therefore, it is necessary to study the response of the critical current of Bi-2223 tapes under different fatigue cycles at external magnetic field.

In this work, we studied the variation of the critical current of the Bi-2223 tapes reinforced by copper alloy under 77 K with the axial

* Corresponding author.
E-mail address: xsyang@swjtu.edu.cn (X. Yang).

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Table 1
Specifications of Bi-2223 tape.

Type	HT-CA
Width	~ 4.5 mm
Thickness	~ 0.34 mm
Lamination materials	Copper alloy
I_c	~ 185 A
Manufacturer	Sumitomo electric

tensile fatigue load and the background magnetic field. Firstly, the effect of different stress ratios and maximum stress on the critical current degradation of the Bi-2223 tape was compared. Secondly, the response of critical current to the external magnetic field at different fatigue cycles was discussed.

2. Experimental

2.1. Samples

Commercially available Bi-2223 tapes, manufactured by Sumitomo Electric Industries fabricated using controlled-overpressure processing, were supplied for the test. The common Bi-2223/Ag tape was laminated by copper alloy in order to improve the mechanical strength. Properties and specifications of the tape samples are presented in Table 1.

2.2. Electromechanical property evaluation of Bi-2223 tapes

The monotonic axial tensile and dynamic axial fatigue tests of Bi-2223 tapes were performed using a computer controlled universal testing machine (equipment model: WDT-30, maximum force: 30,000 N, Shenzhen Kaiqiangli Testing Instruments Co., Ltd). The experimental system mainly includes force loading and critical current acquisition system, as shown in Fig. 1(a). The Bi-2223 tape was mounted between the upper fixture and the lower fixture shown in Fig. 1(b). The upper fixture was attached to the load cell through a universal joint, the lower clamp was connected to an epoxy board, and the epoxy board was fixedly connected to the bottom of the Dewar. In the experiment, the length of the sample between the upper and lower clamps was 100 mm.

In order to understand the basic mechanical properties of the Bi-2223 tape, we performed axial monotonic tension experiments at room temperature (RT) and 77 K, respectively, at a constant rate of 0.5 mm/min. The axial tensile stress can be obtained by dividing the force by the cross-sectional area of the sample. The strain was obtained by removing the original length of the sample between the upper and lower clamps. When testing the relationship between the monotonic tensile stress and the I_c, the test fixture and sample were immersed in liquid nitrogen together. The voltage tap spacing was 40 mm. The *I-V* curve of Bi-2223 tape was measured at different tensile stress levels by four-probe method, and the I_c was determined by the electric field criterion of 1 μV/cm. In order to determine the irreversible stress limit of the Bi-2223 tape, the critical current can be measured by unloading to 5 N at each stress step, which was equivalent to the state of unloading, as in Ref. [13].

The Bi-2223 tape dynamic axial tensile fatigue test and the critical current test after fatigue were carried out in the liquid nitrogen bath. In the fatigue analysis, the following parameters and formulas need to be defined [12]. $\Delta\sigma = \sigma_{max} - \sigma_{min}$, $\Delta\sigma$, σ_{max}, σ_{min} represents stress amplitude, maximum stress and minimum stress, respectively. $R = \sigma_{min}/\sigma_{max}$, where R was called stress ratio. So, $\sigma_{min} = R\cdot\sigma_{max}$. In this paper, the stress ratio was chosen to be 0.1 and 0.5. The frequency of fatigue loading was 0.5 Hz, but the first 100 cycles were set to 0.25 Hz. The sample after fatigue loading for a certain number of cycles such as 1, 10, 10^2, 10^3, 10^4, 10^5 was unloaded to 5 N to test its critical current at self-field. Then, we put the current to the excitation coil to test the critical current of the Bi-2223 tapes under different background magnetic fields. The direction of the background magnetic field $B \perp$ *a-b* plane of the tape, the calibration curve of its strength and excitation current is shown in Fig. 1(c).

3. Results and discussions

3.1. I_c – monotonic axial tensile stress behavior

Fig. 2 shows the axial tensile stress-strain curves of copper alloy reinforced Bi-2223 tape at RT and 77 K. The basic mechanical parameters of the Bi-2223 tape, such as the 0.2% offset yield stress, σ_y, can be obtained from the stress-strain curve [14]. The yield stress of copper alloy reinforced Bi-2223 tapes at RT and 77 K was 226 MPa and 327 MPa, which was equivalent to tensile load of 346 N and 500 N, respectively.

Fig. 3 shows the I_c/I_{c0} of Bi-2223 tape as a function of tensile stress. The ordinate in the Fig. 3 represents the normalized critical current of the Bi-2223 tape, I_c represents the critical current tested at the respective stress level, and I_{c0} represents the critical current at zero tensile stress. In order to test the reversible behavior of the critical current of Bi-2223 tape, the critical current is tested again with unloading from the respective stress level to 5 N. At the same time, the definition of the irreversible stress limit, σ_{irr}, is 99% I_c of the original tape when the force is unloaded to 5 N. Therefore, by comparing the loading and unloading curves, the irreversible stress limit is 281 MPa, corresponding to 430 N. In the fatigue test, the maximum fatigue stress is selected based on the irreversible stress limit measured in monotonic tensile.

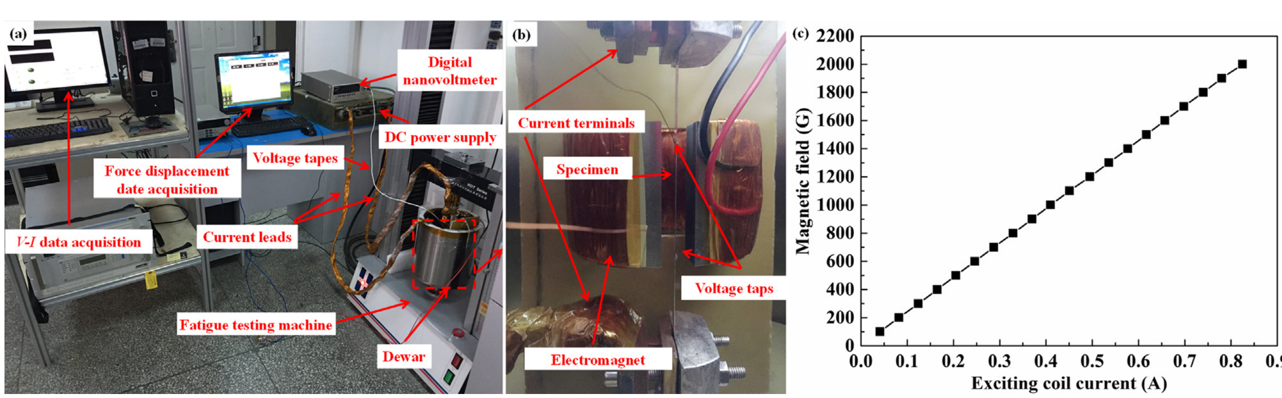

Fig. 1. Load loading and critical current acquisition system; (a) Panoramic photo of the test device. (b) Monotonic tensile and fatigue test installation diagram of Bi-2223 tape at 77 K. (c) The calibration curve between the current of the excitation coil and the magnetic field.