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Irradiation performance of rare earth and nanoparticle enhanced high temperature superconducting films based on YBCO

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ABSTRACT

The new series of commercially produced high temperature superconducting (HTS) tapes based on the $YBa_2Cu_3O_7$ (YBCO) structure have attracted renewed attention for their performance under applied magnetic fields without significant loss in supercurrent compared to the earlier generation of conductors. This adaptability is achieved through rare earth substitution and dopants resulting in the formation of nanoparticles and extended defects within the superconducting film matrix. The electrical performance of Zr-(Gd_x,Y_{1-x})$Ba_2Cu_3O_7$ and (Y_{1-x},Dy_x)$Ba_2Cu_3O_7$ coated conductor tapes were tested prior to and after neutron exposures between 6.54×10^{17} and 7.00×10^{18} n/cm^2 ($E > 0.1$ MeV). Results showed a decrease in superconducting current with neutron irradiation for the range of fluences tested, with losses in the Zr-(Gd_x,Y_{1-x})$Ba_2Cu_3O_7$ conductor being more rapid. Post-irradiation testing was limited to evaluation at 77 K and applied fields of up to 0.5 Tesla, and therefore testing at lower temperatures and higher applied fields may result in improved superconducting properties as shown in previous ion irradiation work. Under the conditions tested, the doped conductors showed a loss in critical current at fluences lower than that of undoped $YBa_2Cu_3O_7$ tapes reported on in literature.

Introduction

The goal of this work is to evaluate the irradiation response of coated conductors based on rare earth and nanoparticle doping of $YBa_2Cu_3O_{7-x}$ (YBCO) high temperature superconductors and to provide a preliminary evaluation of these types for possible fusion magnet applications. The materials under investigation represented different methods for enhanced flux pinning for improved performance under externally applied magnetic fields. Ion irradiation by 5 MeV Ni and 25 MeV Au were previously investigated for coated conductor tapes of $GdBa_2Cu_3O_7$, Zr-(Gd_x,Y_{1-x})$Ba_2Cu_3O_7$ and (Y_{1-x},Dy_x)$Ba_2Cu_3O_7$ [1,2]. While predominantly within in the electronic stopping regime, the ion irradiation conditions studied for these HTS tapes were within a low electronic to nuclear stopping ratio (S_e/S_n). Comparison with earlier data on YBCO tapes revealed a significant sensitivity of conductors to electronic stopping effects [1], but also showed promising irradiation data for the rare-earth and nano-particle doped conductors suggesting that such conductors may perform well under neutron irradiation. Based on the preliminary results from ion irradiation studies further work on the $GdBa_2Cu_3O_7$ tapes was not continued. This was due to the greater sensitivity of this material to ion irradiation compared to the Dy and Zr-doped conductors. While the performance of the ion irradiated $GdBa_2Cu_3O_7$ films was improved with respect to conventional YBCO films, Gd_2O_3 nanoparticles present within the films (which in addition to stacking-fault and intergrowth gives the conductor improved in-field performance) dissolved with increasing irradiation fluence.

In this work, the response of Zr-(Gd_x,Y_{1-x})$Ba_2Cu_3O_7$ and (Y_{1-x},Dy_x)$Ba_2Cu_3O_7$ coated conductor tapes to neutron irradiation is examined. Electrical characterization of two high temperature superconducting (HTS) tapes was performed both prior to and following irradiation. The Zr-(Gd_x,Y_{1-x})$Ba_2Cu_3O_7$ and (Y_{1-x},Dy_x)$Ba_2Cu_3O_7$ tapes are commercially available from SuperPower and American Superconductor, respectively, and utilize nanoparticles and correlated defect structures within the films to produce conductors for operation under higher applied magnetic fields than earlier YBCO tapes. The results of neutron exposures between 6.54×10^{17} and 1.12×10^{19} n/cm^2 ($E > 0.1$ MeV) at irradiation temperatures of ~80 °C were examined.

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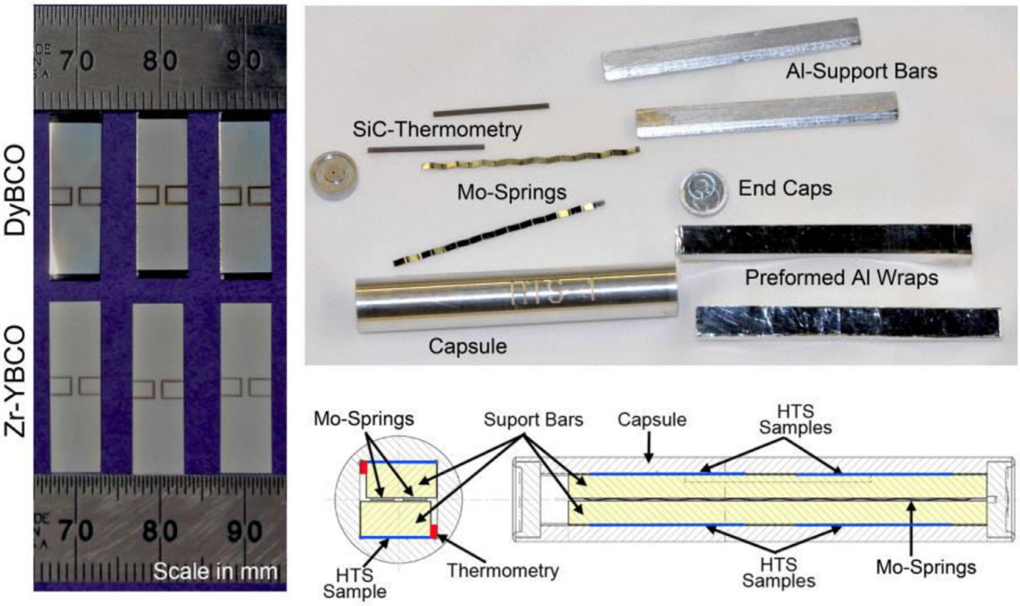

Fig. 1. Photos and schematic diagram of the bridged tapes and components of the neutron irradiation capsules used for this study. The superconducting tapes were placed on high purity aluminum support bars and wrapped in aluminum foil. Inside the capsules the tapes were in contact with the inner wall of the capsule to provide maximum cooling.

Experimental methods

The Zr-(Gd_x,Y_{1-x})$Ba_2Cu_3O_7$ was purchased from Superpower Inc. and consists of an approximately 0.8 µm thick superconducting film deposited via metal organic chemical vapor deposition on a 1-cm-wide MgO IBAD buffered metal strip. The "Zr-YBCO" material involves Zr doping (5 at%) that results in as-grown stacks of barium zirconate nano-disks designed to provide correlated pinning for fields aligned near the *c*-axis [3]. The (Y_{1-x}, Dy_x)$Ba_2Cu_3O_7$ tape, designated "Dy-YBCO", was provided by American Superconductor and was fabricated through metal organic deposition (MOD) on a RABiTS^{TM} template. It has a nominal superconducting layer thickness of 1.2 µm (excluding non-superconducting phases and porosity). The Dy-doping of the Dy-YBCO at Y:Dy of 2:1, resulted in an as-grown random distribution of $(Dy,Y)_2O_3$ nanoparticles and a high density of *ab*-plane defects designed to provide an enhanced self-field critical current (I_c) and strong pinning for fields parallel to the *ab*-planes at temperature > 50 K [4–6].

Prior to irradiation, samples were reduced in width to 6 mm to fit within the irradiation capsules. The samples were then sputter coated with a ~2 µm thick Ag over layer. A 2 mm long and 1 mm width bridge was created using an Eolite QuikLaze 50ST focused-laser-beam scribing system. All samples were characterized prior to and after neutron irradiation. Indium foil was applied between the Ag over layer and the copper current electrodes to limit the electrical contact resistance to between $\sim 10^{-6}$ and 10^{-4} Ω. The mounted sample was placed in liquid nitrogen (~77 K) between the pole faces of a copper-wound magnet, and the critical current, I_c, was measured a) for variable magnetic field strength (up to 0.5 Tesla) and fixed magnetic field angle, ϕ, normal to the tape plane (parallel to the crystal *c*-axis or $\phi = 90°$) and b) for fixed magnetic field strength (0.5 Tesla) and variable magnetic field angle (ϕ from $-20°$ to 120° with respect to the ab-planes). The critical current, I_c, is defined in this paper as the transport current at which the average electric field strength in the bridge was equal to 1 µV/cm.

Neutron irradiation capsules were designed and prepared for High Flux Isotope Reactor (HFIR) exposures using the hydraulic port facility. The irradiation capsules (Fig 1), also called generically rabbit capsules, utilize a square internal cross-section design loaded with internal packets containing samples. Each internal packet contains samples of one type of HTS sample. High purity aluminum bars provide mechanical support for the flexible HTS tapes, with the tapes and bars over-wrapped with high purity aluminum foil to form the packet. The HTS samples within the wrapped packet are placed against the internal wall of the irradiation capsule and are held in place with Mo-springs inserted between sample packets. The temperatures of the capsules were monitored and ~80 °C during irradiations. The irradiations were performed during HFIR cycle 456, in October 2014. The calculated fluences based on the recorded time and position within the core for the four capsules during the irradiation were 6.54×10^{17}, 1.30×10^{18}, 7.00×10^{18} and 1.12×10^{19} n/cm^2 ($E > 0.1$ MeV). Due to the high flux of the hydraulic port location, lower fluence exposures could not be accurately achieved.

The rabbit capsules were dry cut opened at the Irradiated Materials Examination and Testing (IMET) facility, with the internal packets removed and placed in paper tubes containing desiccant and loaded into shielded containers and sealed in plastic bags. Final sample unloading from the packets and electrical testing were performed in the Low Activation Materials Development and Analysis (LAMDA) laboratory at ORNL. The critical current, I_c, was determined at 77 K for both a) variable field up to 0.5 Tesla and fixed field orientation (normal to sample surface) and b) fixed field (0.5 Tesla) and variable field orientation.

Results and discussion

Two tapes each of the Zr-YBCO and DyBCO materials were tested for the 6.54×10^{17}, 1.30×10^{18} and 7.00×10^{18} n/cm^2 ($E >$ 0.1 MeV) irradiation conditions. The tapes exposed to the highest fluence (1.12×10^{19} n/cm^2) were not subsequently tested due to cross-contamination with thermoelectric samples added to the irradiation capsules. While the HTS samples in their aluminum wrapping were protected, the removable contamination level on the outside wrapping was too excessive to handle immediately in LAMDA, and the packets had to be set aside for activity levels to reduce. However, examination of the lower fluence samples was sufficient in evaluating the performance of the conductors.

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