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ABSTRACT

Second-generation high-temperature superconductor (2G HTS) tapes have demonstrated the ability to generate high magnetic fields and critical currents at a wide operating temperature range. In this paper, we study the mechanical properties of 2G HTS tape measured simultaneously with its critical current. The lattice deformations in the tape's substrate caused by applied mechanical stress were measured by neutron diffraction. In our experiments, the 2G HTS tape was exposed to uniaxial tensile force ranging from 250 to 1100 N at temperature 77 K. The current through the tape was scanned in the range from 22 to 42 A. The experimental results have been obtained in a cryogenic testing chamber for neutron scattering measurements of internal stresses under load with the incorporated HTS current leads. Critical stress is a vital parameter required for the modeling and designing of advanced superconducting magnets and also a variety of different superconducting applications based on 2G HTS tapes.

INTRODUCTION

High-temperature superconductors (HTS) are a practical alternative to conventional low-temperature superconducting materials because of their high critical temperature (T_c) and high upper critical field. Second-generation (2G) HTS tape is one of the most promising directions in the area of HTS wire research and development.[1] 2G HTS tapes were successfully used in various recent projects such as 24 kV/1 kA fault current limiter,[2] 275 kV/3 kA power cable,[3] and high field HTS magnet inserts used in a high continuous magnetic field hybrid magnet.[4]

The superconductors' ability to carry high electrical current is influenced not only by the operating temperature and the magnetic field but also by the mechanical strain.[5–7] The electromechanical properties together with the in-field critical current performance of 2G HTS tape are highly important criteria in the process of selection of the tape for a particular application.[7,8] One of the most advanced methods which allow the studying of mechanical properties of engineering materials has proven to be the measurement of strain and stress using the atomic lattice planes as a strain gauge. The ENGIN-X neutron diffractometer is an engineering science facility at ISIS neutron source optimized for this kind of strain measurements.[9] In order to provide a broad temperature range for ENGIN-X beam applications, the ISIS sample environment team has developed cryogenic testing chambers for neutron scattering measurements of internal stresses in engineering materials at cryogenic temperatures.[10,11] An earlier design of the testing chamber has been based on two single-stage cryocooler refrigerators (CCR) allowing measurements of strain and thus stress in engineering components under the uniaxial load up to 50 kN and at temperatures as low as 30 K.[10] The second version of the cryostat used a pair of more powerful two-stage CCRs, which allowed a significant reduction of the base temperature to 6 K and increase the uniaxial load up to 100 kN.[11] Each of the CCRs used in the design of the system produces cooling power around 50 W @ 50 K at the cryocooler's first stage. This extraordinary cooling power significantly exceeds the design's demand for cooling the infrared radiation shield and sample holding grips, so we considered using excessive cooling power for cooling HTS current leads. This design change allows simultaneous measurements of the electrical and mechanical properties of superconducting samples.

Here, we present and discuss the electromechanical properties of 2G HTS tape measured at 77 K. The experimental results have been obtained in the cryogenic testing chamber for neutron scattering measurements of internal stresses under load with the incorporated HTS current leads, which allowed simultaneous measurements of 2G HTS tape critical current. We also discuss the current leads' design, implementation, and test results.

HTS CURRENT LEADS

All cryogenic stress rig systems known to date are based on the same principle of utilizing the cooling power of CCRs for cooling the sample.[10–13] The lowest temperature of 5 K has been achieved in a stress rig cryostat commissioned by JAEA facility.[13] However, mechanical load applied to the sample in this load frame is limited by 10 kN which significantly restricts the area of the system applications. Nevertheless, none of the earlier-mentioned designs allows simultaneous mechanical and electrical measurements. As was explained in the introduction, we have used excess cooling power from the cryocooler's first stages to cool HTS current leads. Each of the current leads is thermally connected to the first stage of one CCR and the second stage of another. This approach gives us an advantage of symmetric positioning of the current leads, which is convenient in the overcrowded space of the cryostat. In order to isolate current leads electrically, we have used Kapton polyimide film with a thickness of 23 μ. The film was clamped between two flat copper surfaces held together by brass bolts with insulating washers.

The photo of the current leads assembly is presented in Fig. 1. In our design, we have used 12 mm SuperOx 2G HTS tape with critical current 500 A at 77 K.[14] The tape is supported mechanically by 2.5 mm thick G10 plate. Electrical contact between copper blocks welded to copper braids (used as normal metal parts of current leads) is provided through 0.1 mm thick indium foil. The foil was pressed between the flat surface of the bottom copper block and the silver-plated side of 2G HTS tape. The tape is squeezed between the upper and bottom copper blocks by brass bolts. Both current leads have been tested in liquid Nitrogen (and later in the assembly in vacuum) up to 120 A current without quench.

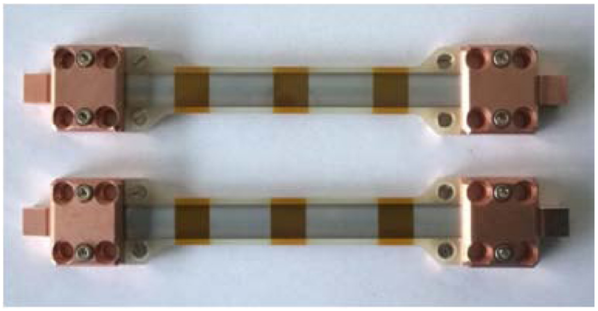

FIG. 1. The photo of the current leads assembly.

As it was mentioned above, "first stage CCR" side of each current lead is connected to an electrical feed-through installed on the outer vacuum can of the cryostat at room temperature through standard copper braid (Ø 5 mm) as another one ("second stage CCR" side) is connected to the sample grip through the copper braid of the same type.

EXPERIMENTAL RESULTS

In experiments, we have used modified 12 mm SuperOx 2G HTS tape.[14] Several multilayer $GdBa_2Cu_3O_7$ tapes (12 mm width, 60 μm Hastelloy thick, 100 mm length) were prepared with different critical currents I_c in the range from 140 to 380 A at 77 K, $T_c = 93$ K. The aim of the experiment was to measure tensile strain obtained from the diffraction measurement in the 2G HTS tape under applied stress and the simultaneous measurement of the superconducting critical current from $I-V$ (current-voltage) curve, to do these measurements a narrow neck was made to limit the current in the range of the current supply. The ends of the tape were pressed through indium foil to grips to ensure proper electrical and mechanical connection.

Initially, the contacts on the sample were damaged by the cooling process due to thermal shrinkage. In subsequent experiments, this factor was taken into account and constant stress was maintained during cooling. To speed up the experiment, a neutron beam was applied to the Hastelloy substrate side because Gd (mainly Gd^{157}) effectively attenuates the neutron signal even in the few microns layer of $GdBa_2Cu_3O_7$ superconductor. For this reason, in future neutron scattering experiments, we would recommend using $YBa_2Cu_3O_7$ tapes.

The sample was measured under the following conditions: the temperature was set to 77 K to stay well below $T_c = 93$ K. The uniaxial tensile force ranging from 250 to 1100 N has been applied to HTS tape and the current through the tape was scanned in the range from 0 to 42 A.

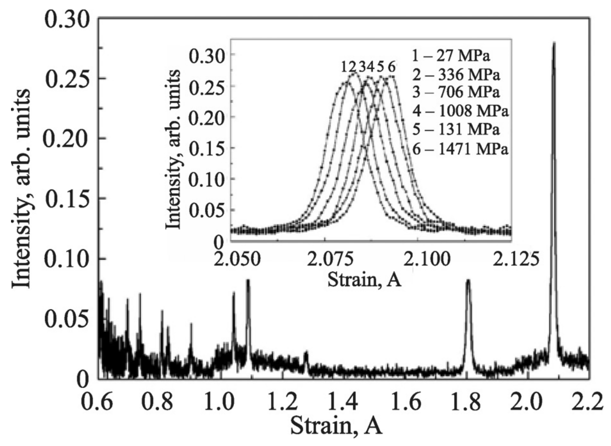

FIG. 2. The spectrum of Hastelloy 2G HTS tape substrate obtained on ENGINX[9] at 77 K and 336 MPa stress. Inset: diffraction peak positions at different tensile stresses.

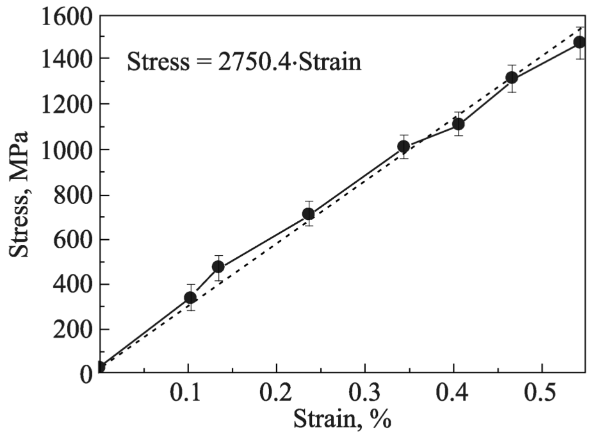

FIG. 3. Linear dependence of the stress vs strain curve obtained from direct strain measurements at 77 K.

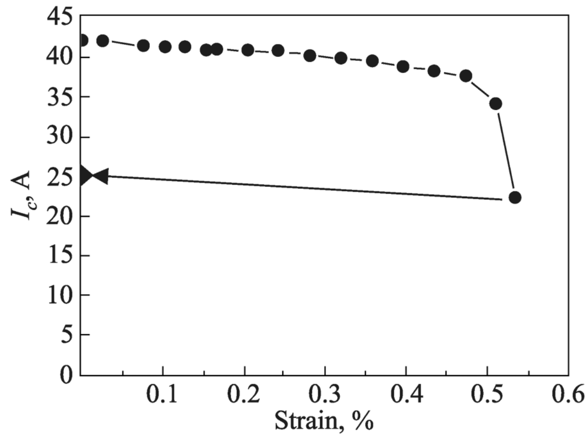

FIG. 5. Critical currents as a function of applied strain for 2G HTS superconducting tape at 77 K.

The internal strain in the Hastelloy substrate of the tape has been obtained from the lattice deformations (measured by neutron diffraction).[9] The strain was caused by an uniaxial mechanical load produced by 100 kN Instron servo-hydraulic testing machine.[11] Fig. 2 shows a neutron diffraction spectrum of Hastelloy at 77 K and 336 MPa stress. In the inset, we present the position of one of the diffraction peaks as a function of increasing stress (data analysis includes all diffraction peaks).

The calibration curve of the atomic 'strain gauge' shown in Fig. 3 was used to define internal strain caused by tensile stress. The conversion coefficient between the stress (in MPa) and strain (in %) was set at 2705 MPa/%.

The value of superconducting critical current for each load has been obtained from $I-V$ curves. It is evident that in Fig. 4, where we present $I-V$ curve for temperature 77 K and load 200 N, the tape loses superconductivity at critical current $I_c = 41.3$ A.

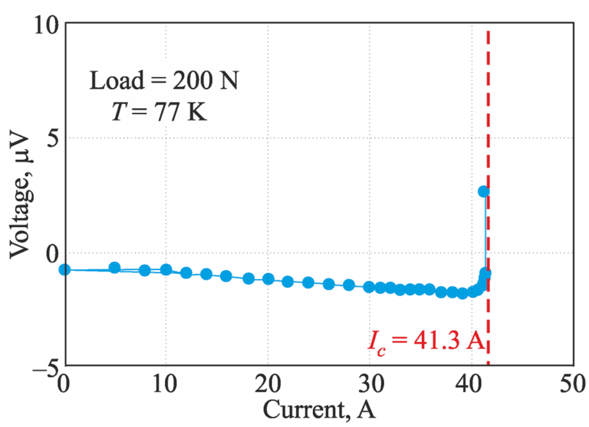

FIG. 4. Critical current (I–V curve) measurements at temperature 77 K and load 200 N.

Figure 5 shows the applied tensile strain dependence of the critical current at 77 K. Here, we can see a monotonic decrease of the critical current I_c by 10% by increasing the stress to 1310 MPa and strain to 0.473%. Until this point, the critical current always recovers to its previous value if the strain is reduced back. However, increasing stress above this point causes a much higher rate of I_c degradation down to 22.3 A at stress 1470 MPa and strain 0.534%. When the stress was reduced to zero, the critical current increased to 25 A, but was not fully recovered. That might be explained by irreversible damage to the tape. This 'step-like' behavior demonstrates close similarity to SuperOx tape strain data previously published in Ref. 8.

EXPERIMENTAL RESULTS DISCUSSION AND CONCLUSIONS

One of the main results of this work is establishing the strain limit of 0.473% beyond which the superconductivity starts to deteriorate irreversibly. Amazingly, this level of strain is significantly lower than one is expected according to the Hastelloy material yield point. That means that mechanical damage most probably happens in one of the seven layers deposited on the Hastelloy substrate. It would be reasonable to suggest that because of its ceramic nature (and as a consequence high brittleness), the HTS superconductor material is most prone to crack formation. In order to check this suggestion, we removed the top silver layer by chemical etching from two samples: one which was exposed to stretching force and another which was not (original one). Few microcracks were clearly observed through the microscope on the surface of HTS superconducting layer on the sample exposed to the stretching force, where as none were seen on the surface of the original one. From this observation, we can conclude that the strain limit of the SuperOx tape is defined by the brittleness of the HTS superconducting layer.

One of the main advantages of the cryogenic testing chamber with incorporated HTS current leads is the ability to measure the superconducting critical current simultaneously with internal stresses in superconducting wires. Similar systems based on strain gauges are broadly used for superconducting wire characterization in the area of applied superconductivity research.[7,8] However, strain-gauge-based measurements have intrinsic problems associated with strain-gauge calibration and reproducibility. These problems are absent in our case because the strain measurements are based on the accurate determination of a lattice parameter by neutron diffraction.[9] For example, in our experiment, the strain point 0.473% where the critical current is reduced by 10% (and after which the I_c deterioration rate dramatically accelerates) is 8% higher than one measured in Ref. 8.

In summary, we studied the mechanical properties of 2G HTS tape measured simultaneously with its critical current under uniaxial tensile force up to 1100 N at temperature 77 K. We also have established the strain limit beyond which the superconductivity starts to deteriorate irreversibly. This limit might be defined by the brittleness of the HTS superconducting layer of the tape. These measurements became possible due to HTS current leads incorporated into stress-rig cryostat.

As a further development, we are planning measurements of superconducting critical current, simultaneously with internal stresses in superconducting coil assemblies under mechanical load. From a long-term perspective, it may lead to the development of strain/stress measurement techniques applicable to real industrial superconducting magnet coils (MRI, NMR, accelerator magnets) using tomography-driven neutron diffraction.

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