Experimental investigations on the vortex instability and time effects of YBa$_2$Cu$_3$O$_{7-x}$ coated conductors

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1. Introduction

The developed high temperature superconducting conductors have a potential for lower cost, and the ability to tailor wire dimensions for specific applications, therefore, the higher $I_c$ in YBa$_2$Cu$_3$O$_{7-x}$ coated conductors (YBCO CCs) indicates the potential for broad use in a number of applications [1–3]. YBCO CCs are manufactured by coating the superconducting YBCO on a textured substrate, which providing a template for bi-axial texturing in the YBCO layer. The substrate is typically comprised of a Ni-alloy (hastelloy or a Ni–W alloy), upon which one or more oxide buffer layers have been deposited to provide a barrier that prevents chemical interactions between the YBCO and Ni. The top surface of the YBCO layer is protected by an Ag “cap layer,” and the entire structure is then typically encased in Cu or another stabilizer material. According to the YBCO CCs applications, the stabilities [4–6] including thermomagnetic, quench, AC loss etc. are attracted much attention during recent years, while there are few reports about the vortex stability and the time effects of the YBCO CCs. It is well known that current–voltage ($I$–$V$) measurement covering the whole range from the zero voltage state to the normal resistive branch is of importance in the investigation of the vortex stability, which, mainly for high bias currents and in particular for wide current sweep rate, to be used for the YBCO CCs large scale applications. In fact, since high power dissipation may damage the superconducting tapes and affect the superconducting properties, the highly dissipative states investigated by $I$–$V$ and voltage–time ($V$–$t$) measurements are important to extend the YBCO CCs further applications.

In this paper, we report experimental observations of the voltage jumps and significant time effects as a function of the current sweep rate (CSR) in the $I$–$V$ curves and $V$–$t$ curves of the YBCO CCs. The relevant current sweep rate is a useful tool in investigation details of the superconducting devices made by the YBCO CCs.

2. Experimental procedure

The YBCO CCs employed here are produced by the SuperPower Inc., with the version of SCS4050. All experimental specimens have a width of 4 mm, a thickness of 0.1 mm, and a length of 10.0 cm, which are cut from a long tape. The IBAD MgO was utilized as the buffer template and Surround Copper Stabilizer (SCS) was applied to encase the wire completely, which is described in details elsewhere [7–9]. The electrical voltage measurements are carried out by using the standard four point method, the electrical potential taps distance by $L = 30$ mm is located in the tape center. The whole sample is submerged with liquid nitrogen. In the experimental, a Keithley 2182 A with optional maximum values such as 10 mV, 100 mV, and relevant resolutions as 1 nV, 10 nV, is used to measure the sample voltage. The SMS magnet power source with the model of SMS 600, which is manufactured by the Crogenic Limit, is used to measure the sweep of the current. Different $I$–$V$ curves are obtained using dc currents with varied CSRs such as...
0.1, 0.2, 0.4, 0.8 and 1.6 A/s. In order to measure the time effects of the vortex stability, an expected current value is selected. Once the current value is reached, the voltage fluctuation with time is recorded. In the experimental procedure, the record time is chosen by 300 s. In addition, a Helmholtz coil with a maximum magnetic field of 150 Oe and a maximum resolution of 0.1 Oe is used to supplement the external magnetic field. Before carrying out the experiment, the external magnetic field is equal to 0, the YBCO CC specimen is cooled in the liquid nitrogen (zero magnetic field cooling). Thus, the \( I-V \) and \( V-t \) curves are divided into two groups. In the first group, the external magnetic field is equal to 0, and in the second group, the \( I-V \) and \( V-t \) curves are measured with different magnetic field values.

3. Results and discussion

Fig. 1 shows a set of the \( I-V \) curves for different CSRs from 0.1 to 1.6 A/s with zero magnetic field, the experimental temperature is room temperature. One can see that with the increase of CSR, the voltage shifts toward a lower voltage region, and at high current values, the difference becomes significant. In order to obtain the comparison of influences of the different CSRs on the voltages, the maximum voltage for different selected current values (i.e., 4.00, 11.30, and 18.84 A) is plotted as a function of the CSR in inset of Fig. 1. It is found that the voltage gradually decreases with the increase of the CSR. At room temperature, a linear \( I-V \) curve of the YBCO bulk sample is reported by Kilic et al. [10], here, one can see that the \( I-V \) curves of the YBCO CC sample are different with their results. According to the linear \( I-V \) curves of the YBCO bulk sample at room temperature, the electrical conductivity of which is the same as prime conductor, while for the nonlinear \( I-V \) curves of YBCO CCs at room temperature displayed in Fig. 1, we suggest that the reasons of the decrease in dissipation with the increase of CSRs are manifold. One of the most important reasons is that at high sweep rates, the increase in current can be concentrated to the YBCO CC surface which is covered by Cu, and this leads to relatively low dissipation values. The typical \( I-V \) curves for different CSRs from 0.1 to 3.2 A/s with zero magnetic field at liquid nitrogen temperature are displayed in Fig. 2. One can see that the \( I-V \) curves are presented by nonlinear characteristic. With the increase of current values, the moving vortex lattice undergoes an instability, leading to an abrupt change from superconducting state to normal state, which is displayed in the \( I-V \) curves as a voltage jump at a critical current or critical vortex velocity, which was observed not only in the lower temperature superconductors [11,12], but also in the high temperature superconductors [13,14].

Several mechanisms to interpret the nonlinear behavior were proposed by many research groups [15–19]. From Fig. 2, it is found that with the increase of CSR, the voltage shifts toward a lower voltage region, and the similar influences of the different CSRs on the voltages (i.e., 120, 130, and 140 A), which are plotted in inset (a) of Fig. 2. In addition, when CSR value becomes high, such as 0.8, 1.6 and 3.2 A/s, voltage jumps are observed in the \( V-t \) curves for the current larger than 120 A, while there are consecutive curves when the CSR is less than 0.8 A/s. The zoom in voltage jump in Fig. 2 is displayed in inset (b) of Fig. 2. In this work, the reason which can cause the voltage jumps seen in \( I-V \) curves is suggested that at high currents the power dissipated at current contacts can be high enough to cause a voltage jump. That is, the superconductivity can be destroyed by the Joule heating which can increase the sample temperature over the critical temperature. Thus, voltage jump is observed in the \( I-V \) curves. Moreover, it is noted that above the jump current values, the voltage decreases with an increase of the injected current with CSRs of 0.8 and 1.6 A/s. The results suggest the negative differential resistance which is displayed by voltage decrease with current increase, was caused by the plastic flow of vortices [10,20,21].

When CSR is equal to 3.2 A/s, the voltage decreases with an increase of current above the jump. The experimental results presented here suggest that the dissipation mechanism should depend on the sweep rate.

From Fig. 2, the voltage jump will be observed in the \( I-V \) curves when the CSR is larger than 0.8 A/s. In order to obtain the relaxation effects, the developing voltage as a function of time (\( V-t \) curves) for different current values (such as 20, 40, 60, 80, 100, 120 and 130 A) at 77 K for zero magnetic field were measured. Once the thermal equilibrium was reached in the YBCO CC sample, the current was injected with the CSR of 0.8 A/s. When the current value was reached the expected value (i.e., 20, 40, 60, 80, 100, 120, and 130 A), the voltage evolution measurement was started. The relaxation time was equal to 300 s. Experimental results were shown in Fig. 3. One can see that the voltage evolution process is divided into two stages when the current value is less than 100 A, in which a voltage gradual decrease with time and stability fluctuation were observed. Moreover, with the current value increase, the period of the voltage decrease became length. For the injected current of 100 A, a trend of voltage increase was observed after 200 s. From the \( V-t \) curves which were displayed in purple (120 A) and yellow (130 A), one can see that behind the voltage decline process, a remarkable voltage inclination was obtained, and then voltage jump was recorded, after that the voltage evolution became stability fluctuation. Now, let us turn to possible interpretations of the observed phenomena in quality. The first stage, which was displayed as voltage decrease in the \( V-t \) curves, was caused by the self-field relaxation with time. Take an example of \( I = 40 \) A, the fitted line with exponential law was shown by black line in Fig. 4. One can see that the fitted line takes good agreement with the experimental result.

For the high injected current (i.e., \( I = 100, 120, \) and 130 A), the voltage instability was observed with the current increase. In case of \( I = 100 \) A, the voltage increases slightly over time above 200 s, and in case of \( I = 120 \) A, the voltage increases within a range of 100–150 s, and for \( I = 130 \) A, the voltage increases within a range of 60–170 s, in which the increase amplitude is larger than that of \( I = 120 \) A (displayed by yellow line in Fig. 3). The reason is that, since the voltage increase was led to the increase dissipation, which was caused by the weak links break [10]. Due to the current penetration, more weak links were broken, which led to enhance the dissipation. After the voltage increase stage, two remarkable jumps were observed in Fig. 3. In order to get more information about the voltage jump, an repeated experimental measurement was carried out with the injected current of 120 A and CSR of...
At first, almost concurrent voltage jumps were observed which could eliminate the experimental random, and which suggested the voltage jump was a natural characteristic of the vortex instability in YBCO CCs. In order to present possible interpretations of the voltage jump, a stretched exponential relation \[ V(t) = V_0 \left[ 1 - \exp \left( -t/t_0 \right)^a \right], \] where \( V_0 \) is the saturation voltage, \( t_0 \) is the characteristic time, and the exponent \( a \) denotes a constant. The calculated \( V-t \) curves by using the model for the time evolution of voltage rise. The characteristic time values \( t_0 \) are taken as 0, 20, 40, 60, 80, 100, 120, 140 and 145 s. In the calculations, \( a \) is chosen by 20, saturation voltage \( V_0 \) is taken as 0.35 \( \mu \)V. Results are shown in Fig. 5(a). One can see that with an increase of \( t_0 \), the calculated results gradually take good agreement with the experimental results which was shown as a black line in Fig. 6(a). The physical origin of the characteristic time \( t_0 \) can be regarded as the relaxation time before voltage jump, which can be correlated to the chemical and anisotropic state of the YBCO CCs specimens. As a compare, the calculated \( V-t \) curves with different \( a \) and a constant \( t_0 \) were drawn in Fig. 6(b). In the calculations, the exponent \( a \) is taken as 1, 2, 4, 6, 8, 10, 12, 14, 16, 18 and 20, while the characteristic time \( t_0 \) is equal to 145.3 s, the saturation voltage \( V_0 \) is taken as 0.35 \( \mu \)V. One can see that the influences of \( a \) on the shape of the \( V-t \) curve are remarkable, with an increase of \( a \) (i.e., \( a \geq 4 \)), the calculated voltage does not immediately grow up with time but begins to keep an invariable value up to a certain time when the voltage starts to incline with time, and the larger the \( a \), the longer is the time. Moreover, with an increase of \( a \), the rise of voltage (jump) becomes extremely sharp. It can be forecasted that the parameter \( a \) is a temperature and magnetic field dependent constant at least. It is physical foundation is the vortex moving by driving current, the complex interplay or competition between pinning and depinning will lead to enhance the dissipation.
the voltage instability occurs at the low injected current (about 60 A), and the voltage increase starting far from critical current and an abrupt drop of the voltage are observed. Subsequently, the $I-V$ curves become stable, which are remarkable differences comparing with the $I-V$ curves without magnetic field. Moreover, take an example of $I = 70$ A, CSR = 0.8 A/s, the $I-V$ curves are plotted in inset of Fig. 7. In the experiments, the external magnetic fields are taken as 5, 10 and 15 mT, one can see that (1) the voltage instability occurs during the period of 50–100 s, voltage inclines with time and then drops sharply, (2) with an increase of the magnetic field, the maximum voltage increases, which is shown by the red arrow direction. We now give possible interpretations of these experimental results. At first, the reason of the voltage instability observed at low injected current which is far from critical current is that, comparing to the $I-V$ curves without magnetic field, vortex is introduced into the superconducting sample, which is significantly enhanced the Joule heating (dissipation) and leads to the voltage increase. Second, the voltage drop which probably corresponds to the sample temperature drop, and which is reached by heat transfer between the sample and liquid nitrogen. The similar experimental results of the Bi-2223/Ag samples were reported by Milan et al. [23]. Third, for the inset of Fig. 7, which is displayed the influences of magnetic field on the voltage increase, one can see that the voltage increases with the increase of magnetic field. The effects of the magnetic field on the voltage instability seen in the $I-V$ curves can be understood by the number of vortex which is determined by the magnetic field value. The more magnetic field, the more is the number of vortex, which enhances the dissipation and leads to the high voltage increase.

Finally we will say a few words about the importance of the current sweep rate on the practical applications of the YBCO CCs. According to the experimental and calculated results presented above, a CSR value should be selected dependent on not only the YBCO CCs intrinsic properties, but also strongly with magnetic field and temperature, the optimal CSR should be obtained by comparing and analyzing the different $I-V$ and $V-t$ curves. It is well known, stability including thermomagnetic, AC loss, quench, etc., is the importance challenge in the practical applications of the YBCO CCs, such as superconducting magnets, power transmission lines. Since the instability of the superconducting devices depend on the CSR, the CSR should be optimized, and relevant CSR in

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**Fig. 5.** $V-t$ curves at the constant current: $I = 120$ A, the CSR is equal to 0.8 A/s.

**Fig. 6.** The calculation $V-t$ curves compare with the experimental result (black line). (a) $t_0$ is taken as 0, 20, 40, 60, 80, 100, 120, 140 and 145 s, and while $x$ is chosen by 20, saturation voltage $V_s$ is taken as 0.35 μV. (b) the exponent $x$ is taken as 1, 2, 4, 6, 8, 10, 12, 14, 16, 18 and 20, while the characteristic time $t_0$ is equal to 145.3 s, the saturation voltage $V_s$ is taken as 0.35 μV.

**Fig. 7.** Set of $I-V$ curves of the YBCO CCs sample measured at liquid nitrogen temperature and external magnetic field of 15 mT, the CSRs are taken as 0.4, 0.8, 1.0, etc. Inset shows $V-t$ curves of the sample measured at liquid nitrogen temperature, CSR = 0.8 A/s, the magnetic fields are selected by 0, 5, 10, and 15 mT, in which the red arrow shows the direction of the voltage increase with an increase of magnetic field. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
designing superconducting devices should be considered and enhanced in future.

4. Conclusions

The influences of CSR on the vortex dynamic in the YBa$_2$Cu$_{3-x}$O$_{7-d}$ coated conductor samples were measured. It is found that (1) CSR has several effects on vortex motion in that it gives rise to enhancement of dissipation as the CSR decreases, (2) significant time effects and instabilities in current–voltage ($I$–$V$) and voltage–time ($V$–$t$) curves with and without magnetic field were observed. Thus, The CSR on practical applications of the YBCO CCs should be optimized by considering the $V$–$I$ and $V$–$t$ curves in the future.

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