YBCO 고온초전도체의 퀜치특성 연구

Quench characteristics of bare and of-laminated YBCO-coated conductor

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Abstract: This paper presents a study on the stability of bare and cu-laminated YBCO-coated conductor. we investigate the characteristics of quench/recovery behavior of YBCO test samples, bare and copper -laminated, by subjecting each test sample, immersed in a bath of liquid nitrogen boiling at 77.3 K, to a transport current pulse superimposed to a baseline DC current of 90-95% the critical current. The current pulse has an amplitude up to ~4.5 times the critical current and a duration of 300 ms. This paper presents both experimental and simulation results.

1. Introduction

Today's high-temperature superconductors are moving out of the laboratory and into the marketplace. Bismuth-based compounds are being fashioned into superconducting wires and coils. Yttrium-based compounds are being formed into the thin films. It is widely agreed that a high-temperature superconductor (HTS) is immune to disturbances arising from routine operation. Because of a great interest in application of YBCO to electric power devices, stability and protection of coated YBCO have become important issues[1-4]. For electric power applications, HTS is expected to remain intact under most fault modes. One such fault mode is an over-current pulse that drives the entire device normal over a brief period of time. The work reported here investigates this over-current fault mode in the simplest possible setting by subjecting test samples of coated YBCO to an over-current pulse with each test sample, bare (Ag coated) or Cu-laminated,immersed in a bath of liquid nitrogen boiling at 77.3 K while it carries a nominal DC transport current has an amplitude of 90-95% the critical current.

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2. Experimental Setup

Fig. 1 shows a schematic drawing of a front (in the direction of current flow) cross- sectional view of a 10-mm wide test sample. Two types of YBCO tape were used in the experiment: 1)10-mm wide and 10-cm long, bare or Cu- laminated; and 2) 4-mm wide and 15-cm long Cu-laminated. A bare sample has a built-in 3 to 8 m Ag layer coated over one surface of a 1-m thick YBCO layer, while a Cu-laminated sample has a 76-m thick copper strip soldered over the original Ag layer. In either sample type, as indicated in the figure, the reverse side is secured to a 150-m thick G-10 backing strip and only the metal side of the sample surface is exposed to liquid for cooling. Fig. 2

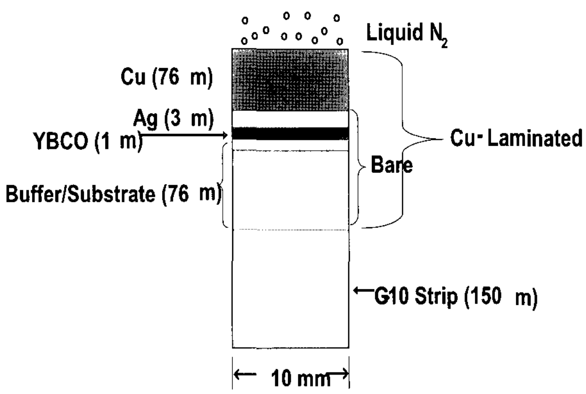


Fig. 1. Front cross-section view of YBCO test sample.

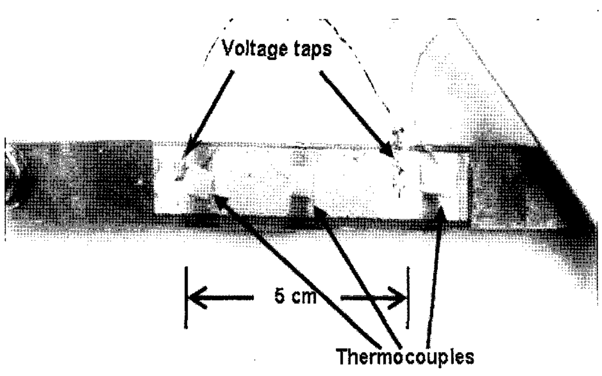


Fig. 2. Photograph of a 10-mm wide test sample with three thermocouples and two voltage taps, 5-cm apart.

shows a photograph of a 10-mm wide test sample in which three thermocouples and two voltage taps, 5-cm apart, are attached to the exposed surface.

3. Experimental Result

3.1 Bare YBCO sample with 10-mm width

It turned out to be very difficult to keep bare test samples from being destroyed when they were subjected to an over-current pulse with an amplitude that ranged from 200 to 300 A, 2 to 3 times the critical current measured at 77 K. Over-current pulses lasted less than 0.3 s. It became quite clear that it would be very difficult to operate a bare sample stably against an over-current pulse and to protect it from damage. It is important factor for stabilizer on the YBCO-coated sample to have higher stability. In the sample without cupper layer, it is difficult to control of the amount of increasing current. It was easily burned out.

3.2.Cu-laminated YBCO sample with 10-mm width

Fig. 3 shows the first set of voltage and current traces for a 10-mm, Cu-laminated test sample. The top graph in Fig. 3 shows V(I) trace of the test sample before the sample was subjected to over-current pulses. Using an electric field criterion of 1 V/cm, we obtain the sample's self-field critical current of 110 A at 77 K.

The next graph shows I(t) and V(t) traces for selected Runs. A typical I(t) trace, shown in the inset, begins at a transport current of 100A, then comes a pulse for a period of 300 ms, and ends with the original current of 100 A. The V(t) trace 1, shows the sample remaining superconducting at a transport current of 100 A, becoming resistive only during the pulse. A monotonic increase in voltage during the pulse indicates the sample temperature rising with time. At the end of the pulse, joule heating flux at the sample surface is only at 0.24 W/cm^2. During the pulse, the sample, in the current-sharing mode, forces an excess current beyond $I_c(T)$, the sample critical current that decreases with rising temperature, into the Cu laminate and Ag coating. The sample recovers immediately after the pulsing.

In V(t) trace 2, the sample had a total current during pulsing of 350 A, 3.18 times the critical current. About a quarter ways during the pulse, the voltage suddenly drops and reaches a plateau, implying that heating is matched by cooling that in turn keeps the sample temperature constant. One possible explanation for this voltage drop is an enhanced cooling that occurred at that heating level. In the plateau state, joule heating flux is 2.2 W/cm^2, well below a maximum nucleate boiling heat transfer flux of ~10 W/cm^2. The sample recovers quickly at the end of pulse.

In V(t) trace 3, the total current during pulsing was 446 A, 4.05 times the critical current. The same voltage drop observed in trace 2 occurs near the end of the pulse. The peak joule heating flux has increased to 8.3 W/cm^2, dropping to 7.3 W/cm^2 at the very end of the pulse. Note that because here the sample is clearly heated to an extent that its joule heating flux approached a maximum nucleate boiling heat flux of ~10 W/cm^2, recovery, instead of almost instant as in trace 1 and trace 2, has a short tail lasting ~50 ms. Fig. 4 shows a second set of voltage and current traces for the same Cu-laminated test sample. The top graph shows I(t) and V(t) traces at 23rd test in which the total current during the pulse is 500 A (max of our power supply), 4.55 times the critical current. As in the previous runs, the voltage drops, in this case, at about a half way into the pulse. The joule heating flux is 10.8 W/cm^2 at the peak, dropping to 8.7 W/cm^2 in the plateau. However, because 8.7 W/cm^2 is also close to the maximum nucleate boiling heat flux, the sample, as in 10th test, recovers with a tail lasting ~50 ms.

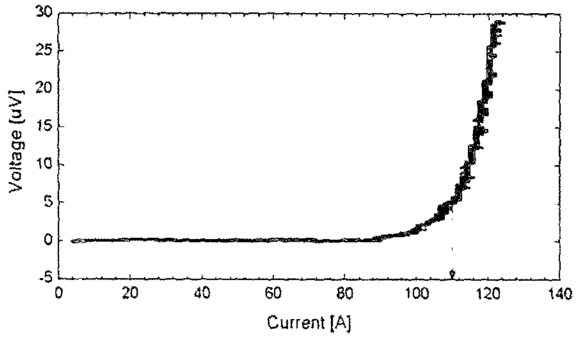
The bottom graph shows the V(I) trace recorded after 24 pulsing events, during each of which a total transport current in the sample reached nearly 5 times the critical current. A measured critical current of 110 A demonstrates that the sample remained essentially undamaged even after 24 shots of pulsing, indicating that Cu-lamination clearly "protects" the sample.

3.3. Cu-laminated YBCO sample with 4-mm width

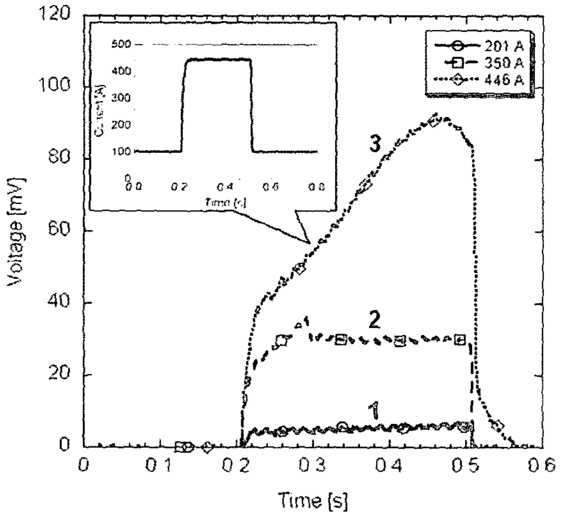
The 500-A power supply of the experiment was sufficient to drive 10-mm wide Cu-laminated samples into stable current- sharing mode during pulsing but insufficient to quench them. To quench these Cu-laminated samples and study their post-pulsing responses with the same power supply, new samples, each 4-mm wide and 15-cm long, were tested in the same sample holder. Two sets of voltage taps, 5-cm (V_5) and 10-cm (V_{10}) apart were attached to each new sample. Measured "virgin" self-field, 77-K critical currents were 55.8 A (V_5) and 55.2 A (V_{10}) or an average Ic of 55.5 A.

Note that scaled to 10-mm width, Ic becomes ~139 A, significantly greater than of 110 A measured for the10-mm test sample, results of which are given above.

Fig. 5 shows a set of graphs recorded with a 4-mm wide, 15-cm long Cu-laminated test sample. The top graph shows a typical I(t) (in the inset) and $V_5(t)$ traces for some selected Runs. I(t) begins at a transport current of 50 A (~0.92 Ic), then increases to 161 A (2.88 Ic) during the 300 ms pulse and returns to 50 A. The $V_5(t)$ trace for 29 tests (solid line), is essentially identical to those of 7th test, 10th test and 24th test, for the 10-mm sample shown before.

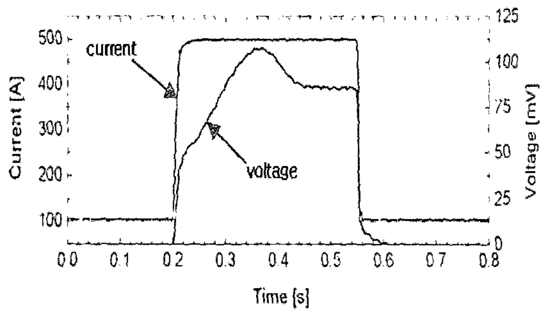


(a)

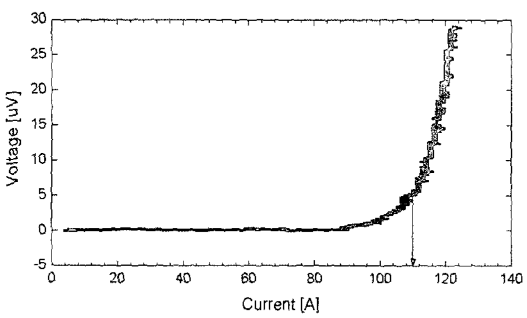


(b)

Fig. 3. (a) Set of V(I), I(t) and (b) V(t) traces for 10-mm wide Cu-laminated YBCO sample subjected to an over-current pulse and cooled by nitrogen boiling at 77K.



(a)

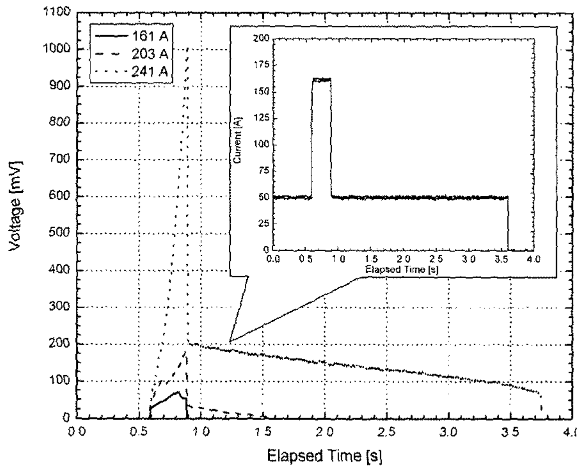


(b)

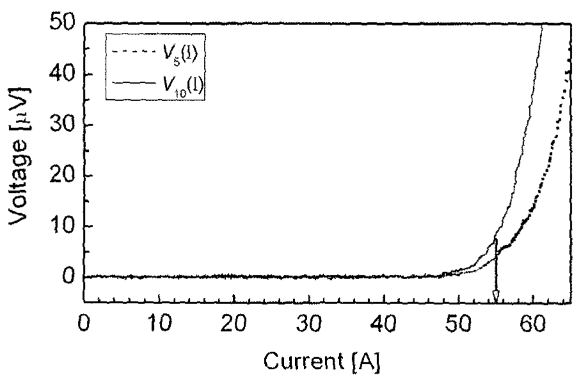
Fig. 4. (a) V(t) traces and (b) Set of V(I), I(t)for 10-mm wide Cu-laminated YBCO sample exposed to nitrogen boiling at 77K.

The second $V_5(t)$ trace (dashed line), from 44th test and for which I(t) reached 203 A (3.66 Ic) during the pulse, indicates that heating clearly exceeds cooling, reaching a peak joule heating flux of 18.6 W/cm2, almost twice the maximum nucleate boiling heat transfer flux for liquid nitrogen. Recovery is gradual, lasting 0.7 s. Finally, the dotted line trace is $V_5(t)$ from 59th experiment. Here I(t) increased to 241 A (4.38 Ic) during the pulse. In this run,heating reaches a peak joule heating flux of 122 W/cm^2, more than 10 times the maximum nucleate boiling heat flux for liquid nitrogen. Recovery thus takes place at a much slower rate than that observed above, in Run 44. Just before the transport current of 50 A was turned off, the sample is at a heating rate of 1 W/cm^2, clearly a rate that eventually leads to a complete recovery.

The bottom graph shows V(I) trace recorded after 15 pulsing events, during each of which a total transport current in the sample reached up to nearly 4 times the critical current. Measured critical currents remained nearly the same as those measured before the sample was pulsed: ~55 A (V_5) and 55.2 A (V10). That the sample remained essentially undamaged even after the sample was heated to a level that drove the cooling to film boiling regime once again shows that Cu-lamination clearly "protects" the sample.



(a)



(b)

Fig. 5. (a) Set of $V_5(t)$, I(t), $V_5(t)$, and (b) $V_{10}(I)$ traces for 4-mm wide Cu-laminated YBCO test sample exposed to nucleate boiling liquid nitrogen at 77K.

4. Simulation

The following power density [W/m^3] equation is applicable for the test sample under study.

$$C_{cd}(T)\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left[k_{cd}(T)\frac{\partial T}{\partial x}\right]+\rho_{cd}(T)J_{cd}^2-\frac{f_p P_{cd}}{A_{cd}}q(T) \qquad (1)$$

where $C_{cd}(T)$ is the temperature-dependent heat capacity of the "composite" conductor; $k_{cd}(T)$ and $C_d(T)$ are, respectively, the composite temperature-dependent thermal conductivity and effective electrical resistivity; f_p is the fraction of the conductor perimeter exposed to cooling; P_{cd} is the total conductor wetted perimeter; A_{cd} is the total conductor cross section area; and $q(T)$ is the heat transfer flux on the sample surface. Note that for "long" conductors, the axial thermal conduction term in the right-hand side of Eq. 1 may be neglected. $C_d(T)$ may be extracted through a parallel-circuit model operating in the Cu-laminated sample, i.e., the effective resistance, $R_{cd}(T)$, over a distance of voltage taps, given by:

$$R_{cd}(T)=\frac{R_m(T)R_s(T)}{R_m(T)+R_s(T)} \qquad (2)$$

$R_m(T)$ and $R_s(T)$ are, respectively, the total temperature-dependent matrix and superconduc- tor resistances across a set of voltage taps. For the Cu-laminated sample, $R_m(T)$and $R_s(T)$ are in turn given by:

$$R_m(T)=\frac{R_{Ag}(T)R_{Cu}(T)}{R_{Ag}(T)+R_{Cu}(T)};\quad R_s(T)=\frac{\partial V_s}{\partial I_s}=n\left(\frac{V_c}{I_c}\right)\left(\frac{I}{I_c}\right)^n \qquad (3)$$

where $R_{Ag}(T)$ and $R_{cu}(T)$ are, respectively, the total silver and copper resistance over the voltage taps. Vc is the critical voltage 5 V for 5-cm voltage taps and 10 V for 10-cm voltage taps; n is the conductor index: for both 10-mm wide and 4-mm wide samples, n was measured to be 18.5. Fig. 6 gives heat flux curve for nitrogen as a function of $T-T_{sat}$ where T_{sat} is the saturated liquid nitrogen temperature of 77.3 K. The shaded zone in the figure covers a range of nucleate boiling heat fluxes used in simulation.

4.1. Simulation Results

Simulation voltage in the current-sharing mode during pulsing agrees well with experiment if a nucleate boiling heat transfer line within the shaded area in Fig. 6 is used. Note that in the quenching mode the joule heating term in Eq. 1 is much greater than the cooling term, which is now given by the film-boiling region of the curve in Fig. 6. Fig. 7 shows both voltage and temperature plots

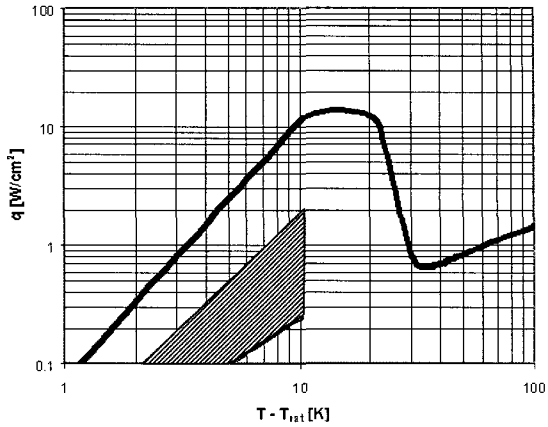


Fig. 6. Heat transfer curve (solid) for nitrogen with saturation temperature of 77.3 K. Shaded zone: nucleate boiling range used in simulation.

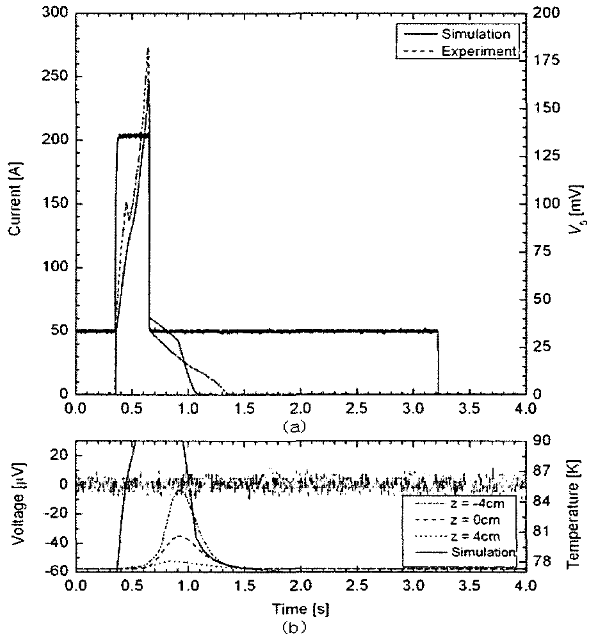


Fig. 7. (a) Voltage and (b) temperature plots during quenching : experiment from 44th test(dashed ling) ;simulation(solid line).

from Run 44 with the 4-mm wide sample. Although out of scale, the peak on the temperature reaches 109 K. If the negative effects of a poor thermal contact of the sensor on amplitude and response time of the temperature trace are taken into account, agreement between experiment (dashed) and simulation (solid lines) is quite good.

5. Conclusion

An over-current pulse experiment was performed on bare and Cu-laminated YBCO samples. The results have demonstrated that "composite"YBCO tape that incorporates a copper lamina of "significant" thickness stabilizes and to a degree "protects" the conductor against a "large" over-current pulse; in sharp contrast bare (Ag coating of thickness less than 10 m) samples were unstable and found easily to be damaged.

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References

[1] Robert C. Duckworth, Jinwun W. Lue, Dominic F. Lee, Robert Grabovickic, and Michael Gouge, "The role of nickel substrates in the quench dynamics of silver coated YBCO tapes," IEEE Trans. Appl. Superconduc. Vol. 13, 2003, p.1768.

[2] Yukikazu Iwasa, Haigun Lee, Jiarong Fang, and Benjamin Haid, "Quench and recovery of YBCO tape experimental and simulation results," IEEE Trans. Appl. Superconduc. vol. 13, 2003, p.1772.

[3] Y. Fu, O. Tsukamoto, and M. Furuse, "Copper stabilization of YBCO coated conductor for quench protection," IEEE Trans. Appl. Superconduc. vol. 13, 2003, p. 1780.

[4] Robert Grabovickic, Jinwun W. Lue, Michael Gouge, Jonathan A. Demko, and Robert Duckworth, "Measurements of temperature dependence of the stability and quench propagation of a 20-cm-long RABiTS Y-Ba-Cu-O tape," IEEE Trans. Appl. Superconduc. vol. 13, 2003, p. 1726.

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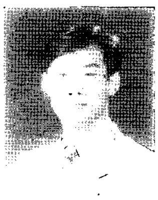

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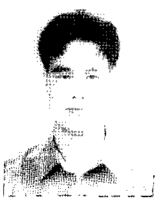

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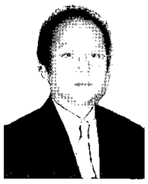

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