스테인레스강 라미네이션된 DyBCO 초전도 선재의 퀜치 특성

Quench characteristics of stainless steel laminated DyBCO coated conductor

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Abstract: As high temperature superconductor applications became a reality due to increase in coated conductor performance, it is important to understand their stability behavior to design safe electrical power systems. Coated conductors can be stabilized with different metals and alloys for different types of application, to yield excellent electrical, thermal and mechanical performance. We have experimentally studied the dependence of quench and recovery characteristics of stainless steel stabilized coated conductors on the amplitude of current and duration time. Stability test of 3 cm long sample were performed in a liquid nitrogen bath cooling condition by applying a short period over current pulses for 50 and 100 ms, with amplitude up to ~ 6 times of the critical current. The transport current that flows before and after the current pulse was fixed at about ~80-85% critical current. We analyzed the quench and recovery phenomena of the test sample using the current voltage characteristic.

1. INTRODUCTION

YBCO coated conductors have attracted intensive interest in recent years because of their potential applications in electrical power industry [1-4]. One such application is in the resistive superconducting fault current limiter (SFCL) that utilizes the rapid rise in resistance at currents over an HTSC material's critical current to suppress successfully fault current. The function of an FCL is to limit the fault current within a limitation level during a fault. To protect the device from exceptionally large faults or electrical and thermal damages, the coated conductors need stabilization of metals or alloys. The selection of stabilizer material depends upon the type of application. Coated conductors used for the power applications like motors, high field magnets and etc are stabilized with copper to minimize the resistance generated if the conductor's critical current density is exceeded by the operating current, or due to thermal or magnetic fluctuations. However, a conductor used for resistive fault current limiter must be designed to make a finite and, ideally, large resistance during a fault event to be effective. Therefore for the resistive type fault current limiters the coated conductors should be stabilized with some high resistivity and excellent thermal conductivity stabilizer. The wire architecture should be robust and electrically and thermally stabilized. In this regard stainless steel is a better candidate to be used as stabilizer of coated conductors for SFCL application. In order to realize its successful application the studies and knowledge of their quench and recovery behavior is very essential. HTS used for electrical power devices are very sensitive to the fault modes and can transform into normal state ("quench")in a few milliseconds. Some of the studies were reported for the stability characteristic of bare and copper laminated coated conductors [5-8]. In this paper, we present our experimental studies for the dependence of quench and recovery behavior of stainless steel laminated DyBCO coated conductors on the amplitude of DC transport current and duration time at liquid nitrogen boiling temperature.

2. EXPERIMENT

The 3-cm long by 1-cm wide coated conductor sample is supplied by THEVA, which has a 90㎛-thick Hastelloy C substrate, 2.5㎛-thick MgO buffer layer, 200 nm-thick MgO "homo epitaxial" cap layer, 800 nm-thick DyBCO layer and 200 nm-thick Au cap layer. The bare sample is laminated with 70㎛-thick stainless steel by soldering. Stability tests were performed in a liquid nitrogen bath cooling condition by applying a short period over current pulse for 50 ms or 100 ms, with amplitude up to about ~6 times of the critical current. The transport current that flows before and after the current pulse was fixed at about ~80-85%, the critical current value of the sample. Two voltage taps V_1 and V_2 were soldered with indium at a distance of 2-cm on the surface of the coated conductor sample. One

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E-type thermocouple is attached between the voltage taps at the center of the sample surface for temperature measurement. Fig.1 shows the photograph of the test sample setup. Each stability test begins with an operating current of 50 A, then proceeds with an over current pulse which is 2 to 6 times of Ic for 50 or 100 ms, and ends with the operating current of 50 A.

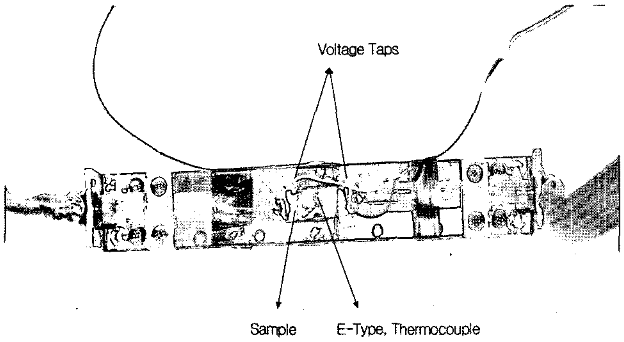

Fig. 1. Photograph of a 10-mm wide test sample with two voltage taps, 2 cm apart and an E-type thermocouple at the center.

3. Results and Discussion

Fig. 2 shows the V (I) trace of the test sample before the sample is subjected to over current pulses. Using the creation 1μV/cm, the measured self field critical current, Ic of the sample was 62 A at 77 K.

Table I shows the peak value (maximum value) of voltage, joule heat flux, peak value of temperature, voltage recovery time and temperature recovery time for different runs of over-current pulse for 50 ms. The resistance and current plots of selected runs for the 50 ms over current pulse are shown in Fig. 3a. Their temperature behavior with respect to time is shown in Fig. 3b.

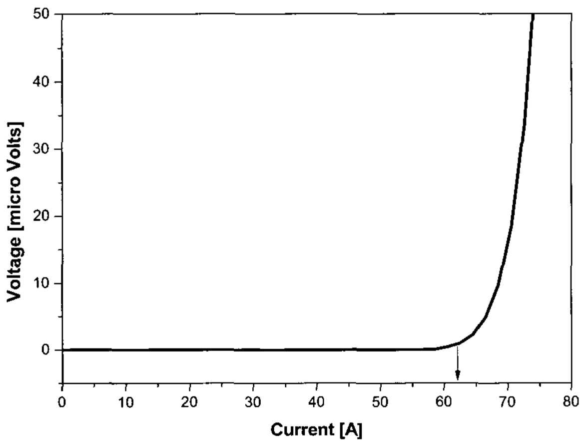

Fig. 2. V (I) traces for the 10 mm wide stainless steel laminated coated conductor.

Table I. Values of current, voltage, heat flux and temperature of a coated conductor sample for 50 milli second over-current pulses.

Nominal Current (A)	Actual Current (A)	Peak Voltage (V)	Peak Joule Heating Flux (W/cm^2)	Peak Temperature (K)	Voltage Recovery Time (s)	Temperature Recovery Time (s)
120	116.13	0.0029	0.168	77.4	0.042	-
180	175.4	0.062	5.437	77.4	0.12	-
240	234.13	0.289	33.83	80.4	1.6	1.6
300	293	0.76	111.4	100.1	4.5	4.6
360	352	1.26	221.7	104.1	10	9.5

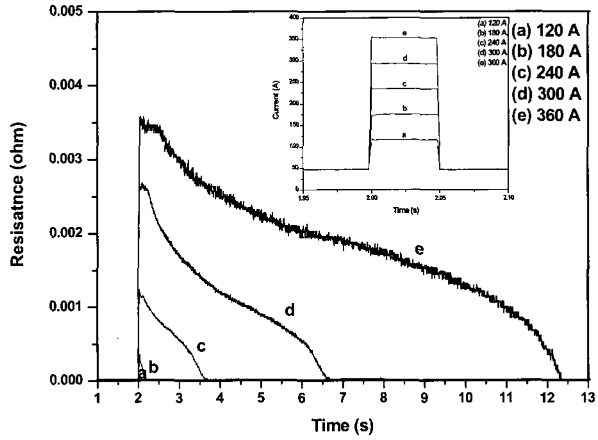

Fig. 3a. Set of R(t), I (t) plot for 50 ms pulse current.

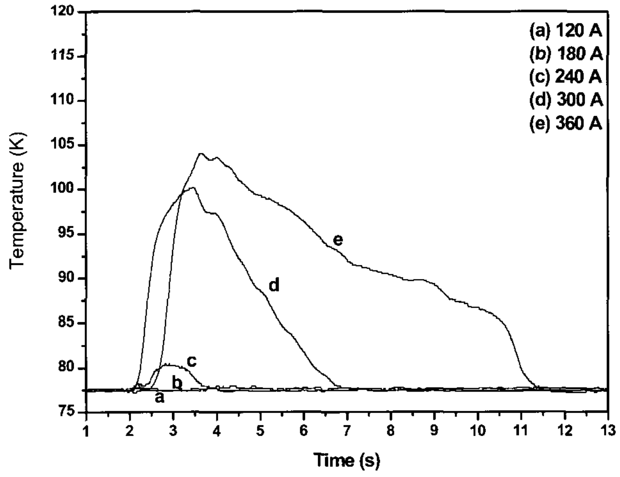

Fig. 3b. Set of T (t) plot for 50 ms pulse current.

The contact resistance between the current lead and the coated conductor is considered to be negligible because there is no voltage generated in the test sample when the operating current of 50 A is applied before the pulse current. It is clear from the table I that for the 50 ms pulse of 120 A the sample becomes resistive only during the pulse. For the 180 A pulse the sample recovery was very fast.

This rapid recovery of resistance is due to the fact that the peak joule heat flux was well below the nucleate boiling heat transfer flux of liquid nitrogen (~10 W/cm^2) [8] and thus sample has not showed rise in temperature.

For the over current pulse of 240 A, 300 A and 360 A, there is a monotonic increase in the resistance during the pulse with time and appear to increase the temperature. In all these three runs, the peak joule heating flux was higher than that of the maximum nucleate boiling heat flux of liquid nitrogen and therefore it took a few seconds to get recovered. For the pulse current of 360 A, the temperature rise up to 104 K and took about 10 sec to get recovered. There is a time delay about 0.4 sec between the resistance generated and the temperature recorded in thermocouple, the possible reason for this delay is that the response time of the thermal sensor may be slow compared to the time scale for heat diffusion and resistance increase in the sample.

The sample is further subjected to 100 ms over-current pulse for the stability experiment. Table II shows the peak value of voltage, joule heat flux, peak value of temperature, voltage recovery time and temperature recovery time for different runs of over-current pulse for 100 ms. The resistance and current plots with time for the selected runs of 100 ms are shown in Fig. 4a and the corresponding rise and recovery of temperature are shown in Fig. 4b.

During the run of 120 A over-current pulse for 100 ms, the sample showed rapid recovery. In the case of 240 A the operating current was switched off after 3 seconds. For the over current pulse of 300 A and 360 A the sample showed recovery in a few seconds which means that heating clearly exceeds cooling. There is increase in joule heating flux which is several times greater than 10 W/cm^2 and therefore it took much time for the sample to get recovered. For the pulse of 360 A the temperature rises up to 136 K and generated joule heat flux of 353.9 W/cm^2 which is about 35 times higher than the nucleate boiling heat transfer flux of liquid nitrogen, therefore it took about 22 seconds to be recovered completely. The zigzag kind of behavior in the temperature profile of 360 A indicates the bulging at the surface of the sample. On further increasing the pulse to 370 A, the sample is burned out with the joule heat flux value of 1125.9 W/cm^2. The peak voltage and temperature values at the time of burnout were 6.2 V and 287 K respectively. In this case also there is a time delay about 0.4 sec between the voltage generated and the temperature recorded in thermocouple.

Table II. values of current, voltage, heat flux and temperature of a coated conductor sample for 100 milli second over current pulses.

Nominal Current (A)	Actual Current (A)	Peak Voltage (V)	Peak Joule heating Flux (W/cm^2)	Peak Temperature (K)	Voltage Recovery Time (s)	Temperature Recovery Time (s)
120	116.8	0.004	0.23	77.4	0.5	-
180	175.6	0.168	14.75	79.5	0.7	0.9
240	233.7	0.45	52.58	99	~4	~4
300	292	1.184	172.8	117.7	12	12
360	352.2	2.01	353.9	136	22	22
370 (Burn out)	363.2	6.2	1125.9	287	-	-

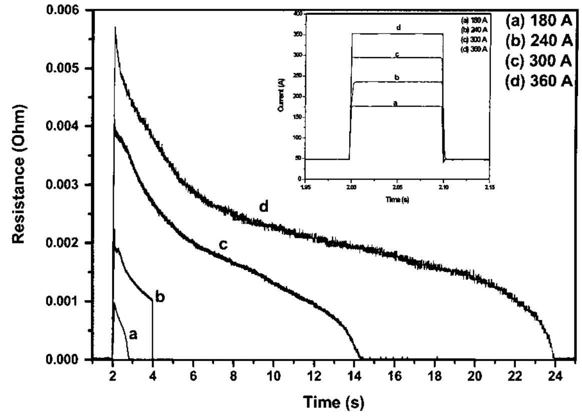

Fig. 4a. Set of R (t) and I(t) plots for 100 ms pulse current.

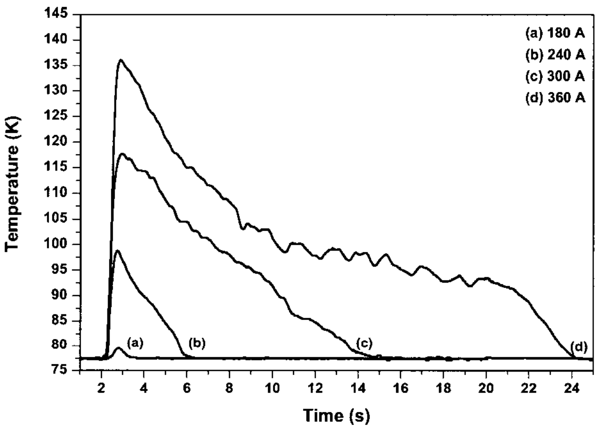

Fig. 4b. Set of T (t) plots for 100 ms pulse current.

During the over current pulse, the critical current of the sample is exceeded by pulse current and there is rapid increase in the resistance. This resistance dissipates the pulse energy as joule heating, and is recovered in a few seconds after the pulse current is over. In both cases of 50 ms and 100 ms pulse for 360A, the peak joule heating flux is 221 W/cm^2 and 353.9 W/cm^2, respectively, which is about 22 and 35 times higher than that of the nucleate boiling heat transfer flux of liquid nitrogen. Therefore, it took about 10 and 22 seconds to get recovered. The sample remained undamaged even when the heating flux was 35 times higher clearly indicates that stainless steel lamination clearly protects the sample.

4. CONCLUSION

DyBCO coated conductor sample laminated with stainless steel was subjected to an over-current pulse to study its stability behavior. The results have demonstrated dependence of the quench and recovery characteristic on the amplitude of current and duration time. It is clear that stainless steel laminated sample experiences a rapid increase in resistance when pulse current exceeds the critical current of superconductor. It also protects the conductor against large over current pulse up to 6 times the Ic for 50 ms and 100 ms and recovers the sample from normal state to superconducting state. The concern issue using the stainless steel stabilizer is firstly to increase the resistance in the superconducting element to reduce the fault current and secondly insuring that the fault energy is safely dissipated once fault current is over, without permanently damaging the HTSc elements.

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REFERENCES

[1] D.K. Finnemore, K.E. Gray, M.P. Malay, D.O. Welch, D.K. Christen, D.M. Kroeger, Physica C, Vol. 320, pp. 1-8, 1999.

[2] J.O. Willis, P.N. Arendt, S.R. Foltyn, Q.A. Jia, R. Groves, R.F. DePaula, P.C. Dowden, E.J. Peterson, T.G. Holesinger, J.Y. Coulter, M. Ma, M.P. Maley, D.E. Peterson, Physica C, vol. 335, pp. 73-77, 2000.

[3] Y. Iijima, K. Matsumoto, Supercond. Sci. Technol. Vol. 13 , pp. 68-81, 2000.

[4] U. Balachandran, M. Li, R.E. Koritala, B.L. Fisher, B.Ma, Physica C, Vol. 869, pp. 372-376, 2002.

[5] R.C. Duckworth, J.M. Pfotenhauer, J.W. Lue, M. J. Gouge, D.F. Lee and D.M. Kroeger, AIP Conf. Proc, Vol. 613, pp. 449-1771, 2001.

[6] J.W. Lue, M. J. Gouge, R.C. Duckworth, D.F. Lee, D.M. Kroeger and J.M. Pfotenhauer, AIP Conf. Proc, Vol. 613, pp. 457-464, 2001.

[7] Y Iwasa, H Lee, J. Fang and B. Haid, IEEE Trans. Appl. Supercond., Vol. 13, No.2, pp. 1772-1775, 2003.

[8] H. M. Kim,J. Jankowski, H. Lee, J. Bascunan, S. Fleshler and Y. Iwasa, IEEE Trans. Appl. Supercond., Vol. 14, No.2, pp. 1290-1293, 2004.

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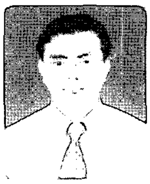

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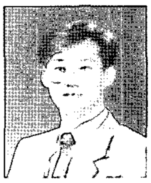

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