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Improvement of Recovery Characteristics of REBCO Tape with Several Surface Conditions for Resistive Fault Current Limiter

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***Abstract*— Superconducting Fault Current Limiters (SFCLs) are required to return to the superconducting state within the proper time (recovery time) after limiting a fault current according to a relay operation scheme in a power system. In order to apply SFCLs to power systems, the recovery time is important property and deeply depends on the heat transfer property of the heated surface of the superconducting tape (normal conducting state) to liquid nitrogen.**

It has been confirmed that REBCO tapes with various shaped fins or PTFE coating improved cooling property. In this paper, to clear the mechanism of cooling property improvement of fins or PTFE coating, boiling phenomena on REBCO tapes with some types of fins or PTFE coating was observed by use of high speed video camera. The influence on the cooling improvement property of cooling fins and PTFE coating was discussed according to the photographical view of the boiling phenomenon.

***Index Terms*— Liquid nitrogen, recovery time, direct transition, cooling fins, PTFE coating**

I. Introduction

Recently, the electric system is becoming more and more complicated and large-scaled because of the electricity deregulation and the increase of distributed generation plants. Therefore, the fault current will be large and the load to circuit breakers will increase. Under this condition, SFCL is expected to suppress the fault current and stabilize power systems.

There are various types of SFCLs, and in this study resistive SFCL is focused on. Under normal operating condition, Resistive SFCL is superconducting state and the impedance is very small. When the fault current flows, the superconducting section of the resistive SFCL turns to normal conducting state and the impedance becomes large. Suppressing the fault currents makes use of the instant transition to normal conducting from superconducting state. Therefore, resistive SFCL functions as soon as the fault occurs.

After limiting the fault current, resistive SFCL have to return to the superconducting state for the next operation. Thus the recovery time, which is defined as the time taken by the superconducting component to recover to the initial state, is important for the practical use. But the heat generated by the resistance during suppressing the fault current is large and the heat transfer reaches the film boiling region. It takes long time for the resistive SFCL to return to the normal-operating state because of the low heat flux on the superconductor surface in the film boiling region. In addition, it was reported that the direct transition phenomenon from the non-boiling region to the film boiling one was observed in the transient pool boiling heat transfer of liquid nitrogen, and the direct transition phenomenon depends on the surface condition of the heater and the heat generation rate [1].

On the other hand, it has been reported that coatings of a poor thermal conductor on metallic components may shorten the lengthy cool-down process of cryogenic equipment [2], [3]. Therefore, we have proposed that cooling fins or coatings of a poor thermal conductor such as PTFE were added on the heater surface, and then it has been reported that cooling fins and coatings of a lower thermal conductor on the heated surface improved the recovery time [4],[5]. Boiling phenomena on the superconducting tape with solder dots was observed optically [6].

In this study, to examine the effects of cooling fins and PTFE coating on the cooling property improvement, the boiling phenomena on REBCO tape with no fins or no coating and on the tapes with Cu fins or PTFE coating were observed with a high speed camera.

II. Experiment

A. Experimental Apparatus

A glass Dewar vessel was used. The inner-diameter is 160 mm, the height is 1270 mm. The glass dewar has a radiation shield and a viewing slit of 14 mm width. The vessel is vacuum insulated and continued to be evacuated to about 10^{-4} Pa by a diffusion pump. The vessel can be used only at atmospheric pressure.

A high speed video camera (NAC image technology) was used to observe the boiling phenomenon. Photographs were taken with the high speed video camera through the slit and LED lamp turned on to brighten a heater surface while photographing a boiling phenomenon.

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B. Test Sample

Test samples were REBCO tapes without fin or with Cu fins (the number of fins is 15). The tapes are pasted on a FRP block to insulate the back side of the tapes. The length, width and thickness of the tapes are 130 mm, 4 mm and 0.2mm respectively. The power leads and voltage taps were soldered on the sample surface apart from cooling fins.

In order to observe boiling phenomena, three kinds of test samples were prepared. The schematic diagram for all test samples are shown in Fig. 1. Sample No.1 was bare without cooling fins and PTFE coating, sample No.2 was with L shaped fins made of copper and these fins were soldered on the tape's surface. Sample No.3 was coated with PTFE (Polytetrafluoroethylen) with several μm thickness.

The specification is listed in Table I. The lengths between the voltage taps are about 97~100mm. Tap to tap voltage at room temperature is about 7.11 ~7.49mΩ.

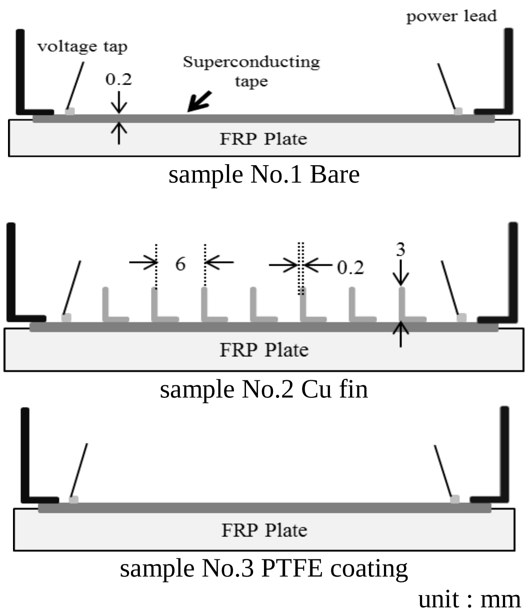

Fig. 1. Schema of test superconducting tapes for all samples

TABLE I
TEST SAMPLES

No.	Surface Condition	Tap (mm)	Ic (A)	n-value	Ave-R (mΩ/mm)
1	Bare	97.0	105.9	34.0	0.0773
2	L-shaped Cu fins	99.4	99.9	32.1	0.0715
3	PTFE coating	97.0	110.9	33.9	0.0762

C. Experiment Method

The test samples were mounted vertically in width direction and horizontally in length direction immersed in LN_2. The pressure of the vessel was kept at atmospheric pressure.

The test circuit was shown in Fig. 2. The voltage of a power source was controlled according to the following equation.

$$V = V_0 exp(t/\tau) \quad (1)$$

The circuit current was increased exponentially before exceeding the critical current of the samples. After the current exceeded the critical current, the resistance of the sample was appeared and increased. The switch was open when the sample resistance reached the set value and the current source of 100 mA was applied to measure the sample resistance during the recovery process. In this study, the heat input with the period τ of 30 ms, 50 ms and 100 ms was applied to the test samples.

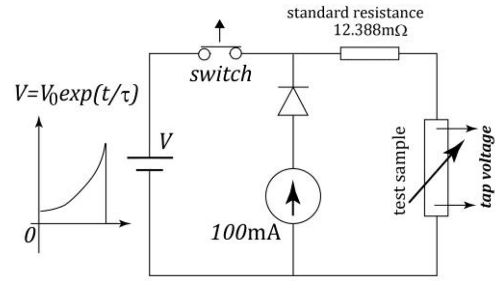

Fig. 2. Test circuit.

A high speed video camera was used to photograph the boiling phenomena of liquid nitrogen. The pictures were taken with the rate of 500 fps (τ = 50 ms and 100 ms) or 1000 fps (τ=30 ms).

D. Results: Resistance change after current shut off

The results of temporal change of applied current and resistance with the period τ of 100 ms are shown in Fig.3 (Sample No.1), Fig.4 (Sample No.2) and Fig.5 (Sample No.3).

The resistance increased up to about 6.0 mΩ just before the switch open in cases of Fig. 3 and Fig. 5. Unfortunately, since the photographs of the sample No.2 when the resistance increased up to 6.0 mΩ was indistinct, Fig.4 shows the result of the resistance up to 5.0 mΩ instead of 6.0 mΩ.

In Fig. 3, the heat transfer is in the film boiling region where the inclination of the resistance is moderate. The transition to the nucleate boiling occurred at 1680 ms and the temperature of the sample became less than its critical temperature (92K). Then the sample returned to super-conducting state at 1766 ms almost at once.

In Fig. 4 and Fig. 5, the inclination was steep even in the film boiling region compared with that of Fig. 3. The transition point from the film to nucleate boiling was unclear. The resistance decreasing inclination was getting steeper and steeper gradually and then the sample recovered to the

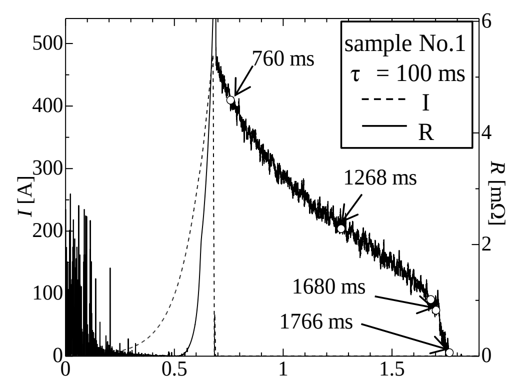

Fig. 3. Temporal change of current and resistance of Sample No.1.

superconducting state. This result suggested that the stable vapor film couldn't stay on the sample surface and the nucleate boiling area and the film boiling area were mixed on the sample. Major improvement of the recovery time can be confirmed by these results.

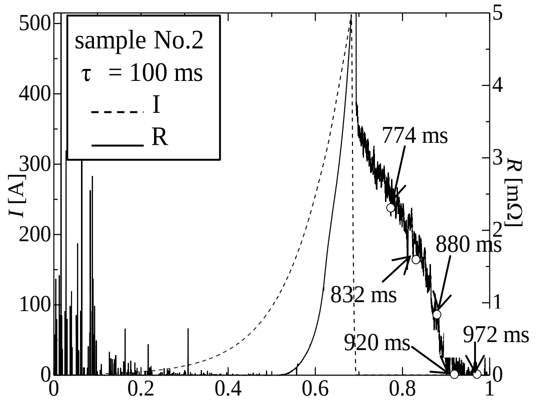

Fig.4. Temporal change of current and resistance of Sample No.2

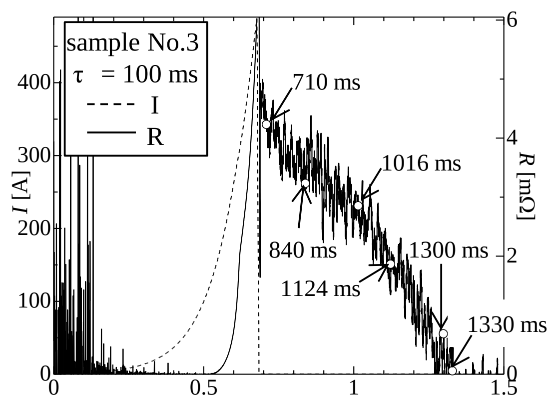

Fig.5 Temporal change of current and resistance of Sample No.3.

E. Results: Discussion with photo view

Fig. 6, Fig. 7 and Fig. 8 show the photographs of bubble behavior taken at the results of Fig. 3, Fig. 4 and Fig. 5 obtained respectively.

In Fig. 6, the surface of the sample (No.1) was covered with the stable film vapor at 760 ms and 1268 ms. At 1766 ms, the nucleate boiling area developed, but the small film boiling area still remained. The sample recovered to the superconducting state after 1766 ms. The vapor film vanished on the surface at 1838 ms, but the nucleate boiling still continued to cool down to 77 K. The Bubbles were gradually getting smaller at 2190 ms.

In Fig. 7, the surface of the sample (No.2) between fins was covered with the vapor film, but the tips of the fins were not covered and the bubbles left upward from the fins (774 ms). The transition from the film boiling to the nucleate boiling began at some surface between fins (832 ms, 880 ms). The nucleate boiling area was developing whole over the sample (920ms,972 ms). The sample recovered to the superconducting state after 920 ms. The nucleate boiling still continued and the bubbles gradually became small (1508 ms).

In Fig. 8, the vapor film was generated on the surface, but the vibration of the film was observed (710ms and 840ms). The vapor film was unstable (1016ms) and the transition from the film boiling to the nucleate boiling was observed at the bottom side edge of the sample surface at 1124 ms. The nucleate boiling area developed from the left-hand side of the sample and the film boiling area still remained on right-hand side (1300 ms). The nucleate boiling area gradually spread to the right-hand side of the samples (1330 ms).

In the film boiling regime, the vapor film on the surface of tape coated with PTFE seemed to be unstable compared to others. However, in the nucleate boiling regime, there is lesser quantity of bubbles left from PTFE coating sample than that of sample No.2. It was considered that the heat transfer through the thin PTFE in the nucleate boiling was worse than that without coating.

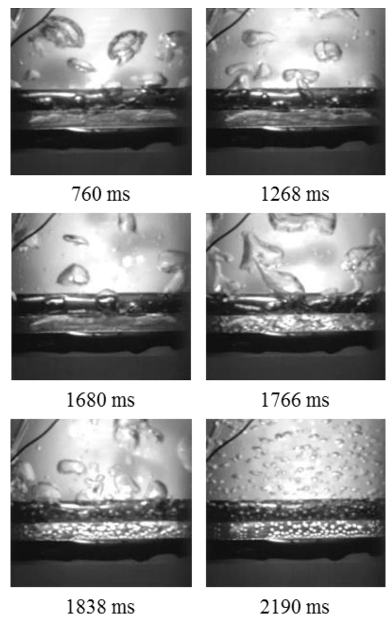

Fig.6. Boiling behavior during quench and recovery for sample No.1.

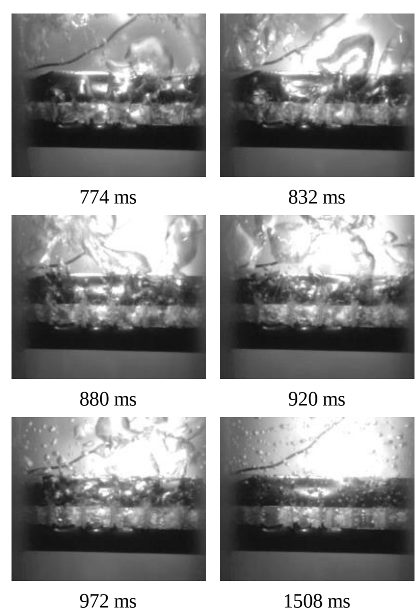

Fig. 7. Boiling behavior during quench and recovery for sample No.2

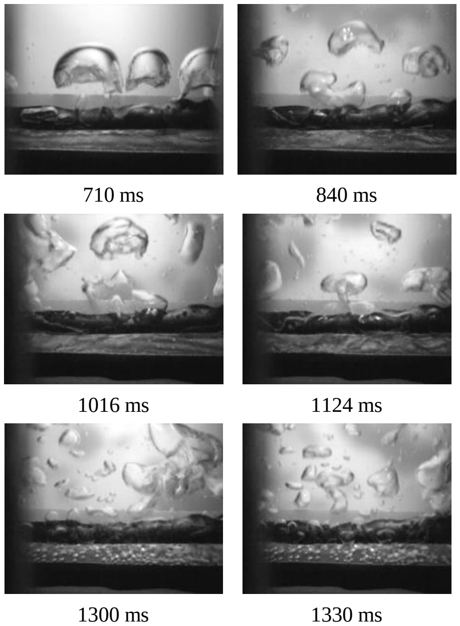

Fig. 8. Boiling behavior during quench and recovery for sample No.3.

F. Discussion: Resistance change after current shut off

Fig. 9, Fig. 10 and Fig. 11 show temporal change of resistance of all samples with the period τ of 100 ms, 50 ms and 30 ms respectively when the resistance increased to about 6.0 mΩ, 3.5 mΩ and 3.0 mΩ respectively.

With the period τ of 100ms (Fig. 9), the resistance inclination of the samples with the Cu fins or the PTFE coating in the film boiling is steeper and the recovery time is smaller than those of the bare sample because the cooling fins and the PTFE coating prevent the formation of the vapor film and the cooling fins activate the bubbles to leave.

There is high quantity of the bubbles from the surface of the sample with Cu fins in the film boiling. So the resistance inclination of the sample with Cu fins is steeper than that of the sample coated with PTFE.

In Fig. 10 and 11, with the higher current increasing rate, the recovery time of the sample coated with PTFE is almost the same with that of Cu fins and they are almost half of that of the bare sample. The thickness of the vapor film with τ=50 or 30 ms at the current shut-off is considered to be thinner than that of τ =100 ms. The effectiveness of the PTFE coating to make the vapor film unstable is larger with thinner vapor film. So the recovery time with PTFE coating was improved with higher current increasing rate.

III. Conclusion

The recovery time of the resistive fault current limiter is important issue for real operations as a power system device. The recovery time of the REBCO short tape from the normal state (current limiting state: exceeding the critical current) to the superconducting state was investigated experimentally with some surface conditions (Cu fins and PTFE coating).

It was confirmed that the recovery times with Cu fins and the PTFE coating become shorter than that of the bare sample. The cooling phenomena w observed by use of video camera. It was observed the Cu fin and the PTFE coating prevent the formation of stable vapor film and bring the faster transition from the film to the nucleate boiling regime.

The recovery time of the PTFE coating was longer than that of the Cu fin with τ=100 ms, however it was almost same with the higher current increasing rate τ=50 or 30 ms.

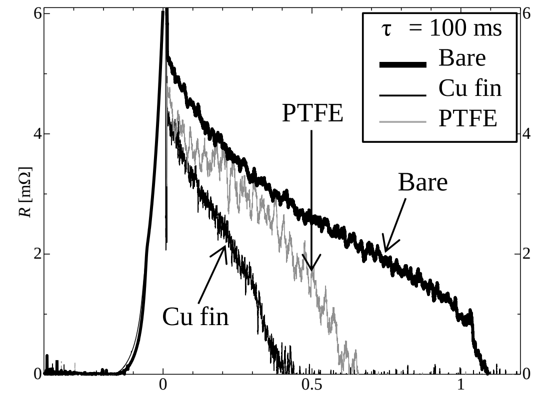

Fig. 9. Resistance appearance of all test samples at the similar heating condition (τ=100 ms)

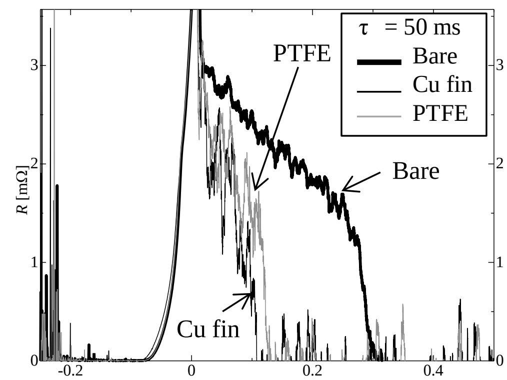

Fig. 10. Resistance appearance of all test samples at the similar heating condition (τ =50 ms)

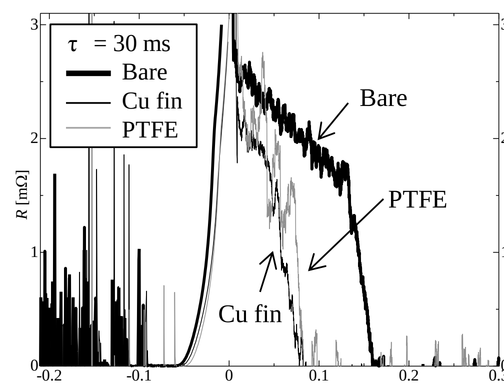

Fig. 11. Resistance appearance of all test samples at the similar heating condition (τ =30 ms)

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