Over-current Properties of MgB$_2$ Wire Cooled by Liquid Hydrogen under Magnetic Field

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Abstract— **Liquid hydrogen (LH$_2$) has excellent properties such as large latent heat, low viscosity and so on. Because of these properties, LH$_2$ is expected to be used as a coolant for high critical temperature superconductor (HTS), including MgB$_2$. Over-critical-current properties of HTS are important for stable designs of HTS devices cooled by LH$_2$, but temperature change of sheathed superconducting wire cannot be revealed only by current-voltage properties beyond critical current, since the current sharing ratio among MgB$_2$ and sheath materials is not unkown. In this study, transient over-critical-current tests were performed on a short MgB$_2$ sample cooled by LH$_2$ under magnetic field, and the sample temperatures were calculated from test data. In addition, the test sample temperature based on the test was compared with that of the computer simulation result. It was found that the temperature change of the wire just after the transport current exceeds the critical current is affected by external magnetic fields.**

Index Terms—**Liquid hydrogen, MgB$_2$ wire, Over-current Properties**

I. INTRODUCTION

LIQUID HYDROGEN (LH$_2$) is expected to be used as a coolant for the high-Tc superconductor, including MgB$_2$ due to its excellent properties, such as large latent heat, low viscosity coefficient and so on. It is necessary for a stability design of the high Tc superconductor cooled by LH$_2$ to make the over-current properties clear.

In case of a high-Tc superconductor, the critical current is not the absolute limit of cooling stability. As the specific heat of the materials in LH$_2$ or liquid nitrogen (LN$_2$) is larger than that in liquid helium (LHe), "thermal runaway" phenomenon is important for the cooling stability. When the conductor is cooled by LH$_2$ or LN$_2$, cooling limit due to critical heat flux of nucleate boiling may correspond to several ten times of the critical current. It is necessary for stable cooling to know the temperature of the wire with over-current.

The current distribution ratio of the sheath and the

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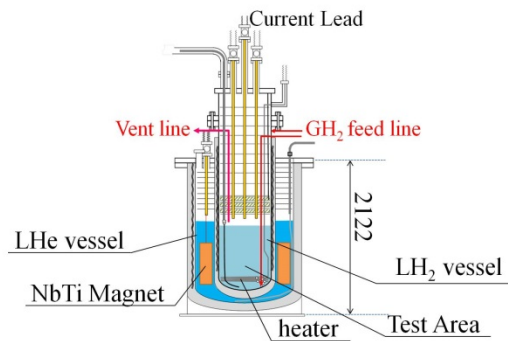
superconductor is needed to calculate the temperature of the wire at the over-current condition. However, the ratio depends on both the temperature of the wire, that is the resistance of the components, and the transport current. Therefore the wire temperature cannot be calculated only from a *V-I* characteristic under steady state conditon.

Using the results of over-current test in some transient conditions with several time constants and applying the transient heat method [1], several *V-I* characteristics for a test wire in different combinations of temperature and transport current are obtained. The distribution ratio and the average temperature of the wire can be calculated. The resistivity of the MgB$_2$ superconductor with over-current can be expressed as the function of the temperature and the transport current.

Hikawa [2] has reported the over-current properties of the MgB$_2$ wire submerged in LH$_2$. Over-current tests were carried out at the bulk temperatures of 21 K, 24 K, 27 K and 29 K under the pressure of 1100 kPa. The test sample was heated by exponential heat inputs $Q = Q_0 e^{t/\tau}$ with wide range of the periods τ up to 10 s. The investigation was stopped at the first appearance of electrical resistivity of MgB$_2$.

In this study, transient over-critical-current tests were performed on a short MgB$_2$ sample cooled by LH$_2$ under magnetic field. The results are analyzed by using the transient heat method, and are extended to the temperature change of the wire. In addition, numerical simulations were performed by modeling the MgB$_2$ superconducting wire and the results of the simulations were compared with that of the transient heat method.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

A. Experimental Set-up

Fig.1 shows the schematic diagram of the LH$_2$ test cryostat. The cryostat has 309.5 mm inner diameter and has 2122 mm height.

Magnetic field can be set to 0-7.0 T by use of the Nb-Ti superconducting magnet cooled by LHe. Pressure in the LH$_2$ test cryostat can be set to 0.1-2.0 MPa by use of the feed hydrogen gas line. The bulk temperature can be changed by use of the sheathed heater equipped at the bottom of the cryostat. Electric current can be applied to the test sample up to 600 A by use of DC power sources.

The detail of this experimental set-up for investigating electrical properties of superconductors cooled by LH$_2$ under magnetic field was described by Shirai [3].

Fig. 1. The schematic diagram of the LH₂ test cryostat.

B. Test Sample

The photo of the test sample is shown in Fig.2, and the schematic diagram is shown in Fig.3.

The test MgB₂ wire is provided by Hyper Tech, Co. The test MgB₂ wire is 160 mm in length, 0.83 mm in diameter. The width between current leads is 105.5 mm, and that between voltage taps is 47.65 mm. The cross section ratio of MgB₂, Nb-barrier, and Cu-sheath is 0.200, 0.382, and 0.418, respectively. The copper plates are soldered at both end of the test wire, and the copper current leads are soldered on the copper plates. Additionally, the BSCCO power leads are soldered at both end of the test wire in order to avoid the joule heat generation from the power leads. The platinum voltage taps are soldered on the sample surface. The test sample is set in the cryostat with its length direction horizontal. A plate made of fiber reinforced plastic (FRP) is set close to the test wire in order to avoid deformation caused by Lorentz force.
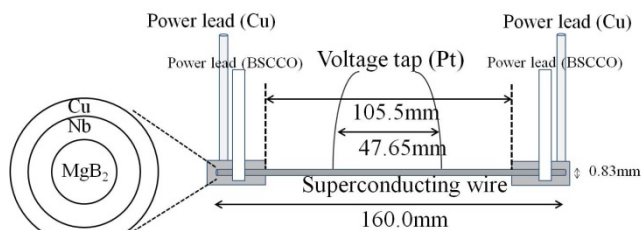

Fig. 2. The photo of the test sample

Fig. 3. The schematic diagram of the test sample

C. Experimental Process

The test sample was heated by applying the electric current I which exceeds the critical current I_C. The theoretical expression of the heat transfer characteristics of a thin round wire in non-boiling regime was given by Shiotsu[1]. The heat flux and the temperature rise of the heated wire surface changes in accordance with the expression. The surface temperature was evaluated by fitting the experimental non-boiling heat transfer curves with several rising speeds of the heat input to to the theoretical expressions. The heat input was controlled as $Q = Q_0 e^{t/\tau}$ with some kind of periods τ which is considered as transient heat input.

In this experiment, the initial current I was about 7.5 A and the current increased exponentially before it reached I_C. After I reached I_C, it was controlled so as to give exponential heat inputs $Q = Q_0 e^{t/\tau}$ with the periods τ ranging from 10 s to 50 ms. The heat input tests were carried out at the bulk temperatures of 21 K, 24 K, 27 K and 29 K under the pressure of 1100kPa. The magnetic fields were set to 0 T, 0.2 T, 0.4 T, and 0.8 T.

D. The Transient Heat Method

The transient heat method is the way to calculate the resistivity of MgB₂ with over-current as the function of the average temperature of the wire and the transport current like the following Eq. (1).

$$R(T) = R_N(T)[1.0 - 1.0 / \{(1.0 - a) + a(I / I_C)^m\}^{0.1}] \qquad (1)$$

In this equation, a and m are fixed numbers, I is the total current through the sample, R is the resistance of the sample, and R_N is combined resistance of the substrate. The combined resistance $R_N(T)$ is previously obtained from literature data of resistivity versus temperature curves for Nb and Cu as a parallel resistance of the tubes. I_C is the critical current as the function of the average temperature of the wire.

If the fixed numbers a and m are assumed, T can be calculated. In this method, the experimental heat transfer curves were fitted to the theoretical expression of non-boiling heat transfer coefficients, and the a and m were determined for the experimental data with each magnetic field.

Fig.4 shows one of experimental results at the bulk temperature of 21 K under the pressure of 1100 kPa. The transport current rises continuously, and the resistance of the wire appeared when the transport current exceeded the critical current. Fig.5 shows the relation between the critical current and the temperature of the MgB₂ superconducting wire for each magnetic field obtained from the V-I characteristics of the wire.

Using these experimental results and Eq.(1), the heat transfer coefficient curves fitted to the theoretical expression are obtained and the values a and m were determined for each magnetic field. Fig.6 shows the heat transfer curves in the condition of 0 T of magnetic field. The heat transfer curves for each period are plotted, and the red broken lines are the theoretical expressions.
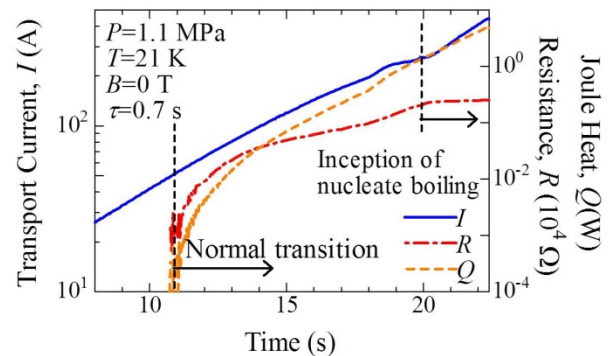

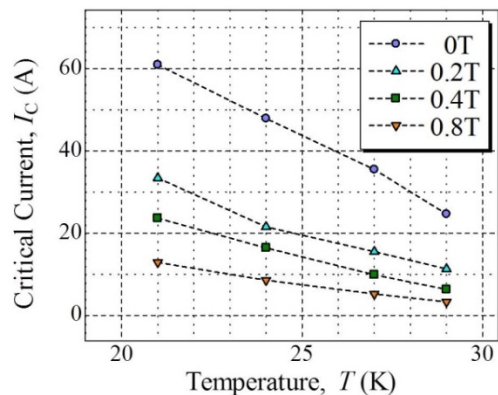Fig. 4. Experimental result with heat input test

Fig. 5. Relation between the critical current and the temperature of the wire for each magnetic field
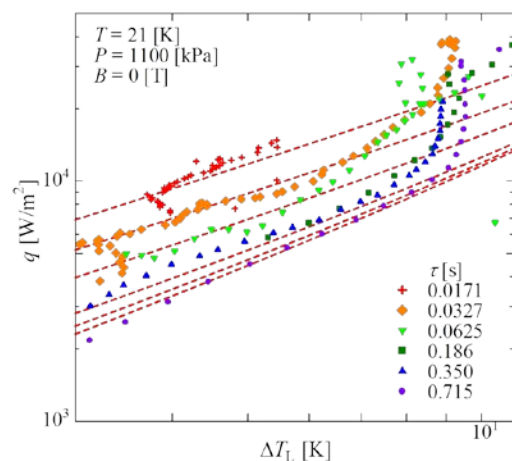

Fig. 6. Heat transfer curves fitted to the theoretical expression in the condition of 0 T.

The fixed numbers a and m of Eq.(1) were determined as 0.38 and 2.60 for 0 T of magnetic field. Under magnetic field, a and m were determined as 0.23 and 2.50 for 0.2 T, 0.23 and 2.30 for 0.4 T, 0.30 and 2.35 for 0.8T. Finally, the relations between the average temperature of the wire and the transport current were obtained from Eq.(1).

III. RESULTS

A. Temperature Change of the Wire

Hikawa[2] mentioned only about the results of the resistivity of the MgB$_2$ superconductor, and in this study the changes of the average temperature of the wire were observed closely.

Fig.7 shows the temperature change for various periods τ at the bulk temperature of 21 K under the pressure of 1100 kPa. T is the average temperature of the MgB$_2$ wire, and I is the transport current. Both T and I are the transient value. In this graph, T starts to rise at the critical current and increases to saturation temperature.

In the cases of 0.71 s, 0.35 s, and 0.18 s, the smaller the period is, the larger the transport current for the same temperature is. For example, the transport currents at 27 K are about 230 A, 250A, and 295A. The faster the heat input rises,

the larger the transport current should rise before the temperature reaches 27 K.

However, in the cases of 0.062 s and 0.035 s, the smaller the period is, the faster the temperature rises just after the transport current exceeds the critical current. If the speed of heat input increasing is larger than that of thermal conduction in the wire, the temperature of the center of the wire may be larger than that of the surface. In such case, the amount of cooling by LH$_2$ may be less than the case that the wire does not have a temperature gradient. Therefore, if the period is too small, the temperature of the wire rises rapidly just after the transport current exceeds the critical current.

In the transient heat method, the temperature gradient is not concerned so it seems that the temperature with small periods was not calculated correctly enough.
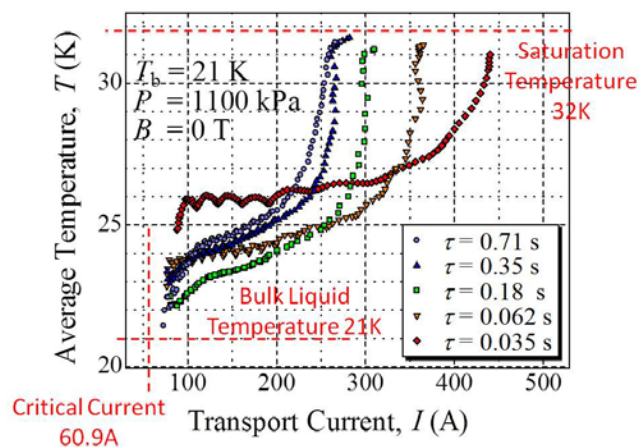

Fig. 7. Temperature with transport current for various periods τ at the bulk temperature of 21 K under the pressure of 1100 kPa.

B. Temperature Change at the other bulk temperature

Fig.8 shows the temperature change for various periods τ at the bulk temperature of 24 K.
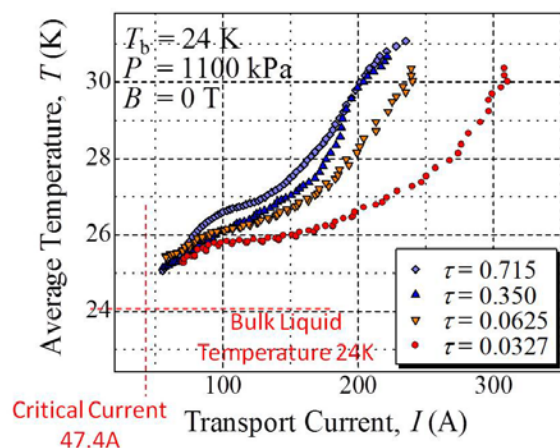

Fig. 8. Temperature with transport current for various periods τ at the bulk temperature of 24 K under the pressure of 1100 kPa

For all period conditions, the smaller the period is, the larger the transport current for the same temperature is. This tendency is noticed in the results of the bulk temperature of 27 K and 29 K. If the bulk temperature is higher, specific heat

and thermal conductivity of the wire is higher. It seemed that the temperature gradient did not occur when the bulk temperature was higher than 21 K.

C. Temperature Change under Magnetic Field

Fig.9 shows the temperature change for various periods τ under magnetic field of 0.8 T at the bulk temperature of 21 K under the pressure of 1100 kPa.
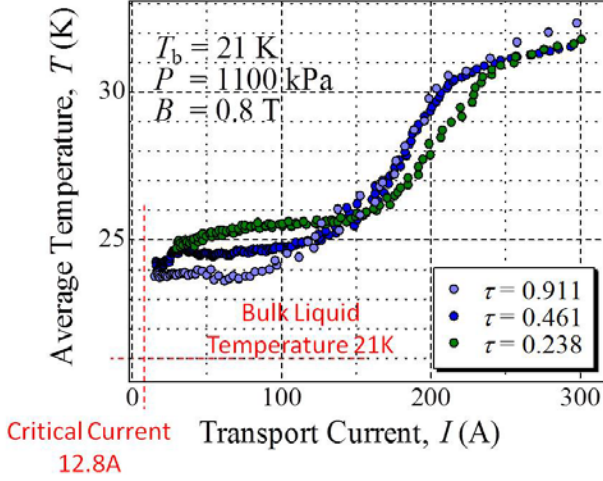

Fig. 9. Temperature with transport current for various periods τ at the bulk temperature of 24 K under the pressure of 1100 kPa under magnetic field of 0.8 T

In the case of 0.911 s, 0.461 s and 0.238 s, the smaller the period is, the faster the temperature rises just after the transport current exceeds the critical current. This tendency can be seen in the case of Fig.7 with small period too. However, under magnetic field of 0.8 T, the period at which this tendency occurs is larger than 0 T.

When external magnetic field is applied to MgB_2, the n-value of MgB_2 goes down and flux flow resistivity just after the transport current exceeds the critical current increase more quickly. Therefore, under external magnetic field, the wire seems to have temperature gradient even if the order of the period is 0.1 s.

IV. DISCUSSIONS

In the transient heat method, the tap voltage V is described as following Eq.(2).

$$V = r(T) I_S = R_N(T) (I - I_S) \qquad (2)$$

In this equation, r is the resistance of the superconductor, I_S is the current which flows through MgB_2, I_C is the critical current, R_N is the resistance of the sheath (Cu and Nb), and I is the transport current. The heat generation at MgB_2 is calculated by rI_S^2 in the transient heat method, using $r(T)$ obtained as described before.

If the resistance $r(T)$ is unknown, the current sharing ratio of MgB_2 and the sheath $I_S/(I - I_S)$ cannot be fixed. In order to verify the transient current method, a numerical simulation was carried out with the simple assumption $I_S = I_C(T)$ where

$r(T)$ is unknown, and the heat generation at MgB_2 is calculated by $VI_c(T) = R_N(T) (I - I_c(T)) I_c(T)$.

The influence of I' which is described as $I' = I_S - I_C$ was discussed by comparing simulation results and experimental results analyzed by the transient current method.

Fig.10 shows one-dimensional model in the simulation. The simulation model of the MgB_2 wire is shown in Fig.3, and thermal conduction in the radial direction of the wire was analyzed by solving the equation of heat conduction with implicit finite difference method. The radial direction of the wire was divided into 20 meshes and the transport current was set so as to give exponential heat input. To calculate the heat flux of the wire into LH_2, the heat transfer curve of PtCo wire immersed in LH_2 which was reported by Horie [4] was used.
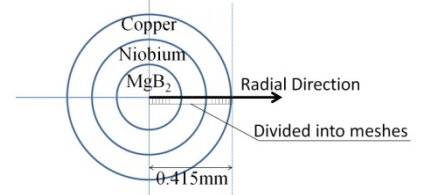

Fig. 10. One-dimensional model of the MgB_2 wire

Fig.11 shows the results of the temperature change with transport current for various periods τ at the bulk temperature of 21 K under the pressure of 1100 kPa. The simulation data are plotted, and the broken lines are the experimental results.
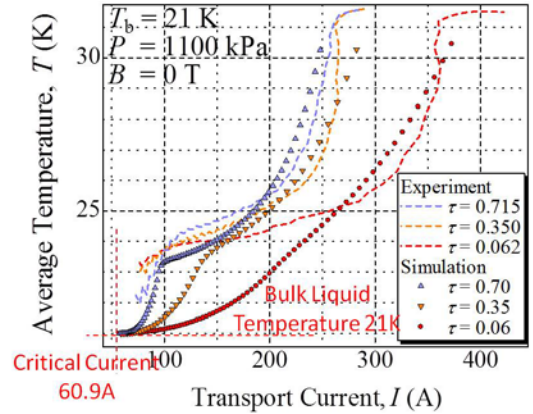

Fig. 11. Temperature with transport current calculated in the simulation

The temperature of the simulation just after the transport current exceeds the critical current are smaller than those of the experiment. This tendency is remarkable when the period τ is small. When the transport current is small, R_N may be much larger than r. In this region, the heat generation is mostly caused by I_S and therefore I' strongly influences on the temperature. The temperature in the simulation is calculated lower. When the period τ is small, the transport current I increases rapidly, and I at the same temperature T becomes large compared with that with large τ. Therefore, the difference between the simulation and the experimental result analyzed by the transient heat method is large where the period τ is small.

On the other hand, in the area of high transport current, the temperature of the simulation is almost same as that of the experiment. This is because r is much larger than R_N in this area, and I' is quite small.

In short, the influence of *I'* cannot be neglected just after the transport current exceeds the critical current. The transient heat method can be used for evaluation of the MgB_2 resistance *r(T)* and temperature of the wire during over-current operation.

V. CONCLUSION

In this study, the critical current of the MgB_2 short wire immersed in LH_2 (21~29 K) was measured under magnetic fields (0 ~1 T). The over-current test was carried out for various heat input speed, and the temperature change of the MgB_2 wire was evaluated by using the transient heat method.

In the case of fast heat input, the temperature increases fast just after the transport current exceeded the critical current. This shows the wire may have the temperature gradient between the center and the surface. This tendency was remarkable under magnetic field.

In addition, numerical simulations were performed, and the result shows the temperature change just after the transport current exceeds the critical current is particularly influenced by the heat generation at the superconductor (MgB_2 part). The transient heat method can evaluate the temperature which contains this influence.

The transient current method can be used for evaluation of the MgB_2 resistance *r(T)* and temperature of the wire during over-current operation, and these procedures can be used to evaluate stability of HTS devices.

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