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Over current properties of HTC superconducting wire cooled by liquid hydrogen

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Abstract

An experimental setup which can energize superconducting wires immersed in LH2 was designed and made. Over current tests were carried out using MgB2 wire. Critical current and resistivity of a test MgB2 wire submerged in liquid hydrogen were measured for exponentially increasing heat input, while the transport current exceeded the critical current. The resistivity of the conductor was obtained as a function of current and the temperature of the conductor by using the transient heating method. The distribution ratio of the current through the superconductor and the sheath, and the resistivity of the MgB2 conductor itself were estimated.

Keywords: liquid hydrogen; MgB2; overcurrent; elecrical resistivity; heat tranfer

1. Introduction

It is expected that liquid hydrogen (LH2) is one of the candidate of a cryogen for superconducting materials, not only MgB2 but also other HTC superconductors due to its excellent properties as a coolant, such as large latent heat, low viscosity coefficient and so on. While YBCO and BSCCO superconducting

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wires are normally cooled by liquid nitrogen, their properties will be significantly improved at around the saturated temperature 20K of liquid hydrogen.

It is necessary for a stability design of a high Tc superconductor cooled by liquid hydrogen to make the over current characteristics of it clear. In case of a high-Tc superconductor, critical current is not the absolute limit of cooling stability. It is well known that the electric resistance gradually increases with the increase in electric current from the critical value because of the relatively weak pinning force compared with that of metallic superconductors. As the specific heat of the materials in liquid hydrogen or liquid nitrogen is rather larger than that in liquid helium, “thermal runaway” phenomenon is important for the cooling stability. When the conductor is cooled by LH2 or LN2, cooling limit due to critical heat flux of nucleate boiling may correspond to several ten times of the critical current.

The purpose of this study is three fold. One is to clarify the critical current of the MgB2 superconductor at several liquid hydrogen temperatures under pressures. Second is to obtain the electrical resistivity of the superconductor as a function of electric current and the temperature of the conductor by using the transient heating method [1]. Third is to estimate distribution ratio of the electric current through the superconductor and the sheath, and the resistivity of the superconductor.

2. Experimental setup

2.1. Test sample

Fig.1 (a) and (b) show a photo and a sketch of a test sample, which was set in the cryostat with its length direction horizontal. Test sample of MgB2 round wire which was provided by Hyper Tech Research, Inc., immersed in liquid hydrogen. Diameter D_a of MgB2 test wire is 0.51mm. The cross section of the sample is shown in Fig 1(b). The cross sectional ratio of MgB2, Nb (barrier) and Cu-sheath is 0.214, 0.357 and 0.429, respectively. The copper current leads and the voltage taps were soldered on the sample surface. Length between power leads is 121.6 mm, that between voltage taps is 98.4mm.

2.2. Liquid hydrogen heat transfer experimental system

Liquid hydrogen heat transfer experimental system [2] was used for the experiments. The system was designed to carry out not only pool but also forced flow experiments without using a pump.

The cryostat used for the pool boiling was 406 mm inner diameter and 1495 mm height made of stainless steel and is designed for a pressure of up to 2.1 MPa. The maximum inventory of liquid hydrogen of the cryostat is 50 l, while the total volume is 100 l. There are four power leads to introduce the heating current of up to 500 A to the test heaters. By taking one of them as a common neutral line, three test heaters can be installed in the main tank at the same time.

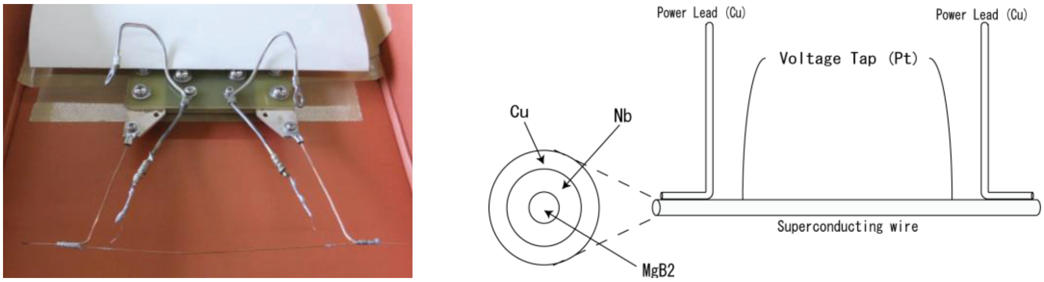

Fig. 1. (a) test sample of MgB2 wire and setup ; (b) schema and dimension of the wire

2.3. Test procedure

The average temperature of the test wire was measured by resistance thermometry using a double bridge circuit including the wires as a branch of the bridge. However, the resistance-temperature relation of the wire is difficult to be fixed previously, because the resistance of the test wire is combined one of the MgB2 strand and the substrate. That is, while the resistance of the substrate is obtained as a function of temperature, the resistance of the MgB2 is a function of not only its temperature but also the shunt current flowing through MgB2 section.

On the other hand, the theoretical expressions for non-boiling heat transfer coefficients on a round wire, that is, the surface heat flux $q(T)$ as a function of the temperature, heated by exponential heat inputs $Q=Q_0 \exp(t/\tau)$ with various periods τ has been already reported. Therefore, the resistance of the wire can be determined to match the experimental results to the theoretical obtained $q(T)$ for various periods.

The output voltages of the bridge circuit together with the voltage drops across the potential taps of the heater and across a standard resistance were measured.

The heat generation rate in the heater was calculated from the measured voltage difference between the potential taps of the heater and the standard resistance. The surface heat flux $q(T)$ is the difference between the heat generation rate $Q(D_a/4)$ per unit surface area and the rate $(\rho(T)c(T)\ dT/dt)(D_a/4)$ of change of energy storage in the test heater obtained from the averaged temperature versus time curve.

The pressure of the main tank was set to 0.7 MPa. The bulk-liquid temperature (subcooling temperature) was set by use of the sheathed heater equipped at the bottom of the cryostat.

3. Critical current and Electrical resistance of the wire

3.1. Quasi steady state heat transfer experiment

One of the experimental results with quasi-steady state heat input (τ= 0.7s) is shown in Fig 2. The bulk temperature of the liquid hydrogen is 24 K (subcooling = 5 K) and the pressure is 700kPa. As the transport current increased, at around 18.9s, the wire resistivity appeared and the heat input to the wire start to increase. At about 22.1 s, the nucleate boiling began.

3.2. Critical Current of the test sample

Fig 3. shows experimental data of the tap voltage versus transport current at the appearance of the resistance of the test wire with the quasi-steady state heat input (τ= 0.7s) under the bulk liquid temperature of 21, 24 and 27K. The intersection point of each line with the constant resistivity line of 10^{-13} Ωm is indicated the critical current.

The critical current of the test MgB2 wire as a function of the temperature was obtained as

$$I_C = 133\{1.0 - (T/39)^{1.9}\}^{2.01} \tag{1}$$

by fitting the critical current versus temperature relations.

3.3. Electrical Resistance of the test sample with over current

When the transport current I is over the critical current of MgB2 wire, the current is shunted to the substrate, that is, Nb(barrier) and Cu(sheath) part according to the resistance ratio of MgB2 part and the substrate part. Then the tap voltage V of the test wire is given as,

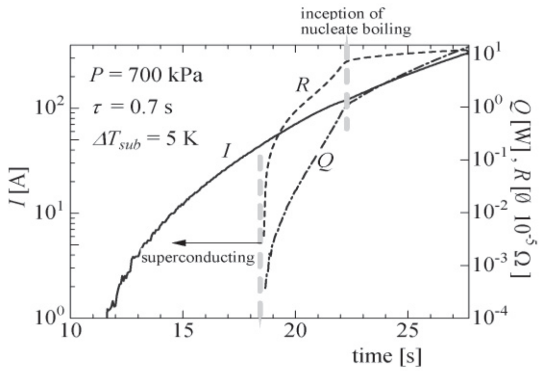

Fig. 2. Experimental results of quasi-steady state heat transfer test.

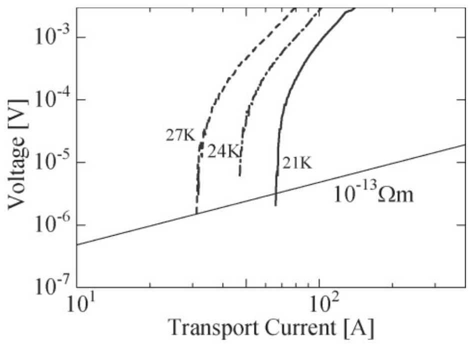

Fig 3. Voltage and transport current relation at various temperature. (Pressure 700kPa).

$$V = R_N(T)\{I - I_S\} = r(T)I_S \tag{2}$$

where, $R_N(T)$ is combined resistance of the substrate (Nb and Cu), I_S is the current through Mgb2 part and $r(T)$ is the resistance of the superconductor. The combined resistance $R_N(T)$ is previously obtained from resistivity versus temperature curves for niobium and copper as a parallel resistance of the tubes. The $R_N(T)$ curve was fitted by

$$R_N(T) = \sum_{i=0} A_n T^n \tag{3}$$

Based on the experimental results of the tap voltage versus transport current as shown in Fig 3., the following expression was chosen for the wire resistance,

$$R(T) = R_N(T)[1.0 - 1.0/\{(1-a) + a(I/I_c(T))^m\}^{0.1}] \tag{4}$$

where the constants a and m are around 0.1 and 4, respectively. However, definite values of these parameters cannot be determined from the V-I curve of Fig 3.

If the values of a and m in Eq.(4) are given, the average temperature of the test sample T can be obtained as the value satisfying Eqs.(1), (3) and (4) simultaneously for the measured values of I and R.

On the other hand, theoretical expression of non-boiling heat transfer coefficients for exponentially increasing heat inputs with various exponential periods had already been obtained by some of the authors.

$$h = (h_c^3 + h_n^3)^{1/3} \tag{5}$$

where $h_c = (k\rho c_p/\tau)^{0.5}$ and $h_n = 0.53(k/D)(GrPr)^{0.25}$ are heat transfer coefficient of transient conduction and natural convection, respectively. (k: thermal conductivity, ρ:density, c_p: specific heat, D:diameter, Gr: Grashof number, Pr: Prandtl number)

The test sample was heated by electric current from a power amplifier whose input signal was controlled by a digital computer so as to give a desired heat input. Exponential heat inputs with the periods τ ranging from 4 ms to 700 ms were given to the test sample in a pool of LH2.

The average temperature of the test sample T was obtained from the measured values of the electric resistance of the sample R and electric current through the test sample I as by the following way.

Temporal value set of a and m in Eq. (4) were first given, then the average temperature of the test sample T at each time was obtained for the measured values of I and R at the time. The heat flux q is the heat input per unit surface area minus the energy storage rate in the test sample obtained from the smoothed average temperature versus time curve. The values of a and m were determined by a trial and error method for the non-boiling heat transfer coefficients thus obtained for various τ agree with those by Eq. (4).

Consequently, the parameter a and m were determined as 0.12 and 3.55, respectively.

$$R(T) = R_N(T)[1.0 - 1.0/\{0.88 + 0.12(I/I_c(T))^{3.55}\}^{0.1}] \tag{6}$$

4. Transient heat transfer experiment

4.1. Transient heat transfer curve

The transient heat transfer curves from non-boiling to nucleate boiling obtained by using Eqs. (1), (3), (5) and (6) are shown on the log q vs. log ΔT_L graph in Fig.4 with τ as a parameter. The ΔT_L is the excess surface temperature of the test sample beyond liquid temperature. The theoretical non-boiling heat transfer curves of Eq.(5) are also shown in the figure for comparison. We can see that the experimental non-boiling heat transfers coefficients agree well with the theoretical values.

In transient non-boiling heat transfer, heating current at a constant temperature rise of the test sample is higher for higher increasing rate of the heat input (shorter exponential period). This means that the resistivity of the test sample, namely distribution ratio of the electric current through the superconductor and the sheath can be estimated can be estimated as a function of the total current and the temperature.

4.2. Distribution ratio of the electric current through the superconductor and the sheath

The second term in the right hand side of Eq.(5) expresses the distribution ratio.

$$I_N/I\,(T) = [1.0 - 1.0/\{0.88 + 0.12(I/I_c(T))^{3.55}\}^{0.1}] \tag{7}$$

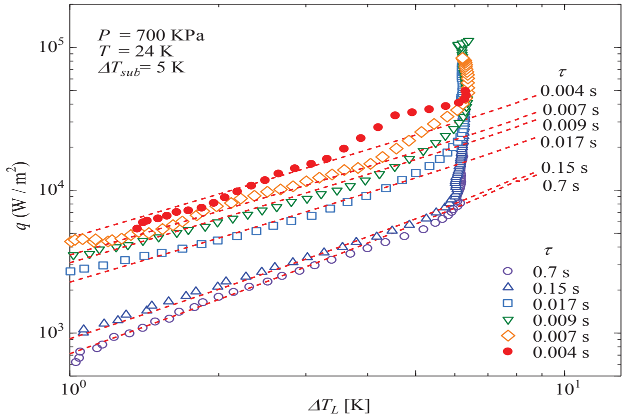

Fig. 4. Experimental results of transient heat transfer test.

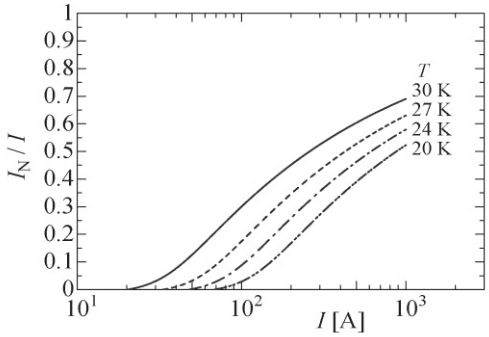

Fig 5. Current distribution ratio of the wire.

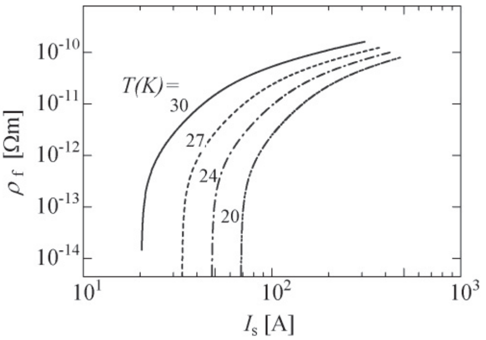

Fig. 6. Resistivity of the MgB2 superconductor.

Values of I_N / I calculated from Eq.(6) are shown in Fig.5 with temperature as a parameter. The ratio at a constant T is higher for higher current and that at a constant I is higher for higher T. We can see that the increasing rate of the ratio with the increase in I is gradual. The ratio becomes about 50 % and 62% for the current 10 times and 25 times higher than Ic, respectively.

4.3. Resistivity of the superconductor

The flow resistivity of the superconductor ρ_f can be obtained from Eq. (1) combined with Eq.(5).

$$\rho_f = rS/L = R_N I_N (S/L)/(I - I_N) \quad (for\ I - I_N > I_c) \tag{8}$$

where S is the cross sectional area of the superconductor and L is the length between the potential taps.

The values of ρ_f are shown in Fig.6 versus Is with the sample temperature as a parameter. As shown in the figure, the resistivity for each temperature first increases significantly and then the increasing rate becomes lower and approaches to a constant value of about unity.

5. Conclusion

Critical current of the test MgB2 wire were measured at several liquid hydrogen temperatures under pressure. The electrical resistivity of a short MgB2 wire as a function of electric current and the temperature cooled by pool liquid hydrogen for $I>Ic$ were measured by using the transient heating method. The distribution ratio electrical current through the superconductor and the sheath was estimated. The resistivity of the conductor was discussed.

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