Superconducting characteristics of short MgB$_2$ wires of long level sensor for liquid hydrogen

M Takeda$^1$, Y Inoue$^1$, K Maekawa$^1$, Y Matsuno$^2$, S Fujikawa$^2$ and H Kumakura$^3$

$^1$ Kobe University, Kobe, Hyogo 658-0022, Japan
$^2$Iwatani Corporation, Amagasaki, Hyogo 661-0965, Japan
$^3$National Institute for Materials Science, Tsukuba, Ibaraki 305-0047, Japan

E-mail: takeda@maritime.kobe-u.ac.jp

Abstract. To establish the worldwide storage and marine transport of hydrogen, it is important to develop a high-precision and long level sensor, such as a superconducting magnesium diboride (MgB$_2$) level sensor for large liquid hydrogen (LH$_2$) tanks on board ships. Three 1.7-m-long MgB$_2$ wires were fabricated by an in situ method, and the superconducting characteristics of twenty-four 20-mm-long MgB$_2$ wires on the 1.7-m-long wires were studied. In addition, the static level-detecting characteristics of five 500-mm-long MgB$_2$ level sensors were evaluated under atmospheric pressure.

1. Introduction

Hydrogen is a promising secondary energy for transforming a primary energy, such as a renewable energy, to resolve the problems of global warming and energy supply. For the storage and transport of a large amount of hydrogen originating from overseas renewable energies, a marine transport project for liquid hydrogen (LH$_2$: 20 K) has recently been attracting attention [1]. It is important for a high-precision and long level sensor to be installed in LH$_2$ tanks of about 10 m diameter on board ships. So far, Haberstroh [2] and Kajikawa [3] have developed self-heating-type magnesium diboride (MgB$_2$) level sensors for LH$_2$, on the other hand, we have studied an external-heating-type MgB$_2$ level sensor and its application to sloshing measurements of LH$_2$ [4-9]. A superconducting level sensor for LH$_2$, such as a MgB$_2$ level sensor, demonstrated high precision and high linearity in comparison with conventional level sensors/gauges: a differential pressure gauge, a capacitance-type level sensor, etc. In the case of enlarging/lengthening the MgB$_2$ level sensor, it is important to study, for example, the uniformity of the superconducting characteristics of long MgB$_2$ wires, the static and dynamic level-detecting characteristics of long MgB$_2$ level sensors, and the heater input and sensor length dependences of the level-detecting characteristics. The purpose of the present work is to perform an individual-difference performance evaluation of superconducting characteristics, taking twenty-four short MgB$_2$ wires (20 mm long) on three 1.7-m-long MgB$_2$ wires as the objects of study. In addition, the static level-detecting characteristics of five 500-mm-long MgB$_2$ level sensors are tested briefly.

2. MgB$_2$ wires for use as liquid hydrogen level sensor

The external-heating-type MgB$_2$ level sensor for LH$_2$ investigated in this study is composed of a MgB$_2$ wire of 0.32 mm diameter and a resistive heater (polyester-coated manganin wire of 0.2 mm diameter) wound around the entire MgB$_2$ wire with a pitch of 2 mm to prevent cooling by the hydrogen vapor around the liquid surface. Three 1.7-m-long MgB$_2$ wires (wires A, B and C) were fabricated by an in
situ method with a heat treatment of 1 h at a temperature of 873 K in an argon gas atmosphere and reinforced by a CuNi (7:3) sheath. To suppress the superconducting transition temperature $T_c$ to about 32 K below the critical temperature of LH$_2$, an impurity of 10% SiC was added to the MgB$_2$ core [4]. A photograph of the cross section of a MgB$_2$ wire is shown in Figure 1.

Figure 2 shows the positions of short MgB$_2$ sections on the 1.7-m-long MgB$_2$ wires. Nine 20-mm-long MgB$_2$ sections on wire A (denoted A-a1 to A-c3), nine 20-mm-long MgB$_2$ sections on wire B (denoted B-a1 to B-c3) and six 20-mm-long MgB$_2$ sections on wire C (denoted C-a1 to C-b3) were prepared as the short MgB$_2$ wires. A photograph of a short MgB$_2$ wire, which has current/voltage taps based on a four-wire technique, is shown in Figure 3.

3. Experimental apparatus and methods
Figures 4 and 5 show schematic diagrams of the system for measuring the superconducting characteristics of the short MgB$_2$ wires and the sample holder containing a vacuum space, respectively. The measuring system consists of the sample holder, which has a length of about 1 m, a liquid helium vessel, current generators, a power generator, voltmeters and a PC with a LabVIEW program. Two short MgB$_2$ wires, a Cernox thermometer and a resistive heater were mounted on the sample holder. The output voltages of the short MgB$_2$ wires with a 10 mA excitation current and the Cernox

Figure 1. Photograph of cross section of MgB$_2$ wire of 0.32 mm diameter.

Figure 2. Positions of short MgB$_2$ sections on 1.7-m-long MgB$_2$ wires.
thermometer with a 10 \( \mu \) A excitation current were measured by a DC four-wire technique utilizing Ohm’s law. In the experiment on the superconducting characteristics, the onset temperature of the superconducting transition \( T_{c,\text{on}} \), the offset temperature of the superconducting transition \( T_{c,\text{off}} \), the electric resistance \( R_{\text{on}} \) at \( T_{c,\text{on}} \) and the temperature dependence of the electric resistance \( dR/dT \) were the measurements we focused on; a high-precision level sensor requires a narrow superconducting transition temperature difference \( \Delta T_c \), a relatively high \( R_{\text{on}} \) and low \( dR/dT \).

**Figure 3.** Photograph of a 20-mm-long MgB\(_2\) wire.

**Figure 4.** Schematic diagram of system for measuring superconducting characteristics of short MgB\(_2\) wires.

**Figure 5.** Schematic diagram of sample holder containing vacuum space (unit: mm).
4. Experimental results

4.1. Superconducting characteristics

Figures 6-8 show the experimental results of the relationship between the resistance per unit length and the temperature of the 20-mm-long MgB$_2$ wires on wires A, B and C, respectively. Table 1 shows the averages and standard deviations of the superconducting characteristics of all the short MgB$_2$ wires. The average values of $T_{c\_on}$ were 33.79 K for wire A, 33.81 K for wire B and 33.60 K for wire C with standard deviations of 0.4 K or less, indicating an almost uniform property. The average values of $T_{c\_off}$ were 30.98 K for wire A and 31.48 K for wire C with standard deviations of 0.5 K, whereas it was 30.52 K for wire B with a standard deviation of 2.6 K, indicating relatively large variations of 23.92 K for B-c3, 28.43 K for B-a1 and 30.45 K for B-a2 as seen at the offset of the resistance per unit length measurements shown in Figure 7. The average temperature difference $\Delta T_{c}$ between $T_{c\_on}$ and $T_{c\_off}$ was 3.3 K for wire B, which was relatively large.

The average values of $R_{\ast\_on}$, where the asterisk denotes the resistance per unit length, were 5.053 $\Omega$/m for wire A, 5.046 $\Omega$/m for wire B and 5.013 $\Omega$/m for wire C. The standard deviations were 0.16 $\Omega$/m for wire B, and 0.18 $\Omega$/m or more for wires A and C, which are relatively large values. The average values of $dR'/dT$, where the asterisk denotes the resistance per unit length, were 0.004 $\Omega$/m/K with standard deviations of 0.001 $\Omega$/m/K for wires A-C.

To clarify the reason why $T_{c\_off}$ for wires B showed a relatively large variation, B-c3 was cut into four parts. Photographs of the six surfaces taken using a microscope are shown in Figure 9. A small region of MgB$_2$ on one of the surfaces showed some deformation, which is thought to be the main cause of the relatively large variation of $T_{c\_off}$; some deformation may be related to weak coupling in superconducting transition.

![Figure 6](image_url)

**Figure 6.** Relationship between resistance per unit length and temperature of 20-mm-long MgB$_2$ wires on wire A.
Figure 7. Relationship between resistance per unit length and temperature of 20-mm-long MgB$_2$ wires on wire B.

Figure 8. Relationship between resistance per unit length and temperature of 20-mm-long MgB$_2$ wires on wire C.
4.2. Level-detecting characteristics

Five 500-mm-long MgB$_2$ level sensors (A1, A2, B1, B2 and C) were fabricated from three 1.7-m-long MgB$_2$ wires. Static level-detecting characteristics were evaluated under atmospheric pressure by a four-wire technique with a current of 10 mA using an LH$_2$ glass Dewar during a spontaneous decrease in the LH$_2$ level. Figure 10 shows the experimental results of the relationship between the level read from the scale and the output voltage of the 500-mm-long MgB$_2$ sensors at a heater input of 6 W. As can be seen in this figure, the output voltage of A1 was 0.7 mV higher than those of the other sensors at a liquid level of zero; the main cause can be explained as a difference of length between voltage taps of A1. In contrast, the five 500-mm-long MgB$_2$ level sensors, including B1 and B2 with the relatively large variation of $T_{c,off}$, showed a correlation coefficient of 0.999 or more with high linearity and a gap of the maximum level-detecting length between A1 and A2 of 4 mm (about 1%) for heater inputs in the range from 3 W to 9 W.

5. Summary

The superconducting characteristics of twenty-four 20-mm-long MgB$_2$ wires on three 1.7-m-long MgB$_2$ wires were evaluated. It was found that several short wires showed different characteristics, for example, $T_{c,off}$ for wire B and $R^{*}_{on}$ for wires A and C regardless of the position on the 1.7-m-long MgB$_2$ wires. Static level-detecting characteristics were evaluated under atmospheric pressure for five 500-mm-long MgB$_2$ level sensors made from three 1.7-m-long MgB$_2$ wires. It was found that all the 500-mm-long MgB$_2$ level sensors exhibited good level-detecting characteristics for LH$_2$ and little variation among their individual performances. The mass production of long MgB$_2$ level sensors for LH$_2$ is thus believed to be feasible.

Table 1. Averages and standard deviations of superconducting characteristics of short MgB$_2$ wires.

| Wire  | Ave. | σ  | Ave. | σ  | Ave. | σ  |
|-------|------|----|------|----|------|----|
| $T_{c,off}$ [K] | 33.79 | 0.23 | 33.81 | 0.41 | 33.60 | 0.44 |
| $T_{c,off}$ [K] | 30.98 | 0.42 | 30.52 | 2.60 | 31.48 | 0.54 |
| $R^{*}_{on}$ [Ω/m] | 5.053 | 0.208 | 5.046 | 0.164 | 5.013 | 0.185 |
| $dR^{*}/dT$ [Ω/m/K] | 0.004 | 0.001 | 0.004 | 0.001 | 0.004 | 0.001 |

Figure 9. Photographs of cross sections of B-c3 showing six cutting surfaces.
Acknowledgments
The authors would like to thank Professor Katsuya Fukuda and Dr. Mineo Tanaka for helpful discussions and technical support. This work was supported in part by a Grant-in Aid for Scientific Research, JSPS KAKENHI Grant Number 24246143, Japan.

References
[1] Kamiya S 2015 Physics Procedia 67 11
[2] Haberstroh C, Dehn G and Kirsten G 2007 Proc. ICEC21-ICMC2006 357
[3] Kajikawa K, Tomachi K, Tanaka K, Funaki K, Kamiya T, Okada M and Kumakura H 2009 Proc. ICEC22-ICMC2008 425
[4] Takeda M, Matsuno Y, Kodama I, Kumakura H and Kazama C 2009 IEEE Trans. Appl. Supercond. 19 764
[5] Takeda M, Yagi S, Kodama I, Fujikawa S, Kumakura H and Kuroda T 2010 Adv. Cryo. Eng. 55 311
[6] Maekawa K, Takeda M, Matsuno Y, Fujikawa S, Kuroda T and Kumakura H 2013 Proc. ICEC24-ICMC2012 59
[7] Takeda M, Fujikawa S, Matsuno Y, Maekawa K, Kuroda T and Kumakura H 2013 Proc. ICEC24-ICMC2012 311
[8] Maekawa K, Takeda M, Matsuno Y, Fujikawa S, Kuroda T and Kumakura H 2015 Physics Procedia 67 1164
[9] Takeda M, Nara H, Maekawa K, Fujikawa S, Matsuno Y, Kuroda T and Kumakura H 2015 Physics Procedia 67 208

Figure 10. Relationship between level read from scale and output voltage of 500-mm-long MgB$_2$ sensors at a heater input of 6 W under atmospheric pressure.