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10kJ SMES용 고온초전도 전류리드의 설계 및 제작

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Design and manufacture of HTS current lead for 10kJ SMES

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Abstract - In superconducting magnetic energy storage (SMES) systems, the current leads are usually divided into two parts. Normal metals like brass or copper are often used in the first part from the room temperature to the 1st stage of the cryocooler. Their dimensions were decided to minimize the conduction heat penetration and Ohm's heat generation. The second part down to the cryogenic coil is made of high temperature superconductor (HTS). HTS current leads can reduce the conductive heat penetration because they have poor thermal conductivity and generate no Ohm's heat generation. The brass current lead and the HTS current lead were designed and fabricated for application to the 10kJ class SMES system. The HTS current lead is 300A class. The HTS current lead was stacked with 2 HTS layers using the $Bi_2Sr_2Ca_2Cu_3O_x$ (BSCCO)/Ag. In this paper, we introduce the design procedure of the current leads and discuss the test results of the current leads.

1. Introduction

In conduction cooled superconducting devices such as SMES and Magnet, HTS current leads are often used. Conventional copper and brass leads can be used to transport the current from room temperature to the 1st stage of the cryocooler but HTS leads are recommended for the lower part down to the cryogenic coil. This is due to the facts that HTS leads generate no Ohm's heat generation in the lead itself and the thermal conductivity of the lead is significantly lower if compared to the best possible conventional leads and thereby operating costs are reduced. HTS current leads are usually made with HTS tapes or with a HTS bulk in between high conductivity copper terminals. When the HTS bulk is used, the heat load can be four times smaller compared to the HTS tapes. However, there can be problems with electrical and mechanical stability. Thus, HTS tapes with a high conductivity matrix offer good compromise between stability and thermal conduction [1]. The brass and HTS current lead are series combination, and are cooled by a contact with distributed or staged cryocooler. This is called binary or hybrid current lead [2]. We designed and fabricated the brass current lead and Bi-2223/Ag HTS current lead for application to the 10kJ class SMES system. More details about the research goal of the 10kJ SMES system can be found in [3]. The HTS current lead is 300A class. And the brass current lead was optimized by varying its cross sectional area along the length. The cool-down characteristics of the current leads are experimentally investigated by applied current.

2. Current leads design

2.1 Design conditions

The shape of the current leads determined by the cooling methods and types of system that they will be applied. The design of the HTS current lead focuses on the following conditions:

1) Transport current capacity : 300A class
2) Cool-down stability of HTS current lead according to the radiation
3) Minimization of heat leak to the cryogenic coil.

2.1.1 Metal current lead design

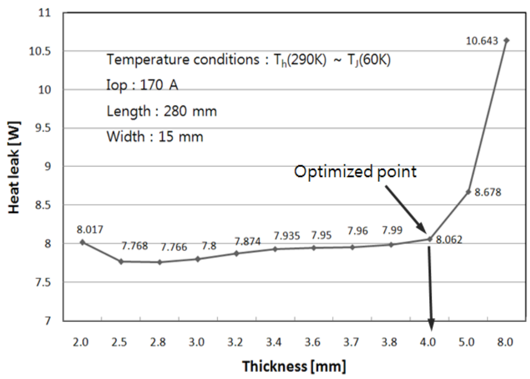
The metal thermal conductivity (k(T)) and electrical resistivity (ρ(T)) obey the Wiedemann-Franz-Lorentz law (1). The material of the metal current was selected the brass because of better mechanical characteristic than copper. The brass current lead was optimized by varying their cross sectional area along the length. The optimization equations are following [4] :

$$\rho(T)k(T)= L_0 T, \quad (L_0 = 2.45\times 10^{-8}[W\Omega/K^2]) \qquad (1)$$

$$\left(\frac{L}{A}\right)_{opt} = \frac{1}{I}\int_{T_J}^{T_h}\frac{k(T)}{\sqrt{L_0\left(T_h^2 - T^2\right)}}dT \qquad (2)$$

<Table 1> Optimized shapes of metal current lead

Metal	Brass	Better mechanical characteristic than copper
Area (A)	60 mm^2	Dimensions
Length (L)	280 mm	
T_h	290 K	Room temperature
T_J	60 K	Temperature of 1st stage cold-head
Iop	170 A	Operating current @20K

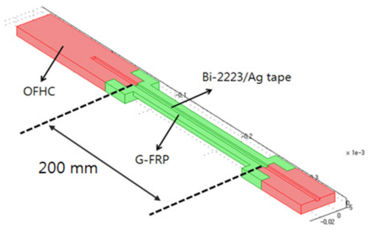


<Fig. 1> Optimization of the brass lead

2.1.2 HTS current lead design and manufacture

The quantity of heat leak through the Bi2223/Ag current lead bigger than $YBa_2Cu_3O_y$ (YBCO) tape and Bi-2223/(Ag + 1 at. % Au) alloy [5, 6]. But the choice of the HTS tape aims to have good cool-down stability according to the radiation to ensure efficient cool-down of the HTS current lead. So, we selected the Bi-2223/Ag HTS tape. The HTS current lead was manufactured using glass fiber-reinforced plastics (G-FRP) rod with oxygen free high conduction (OFHC) copper terminals in both ends as shown in Fig 2. The HTS tapes were stacked with 2 layers. Sumitomo electric industries (SEI) manufactured Bi-2223/Ag tape was then installed to the 350mm long groove in the rod. The two-stacked HTS tape had Ic = 260A at 77K, self field and had no stabilizer such as steel and copper. Table 2 shows the specifications of the HTS current lead.

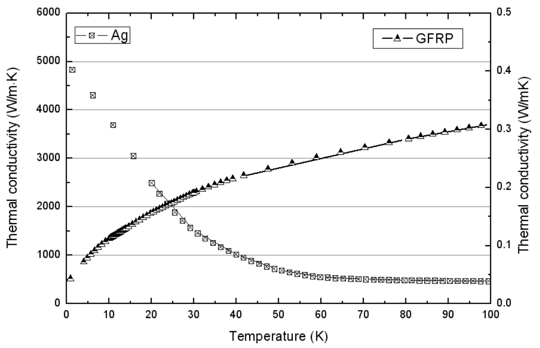
And Fig. 3 shows the thermal conductivities of G-FRP and Ag. Fig 4 shows the cool-down stability of the G-FRP support and HTS tape according to the radiation heat using the finite element method (FEM). The temperature conditions are 20K to 60K. The cross sectional area of the Bi2223/Ag tape was assumed that it was 60% of the total with Ag and its length was 200mm.



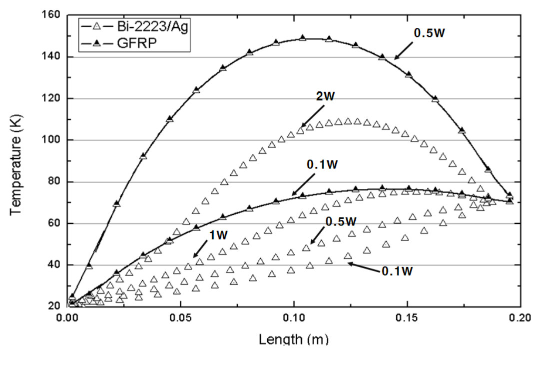
<Fig. 2> Scheme of the HTS current lead

<Table 2> Specifications of HTS-lead and Cryocooler

	HTS lead	Cryocooler	
Material	Bi2223/Ag	Manufacturer	DAIKIN
Width(mm)	4.4	1st stage 35W @52K 2nd stage 2W @5K	Test results
Thickness(mm)	0.27		
Length (mm)	350		
Heat leak	1W/per		



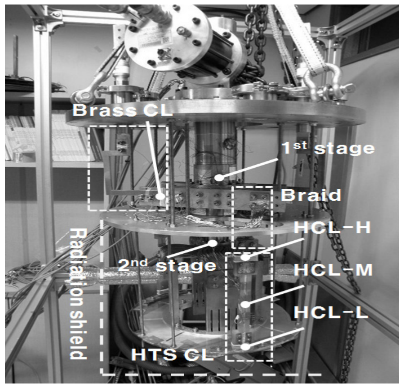
<Fig. 3> Thermal conductivity of Ag and G-FRP



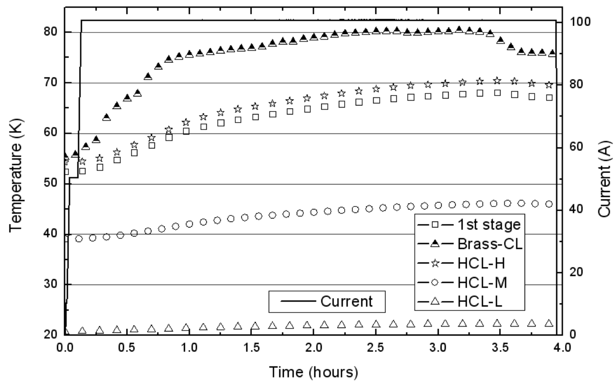
<Fig. 4> Cool-down stability analysis results of Bi2223/Ag and G-FRP according to the radiation heat

3. Test result

To monitor the development temperature of the current leads and the cold-head of two stage cryocooler by the transport current, six silicon diode sensors were fixed on each parts as shown in Fig. 5. Fig. 6 shows the temperature on the each parts when applied the 100A for 4 hours. Since the temperature at the warm part end of the HTS current lead increased to 70K, the transport current can not be increased. We estimate that the problems are the degree of a vacuum in the cryostat and bulk radiation shield related to the cooling capacity of the cryocooler. The vacuum pump was operated at 1720rpm. The cryostat evacuated to 10^{-1} torr before the turn-on the cryocooler.



<Fig. 5> Structure of current leads and temperature sensor locations



<Fig. 6> Measured temperature at the current leads and cold-head of cryocooler (Transport current 100A)

4. Conclusion

The current leads for 10kJ SMES system were designed and fabricated. In the performance test, the leads were expected to have 300A. But the test result was only 100A. Based on the result, we will revise the cryostat, radiation shield and improve the connection between cryocooler and leads.

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