Standardization of Critical Temperature Measurement by Magnetic Method

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Abstract. Magnetic critical temperature of composite superconductors has been studied for providing a new standard method for the critical temperature measurement. Various magnetization-temperature curves of Cu/NbTi, Cu/Nb3Sn and Ag/Bi-2223 wires were measured using a SQUID magnetometer and an ac susceptometer. In the case of SQUID magnetometer measurements, we employed a two-field-direction method to obtain higher resolution near the onset temperature. In ac susceptometer measurements, various amplitudes from 2 Oe to 10 Oe with frequencies from 11.3 Hz to 1033 Hz were applied to three specimens to study the suitable ac magnetic field and frequency range. Analytical comparison of the magnetic curves with the resistive curves was also accomplished to investigate the validity of the new method as compared with the existing one.

1. Introduction

The critical temperature is a basic and an important parameter for characterizing a superconductor. There are various test methods to measure the critical temperature including resistive method, magnetic method, etc. The resistive method is more often used to define the critical temperature because the resistive method is simpler than a magnetic method. In 2002, the IEC, International Electrotechnical Commission, published an international standard on a resistive method for NbTi, Nb3Sn, and Bi-system[1]. As well as the resistive method, the magnetic method is also a significant and useful method to evaluate the quality of a superconductor. If the specimen is composed of inhomogeneous grains or the spaces between their grains are insulating, the resistive method is not adequate to measure the critical temperature. For providing a standard on the measurement of magnetic critical temperature, we have studied various magnetization-temperature ($m-T$) curves of Cu/NbTi, Cu/Nb3Sn, and Ag/Bi-2223 composite wires.

2. Experiments

In this study, we used multi-filamentary Cu/NbTi and Cu/Nb3Sn, and Ag-sheathed Bi-2223 tape. A SQUID magnetometer (QD : MPMS) and an ac susceptometer (QD : PPMS) were used for measuring the dc $m-T$ curves and ac $m'-T$ curves, respectively. Diameters and lengths of Cu/NbTi and
Cu/Nb₃Sn specimens were 0.78 mm × 3.72 mm (0.013 g), 0.77 mm × 5.20 mm (0.022 g), respectively. Dimension of a rectangular Ag-sheathed Bi-2223 tape was 4.05 mm × 0.30 mm × 5.33 mm (0.053 g).

The specimens were mounted in a non-magnetic holder and then installed inside the detection coils of the SQUID magnetometer or ac susceptometer. After stabilization at the designed temperature through a zero-field cooled process, a suitable magnetic field was applied to the specimen and then the $m$-$T$ curves were measured with increasing temperature.

3. Results and Discussion

We measured several types of $m$-$T$ curves of our specimens, but the mid-point criterion as in the case of the resistive method was not adequate for the magnetic method. Rather, we found that the onset temperature criterion from the normal to the superconducting state is more reasonable. To obtain higher resolution near the superconducting transition when using a SQUID magnetometer, we employed a two-field-direction method which measures $m$-$T$ curves of a specimen first in positive and then in negative fields[2]. In this way, the background part of the magnetization was double-checked. Determining the background part as accurate as possible was important to determine the onset temperature as described below.

Fig. 1 shows the dc $m$-$T$ curves of three specimens in a dc magnetic field ±10 Oe using two-field-direction method after zero-field cooled. As shown in Fig.1 (a), $m$ of NbTi specimen change slowly in a temperature range from 6 K to 8.7 K, but from 8.8 K to 9 K, near the critical temperature, its value changes rapidly. If the region near the transition at 9 K in Fig.1 (a) is expanded, the onset temperatures from the normal to the superconducting state can be easily determined with a reasonable accuracy as 9.03 K. The onset temperature is determined by the intersection between the linear extrapolation of the abrupt change in $m$ and the background signal. Fig. 1 (b) shows the results of $m$-$T$ curves of Nb₃Sn specimen. Here the change of $m$ near the transition is rather gradual when compared to the NbTi case, the onset temperature still can be easily obtained as 17.3 K. The results of $m$-$T$ curves of Bi-2223 specimen are illustrated in Fig. 1 (c). The onset temperature of the superconducting transition in this case was obtained as 108 K.

The critical temperature in general depends on an applied magnetic field, but for the materials of high critical fields such as the current specimens, we observed that applying much smaller fields than the critical field, in the range of 5 Oe – 120 Oe, did not significantly affect the critical temperature measurement. One of typical $m$-$T$ curves of Nb₃Sn specimen is shown in Fig. 2. Besides a slight shift of $m$-$T$ curves in the normal state due to the paramagnetic component of the normal material such as Cu or bronze, each onset temperature was not deviated more than 1%.
An ac susceptometer is another important tool for measuring the magnetic properties of the superconducting specimens[3] and we employed ac susceptometer to a magnetic method of the critical temperature measurement. In Fig. 3, the results of ac \( m' \)-\( T \) curves of three specimens are illustrated with various amplitudes of ac fields from 2 Oe to 10 Oe at a frequency of 11.3 Hz.

As shown in Fig. 3, ac \( m' \)-\( T \) curves are somewhat noisy at \( 10^{-4} \) emu level compared to the corresponding dc \( m' \)-\( T \) curves, but the resolution was sufficient enough to define a transition temperature from the data. The onset temperatures did not significantly depend on the amplitudes of the ac field up to 10 Oe.

We also investigated a suitable frequency range for measuring the critical temperature. Low-frequency ac data were quite consistent with those of dc results, and an example of results is illustrated in Fig. 4. As shown in Fig. 4, the ac and dc \( m' \)-\( T \) curves of Nb\(_3\)Sn specimen are nearly the same and the onset temperature are 17.3 K and 17.4 K, respectively. As the frequency was increased from 11.3 Hz to 1033 Hz, the ac \( m' \)-\( T \) curves of all the specimens were shifted toward more negative magnetization and eventually the sharpness of the transition gradually disappeared when the frequency was well above 100 Hz, presumably due to the additional contribution of the conducting sheath at this frequency range.

As discussed in the introduction, the international standard, IEC61788-10, defines the critical temperature as a mid-point temperature of resistive transition (\( R \)-\( T \) curve) between the normal and the zero resistance state. There is a certain possibility of discrepancy between \( m' \)-\( T \) curve and \( R \)-\( T \) curve when the specimen consists of inhomogeneous superconducting grains. Although the specimen is
inhomogeneous, $R-T$ curve may show a sharp transition because a test current can percolate through the best grains in the resistance measurement.

An example of comparison for Bi-2223 specimen is shown in Fig. 5. As shown in Fig. 5, $R-T$ curve shows a sharp transition while $m-T$ curve shows a broad transition. However, the critical temperature determined by the resistive method is 107.5 K, almost the same as the onset temperature of the $m-T$ curve (107.8 K). This implies that the magnetic method is also useful to determine the critical temperature.

![Fig. 5. Comparison of $m-T$ curves with $R-T$ curves for Ag/Bi-2223 specimen.](image)

### 4. Conclusion

We studied various $m-T$ curves of Cu/NbTi, Cu/Nb$_3$Sn and Ag-sheathed Bi-2223 specimens for standardization of critical temperature by a magnetic method. Differently from the resistive standard, the mid-point temperature of $m-T$ curve was not adequate to determine the critical temperature. Thus, we suggest the onset temperature as a definition of the critical temperature. Especially, if dc magnetization is measured, a two-field-direction method is recommended for higher resolution near the onset temperature.

In ac $m^*_T$ curve measurements, ac fields of 7 Oe - 10 Oe with 11.3 Hz - 113 Hz were found to be suitable for measuring the onset temperature.

We think that this method would be useful to provide a magnetic standard of the critical temperature in addition to IEC 61788-10 international standard. Through further research and international comparison, this study could lead to establish a new standard of the critical temperature measurement in superconductive materials.

### References

[1] IEC 61788-10 Critical temperature measurement by a resistive method (2002).
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