Determination of critical current density in flux creep state for MgB₂

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Abstract

We propose a method to determine critical current density j_c for MgB₂ with flux creep from the real part of AC susceptibility (ACS), which facilitates the determination of j_c at different DC fields R_d in temperature range as wide as 5 - 38K. Influence of criterion E_c on j_c was studied by varying amplitude (B_{ac}) and frequency (f) of AC field. The result shows that it is not proper to obtain temperature dependence of j_c by measuring only the peak temperature of imaginary part of ACS.

Key words: j_c; flux creep state; AC susceptibility;

1. Introduction

In the critical state model, the real or imaginary parts of ACS have been connected to j_0, the j_c without flux creep [1] by the called ACS method. In addition to the analytical relation [1], j_c usually is determined based on the critical state model by ACS technique using the equation below:

\[ j_c(T_p) = \frac{B_{ac}(T_p)}{\mu_0 d} \]  (1)

Nevertheless, due to flux creep, the current density has already decayed before reaching j_0, and its magnitude depends on time and the position in the sample. Here we extend the method to the case with flux creep and determined j_c in a wider temperature range for a MgB₂ sample. Then influence of the criterion on j_c was studied.

It is shown that a spatially constant but time dependent j(t = 1/f) smaller than j_0 inside the sample is a good approximation to describe the dynamics of highly non-linear flux creep [2]. Then the relations between \chi' and j_c can be written formally as:

\[ j_c(f, T_p) = \frac{B_{ac}(T_p)}{\mu_0 d} \]  (2)

\[ \chi' = -1 + \frac{z'}{2}(B_{ac} \leq \mu_0 j(f)d) \]  (3)

\[ \chi' = \left(\frac{-1 + \frac{z'}{2}}{\cos^{-1}(1 - \frac{z'}{2})} + \left[-1 + \frac{\frac{z'}{2}}{\sin^{-1}(z')} - \frac{4}{(z')^2} \right] \right) \left(1 - \frac{1}{2} \right) \]  (4)

Here \chi' = \frac{B_{ac}}{\mu_0 j(f)d}. T_p is the temperature at which the imaginary part \chi'' peaks and d is the half width of the slab. According to the definition, the critical current density is a j at certain criterion such as electric field E_c. Hence j_c extracted from the above equations is in fact the j at certain criterion. Here the electric field at the surface of the sample is used as E_c, i.e. E_c = E(0) [3,4], which can be approximately obtained by:

\[ E_c = \frac{1}{4f} \int_0^{1/4f} E(0, t) dt = 4dfB_{ac} \]  (5)

Here \int_0^{1/4f} E(0, t) dt = \frac{\int_0^d (-\partial B(x, t)_{ac}) dx}{\mu_0 d} = 2\pi d B_{ac} \cos(2\pi ft).

Note that the same case also takes place in other methods as long as flux creep is important [5,6] but it was rarely mentioned in previous ACS and VSM methods.

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2. Results and discussions

The sample used here is a sintered MgB$_2$ rectangular slab. From $\chi'$ data in the insert of Fig. 1 and equation (2) and (3), $j_c$ in the range of 38K - 5K are determined and shown in Fig. 1, where $j_c(0T, 37K) = 10^3 A/cm^2$. Each $j_c - T$ curves are determined by a single $\chi' - T$ curve and easy to obtain in broader temperature range.

Shown in Fig. 2 are the $j_c(T, E_c)$ curves indicating the influence of $f$ and $T$ on the magnetic $j_c$. It is apparent that the higher the $f$, the larger the $E_c$, the higher the $j_c$, which coincides with the transport measurements [5,6]. For example, $j_c(9.8V/cm)$ is more than one order of magnitude larger than $j_c(0.7V/cm)$ at 11K. If this influence is extrapolated to $j_c$ measurements by ACS in a wider frequency range, E.G. $0.1kHz \leq f \leq 10kHz$, one can expect that $j_c(10kHz)$ is approximately two orders higher than $j_c(0.1kHz)$. The fact that the $\chi' - T$ curve are dependent on $f$ is a strong evidence that flux creep is also giant in MgB$_2$ and could not explained by any critical state model.

Because $E_c$ is also proportional to $B_{ac}$, $B_{ac}$ influences $j_c$ as well. Shown in Fig.3 are examples of the influence by $B_{ac}$, where it is also seen that a larger $B_{ac}$ corresponds to a larger $E_c$ and thus a higher measured $j_c$. These experimental data, in addition to the above argument, show that it is not proper to determine temperature dependence of $j_c$ from $j(T_p)$ measurement of peak temperature $T_p$ of $\chi''$ at different $f$ or $B_{ac}$ based on equation (1)[7] because shifting $T_p$ by changing either $f$ or $B_{ac}$ simultaneously changes $E_c$ as well.

Fig. 1. $\chi(T)$ (insert) and corresponding $j_c(T)$ curves at $B_d = 7T$ and $5K \leq T \leq 39K$ for MgB$_2$

Fig. 2. Influence of $f$ ($E_c$) on $j_c$ determination at four different temperatures for MgB$_2$

Fig. 3. Influence of $B_{ac}$ ($E_c$) on $j_c(T)$ curves in magnetic measurement for MgB$_2$

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References