On the scaling analyses of the flux pinning force density estimated for two types of MgB₂ specimens

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Abstract. Magnetic hysteresis loops have been measured for polycrystalline and powder MgB₂ samples. Hysteresis loop width ΔM measured for polycrystalline sample was less than one order of magnitude smaller than that measured for powder sample. Magnetic field dependence of the critical current density estimated from the ΔM is essentially divided into three regions. The irreversibility field $B_{irr}$ for each sample has been derived from so called Kramer plots using relevant magnetic field dependence. The scaling law of the reduced pinning force density was satisfactorily applied to the experimental results for each sample by using thus determined $B_{irr}$. If we define the $B_{irr}$ as a field at which the critical current density becomes $10^6$ (A/m²), such scaling law is apparently applicable to polycrystalline sample and not applicable to powder sample. Such discrepancy may come from that the $B_{irr}$ by two types of definition belongs to different flux regime.

1. Introduction

The flux pinning is very important for practical use of the superconductivity and several mechanisms of the flux pinning have been discussed. Among them, Kramer and Dew-Hughes showed that the magnetic field dependence of the pinning force density has the general form of

$$f_p \propto b^p (1-b)^q,$$

where $f_p$ is defined as $f_p = F_p / F_{pmax}$ [1,2], $F_p$ is the pinning force density and $F_{pmax}$ means the maximum value of the $F_p$. In Eq. (1), the exponent’s $p$ and $q$ are characteristic pinning parameters and $b$ is the reduced magnetic field $B/B_{c2}$, where $B$ is magnetic flux density and $B_{c2}$ is the upper critical magnetic flux density. The parameters $p$ and $q$ depend on the pinning mechanism and several sets of $p$ and $q$ for dominant elementary pinning forces are predicted [2]. In case of cuprate high $T_c$ superconductors or MgB₂, however, $B_{c2}$ should be replaced with the irreversibility field $B_{irr}$ because $F_p=0$ at $B=B_{irr}$. A distinctive feature of Eq. (1) is that the $f_p$ versus $b$ curves at all measuring temperatures are merged into one curve with a value set of $p$ and $q$. This is called as scaling law. Examination of the validity of the scaling law is important in order to know the flux pinning mechanism of the sample.
There are many reports discussing the validity of the scaling law represented by Eq. (1) in MgB$_2$. Among them, some studies have reported that the scaling law is not applicable to the experimental results of pure and doped MgB$_2$ specimens [3-5]. On the other hand, there are some studies showing the scaling law is a good fitting model with their experimental results [6-8]. There is a remarkable difference on the validity of the scaling law in case of MgB$_2$. Such contradictory experimental results to each other may come from complex flux pinning mechanisms which depend on the sample characteristics. But, one important point for the problem is that such discrepancy comes from how to decide the irreversibility field.

In this paper, we show that the scaling law explains the experimental results if the irreversibility field is appropriately determined.

2. Experimental
Polycrystalline samples were prepared by stainless steel packed method [9,10]. Starting materials of Mg and B with the stoichiometric ratio of 1:2 are contained in a stainless steel pipe (30mm in outer diameter, 1.5mm in thickness and 110mm in length). Both sides of the stainless steel pipe were shielded by an arc melt method and heated at 1200°C for 12h. Thus prepared MgB$_2$ poly-crystals consist of irregular shape particles with the size of 50–100μm. The X-ray diffraction measurements showed a typical pattern of this material. The poly-crystals were ground into powder with small grain (polycrystalline powder). Powder specimens were made using commercially available powder (Alfa Aesar Co.). At first, powder with the particle size of 50–63μm was selected using a relevant size of sieve for two kinds of raw powder. One particle of thus selected polycrystalline powder consists of a few single crystals with a mean grain size of ~10μm. On the other hand, one particle of thus sieved commercially available powder (powder sample) consists of so many small grains with the size of less than 0.1μm. Each selected powder was mixed with epoxy resin in order to avoid particle connection. Magnetization measurements were done using PPMS (Physical Properties Measurement System, Quantum Design Co. Ltd) magnetometer at temperatures of 5–40K and under a magnetic field of 0–9T.

3. Results and Discussion
At first, we measured temperature dependence of the magnetization under a field of 0.5mT in order to determine the superconducting transition temperature $T_c$ of each sample. As the results, $T_c$=38.5K for powder sample and $T_c$=38.1K for polycrystalline sample were obtained.

Magnetic hysteresis loops of two types of sample were measured. Current critical density $J_c$ was estimated using the Bean model of $J_c$=3ΔM/d, where $\Delta M$ (A/m) is the hysteresis width and $d$(m), the diameter of a particle of the sample. Magnetic field dependence of the $J_c$ for both samples is shown in Fig. 1, where solid marks correspond to the polycrystalline sample and open marks, to the powder sample. Circles are for $T$=10K and squares, for $T$=25K, respectively. Results at other temperatures are neglected in order to avoid confusion.

Magnetic field dependence of the $J_c$ is essentially divided into three regions specified I, II and III in the figure. In region I, the $J_c$ is approximately independent on magnetic field. In region II, the $J_c$ exponentially decreases with increasing magnetic field as a function of $B^{3/2}$. In region III, the $J_c$ has another decreasing function of $B^{-3}$. Region II’ in the figure means a mixed flux regime of II and III. These characteristic regions of I, II and III may correspond to single flux, small flux bundle and large flux bundle regime, respectively [11].
In order to discuss the scaling law, it is important how to determine the $B_{irr}$. One of the common methods is so called Kramer plots [2], where it is necessary to know which flux pinning mechanism is applicable to the experimental results of the $F_p$. In case of polycrystalline sample, the flux pinning is affected by normal point pinning and $\Delta\kappa$ pinning [10]. But, the experimental points are rather close to the $\Delta\kappa$ pinning. Therefore, we use Eq. (1) with $p=3/2$ and $q=1$ which is characteristic for $\Delta\kappa$ pinning.

Then, $J_c B^{-1/2}$ is a function of $1 - B/B_{irr}$ and the irreversibility field $B_{irr}$ is determined as a field at which the $J_c B^{-1/2}$ becomes zero. Such plots at each temperature are shown in Fig.2 (a).

The flux pinning mechanism for powder sample is the grain boundary pinning [6]. In this case, we have $p=1/2$ and $q=2$ as the pinning parameters. Then $J_c^{1/2} B^{1/4}$ is proportional to $1 - B/B_{irr}$ and the experimental points should lie on a straight line. Such plots are shown in Fig.2(b) and also the $B_{irr}$ is determined by the same way as mentioned above.

Temperature dependence of thus determined $B_{irr}$ has a functional form of $\{1 - (T/T_c)^2\}^n$, where $n$ is a characteristic index. Analytical result of $n=1.3$ has been obtained for polycrystalline sample and approximately the same value of $n=1.4$, for powder sample. If the $B_{irr}$ is determined by the $J_c$ criterion, then $n=1.3$ for polycrystalline sample and $n=2.2$ for powder sample have been obtained, respectively. In case of polycrystalline sample, the $B_{irr}$ by the $J_c$ criterion is more than one order of magnitude larger than that by the Kramer plots. But, the index $n$ for both criterions is approximately the same value. Typical value of $n$ is 3/2 which is characteristic of 3D flux creep [11]. The $n$ value of 2.2 by the $J_c$ criterion for powder sample is fairly different from the typical value and there is no report of such value within our knowledge. But, we have to emphasize that the $n$ value becomes 1.6 if we adopt the $J_c$ criterion of $10^7$ (A/m$^2$) for the irreversibility field definition. The $n$ value is strongly depend on the criterion and hence the field dependence of the $J_c$.

By using thus determined irreversibility fields at relevant temperatures, normalized pinning force density $f_p=F_p/F_{pmax}$ was plotted as a function of the reduced field $b$ defined by $b=B/B_{irr}$. In case of polycrystalline sample, such plots at each temperature are shown in Fig.3(a). A theoretical curve with $p=3/2$ and $q=1$ in Eq. (1) is also plotted in the figure. It is obvious from the figure that the experimental points deviate from the theoretical curve in the region of $b$ larger than ~0.8 at all temperatures. The field at which the deviation begins to occur coincides with the field at which the experimental points deviate from the theoretical curve in the region of $b$ larger than ~0.8 at all temperatures. The field at which the deviation begins to occur coincides with the field at which the experimental point of $J_c B^{-1/2}$ begins to deviate from the straight line at each temperature as shown in Fig.2(a) by arrows. The inset shows the scaling plots when the $B_{irr}$ by the $J_c$ criterion was used. In this case, the experimental points look also like lying on a curve. But there is no pinning model for such curve with the peak value of $f_p$ at $b=0.035$. Apparent applicability of the scaling law shown in the inset of Fig.3(a) comes from that the $B_{irr}$ by the $J_c$ criterion has accidentally the same temperature dependence as the $B_{irr}$ by the Kramer plots.
Fig.3(a) The $f_p$ vs $b$ plots for polycrystalline sample. Fig.3(b) The $f_p$ vs $b$ plots for powder sample.

In case of powder sample, the $f_p - b$ plots are shown in Fig.3(b). We can see the analytical results at all temperatures are approximately merged into a characteristic curve shown by a solid line which is a theoretical one with $p=1/2$ and $q=2$. This $p$ and $q$ value set is caused by the grain boundary pinning. If the $J_c$ criterion is adopted as a definition of the $B_{irr}$, then the $f_p - b$ plots do not merge into a curve as shown in the inset of Fig.3(b). The reason why the scaling function of Eq. (1) does not explain the experimental results in such case is clear: The $f_p - b$ plots are evaluated in the field region of I and II, but the $B_{irr}$ determined by the $J_c$ criterion lies in the field region III or II’.

As a conclusion, when we discuss the vortex pinning mechanism using the scaling law for MgB$_2$ or high $T_c$ superconductors, the important point is how to decide the irreversibility field $B_{irr}$ i.e. the $B_{irr}$ should be decided in the same flux bundle regime as the $F_p/F_{p,max}$ values are evaluated.

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