Modified scaling law of the critical current density in polycrystalline MgB$_2$ specimens

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Abstract. Magnetic hysteresis loops have been measured for polycrystalline MgB$_2$ specimens at temperatures 5 to 30K and under magnetic field up to 1T. Resultant hysteresis width is very narrow, which means the flux pinning is very weak. To such case, a flux creep – flux flow model proposed by Matsushita et al.[1] may be valid. But, the temperature dependence of the irreversibility field was far from their prediction. Direct comparison between the scaling law and the experimental results successfully explains temperature dependence of the $J_c$, but field dependence of the $J_c$ is only partly reproduced. It is necessary to introduce an exponential decay with increasing magnetic field proposed by Blatter et al.[2] in order to explain the experimental results in high field region.

1. Introduction
The critical current density, $J_c$, of the second type superconductor is determined by the strength of the flux pinning force. It is well known that the normalized flux pinning force $F_p/F_{p\text{max}}$ is scaled in one characteristic curve as a function of the reduced field $b=B/B_{c2}$, where $B$ means the magnetic flux density and $B_{c2}$, the upper critical field. The situation is well known as the Kramer’s scaling law[3]. In case of high-$T_c$ cuprates, however, the scaling law is applicable only to the experimental results at high temperatures near $T_c$. One reason for such circumstance may be that the effect of thermally activated flux motion (flux creep) is not negligible. The flux creep effects on the irreversibility field and also on the pinning parameters have been discussed by Matsushita et al.[1]. In case of MgB$_2$, almost studies have reported that the scaling law is not applicable to the experimental results for pure and doped specimens[4,5]. Effect of the flux creep should not be neglected for the case of MgB$_2$ also. Such report has been done by Kitahara et al., in which the temperature dependence of the irreversibility field and the field dependence of the $J_c$ for powdered specimens with strong pinning force have been successfully explained by the flux creep – flux flow model[6]. Effect of the flux creep will be more conspicuous in specimens with weaker flux pinning. Here, we report the experimental and analyzed results for polycrystalline MgB$_2$ specimens with very weak flux pinning.

2. Experimental
Poly-crystals of MgB$_2$ were prepared by an enclosed stainless pipe method[7]. Raw materials of magnesium ribbon (99%) and boron crystalline lump (99.8%) were stoichiometrically weighed and sealed in a stainless tube (30mm in outer diameter, 100mm in length and 1.5mm in thickness) in the air followed by heat treatment of 12h at 1200°C. Prepared poly-crystal consists of a few single crystals with a typical size of 10μm. Restricted poly-crystals with the particle size between 50 to 63μm were selected using relevant size of sieves and were mixed with epoxy resin in order to avoid particle connections. Magnetization measurements were accomplished using a SQUID magnetometer (Quantum Design CO.)
under a magnetic field up to 1T and at temperatures 5-40K.

3. Results and discussion

The \( T_c \) of the specimen was determined by temperature dependence of the magnetization under a field of 0.5mT and its value was 38.1K. Experimental results of magnetic hysteresis measurements are shown in Fig.1. Characteristic feature of the hysteresis is that the magnetization is negative even in field decreasing branch and the hysteresis width is very narrow which means the flux pinning is weak. Such narrow hysteresis width has been measured in single crystals[8].

\[ J_{c0} = J_{c0}(0) \left[ 1 - \left( \frac{T}{T_c} \right)^2 \right]^{m} \left( 1 - \frac{B}{B_{c2}} \right)^{\gamma}, \]

where \( m, \gamma \) and \( \delta \) are pinning parameters[1]. Equation (1) is known as the scaling law[1]. In case that the flux creep effect is not negligible, the scaling law is not applicable. Matsushita \textit{et al.} proposed a theoretical expression in which these pinning parameters should be modified owing to the flux creep effect[1]. Such analyses have been successfully applied to the experimental results of magnetization measurements on powdered MgB\(_2\) specimens[6].

Flux creep effect should more remarkably appear in superconductors with weaker pinning force. Our poly-crystal MgB\(_2\) will be most suitable for such case, because the magnetization hysteresis width is very narrow,
as shown in Fig.1. Narrow histeresis width means small $J_c$, and hence weak flux pinning. Then, the flux creep model will be more applicable to our experimental results. Unfortunately, our experimental results of irreversibility field did not obey to the flux creep model except high temperature region near $T_c$. Therefore, we analyzed the temperature dependence of the $J_c$ using equation (1), where the temperature dependence of the $B_{c2}$ has a form of $1-(T/T_c)^2$ as mentioned above. Analyzed results are shown in Fig.2 in which we can see coincidence between the experimental points and the fitting curve (solid lines in the figure) is fairly good. At every field of 0.1T from 0.2T to 0.8T, fitting parameters $J_c(0)'B^{-\gamma}$ and $m$ were determined by the least square fitting method, where we adopted $\delta=2.5$. Then, $J_c(0)'$ and $\gamma$ were decided from field dependence of $J_c(0)'B^{-\gamma}$. Resultant parameters are $J_c(0)'=7.34 \times 10^7$, $\gamma=-0.325$ and $m=3.47(0.2T) \sim 4.71(0.8T)$.

![Figure 3](image1.png)  
**Figure 3.** $\log J_c$ vs. $B^{3/2}$ at several temperatures. Solid circles at 5K, open circles, 10K, solid squares, 15K, open squares, 20K and solid triangles, 25K, respectively.

![Figure 4](image2.png)  
**Figure 4.** Field dependence of the $J_c$ with two types of theoretical curves represented by Eq.(1) (red lines) and Eq.(2) (blue lines). Marks have the same meaning as in Fig.3.

Magnetic field dependence of the $J_c$ was calculated using thus determined parameters, where we used constant $m$ of $m=3.5$. Calculated results showed that coincidence between the experimental points and the theoretical ones is fairly good in low field region, but that is poor in high field region. Such circumstance means that equation (1) with one group of fitting parameters can not explain the experimental results as a whole. We should consider another flux pinning mechanism in order to overcome such discrepancy.

Blatter *et al.* have proposed a mechanism for vortex pinning that the pinning of small vortex bundles becomes to be dominant at higher fields than a crossover field[2]. According to them, the $J_c$ has an exponential form of

$$J_c(H) = J_c(0) \exp \left\{ -\left( \frac{B}{B_o}\right)^{3/2} \right\},$$

(2)
where \( B_0 \) is a normalization parameter. Equation (2) means that logarithm of the \( J_c \) is a linear function of \( B^{3/2} \). Plots of \( \log J_c \) versus \( B^{3/2} \) at temperatures 5 to 25K are shown in Fig.3. Determined parameters are listed in Table 1. It is obvious that experimental points are on a straight line as shown by a solid line at every temperature.

**Table 1.** Determined parameters \( J_{co}(0) \) and \( B_0 \) in Eq.(2).

| Temperature (K) | 5   | 10  | 15  | 20  | 25  | 30  |
|-----------------|-----|-----|-----|-----|-----|-----|
| \( J_{co}(0) \times 10^{-8} \) (A/m^2) | 3.48| 2.74| 2.09| 1.42| 0.583| 0.421|
| \( B_0(T) \)    | 0.579| 0.571| 0.530| 0.469| 0.423| 0.236|

Curve fittings using Eq.(1) and Eq.(2) are shown in Fig.4 at temperatures from 10 to 25K. It is clear that equation (1) explains the experimental results in low field region (red lines) and equation (2) is valid in high field region (blue lines). The situation at other temperatures is just the same as in Fig.4, but the results are neglected in the figure to avoid complexity. From the figure, it is obvious that plural flux pinning mechanisms contribute to the experimental results.

**Conclusion**

We analyzed the field and temperature dependences of the \( J_c \) in polycrystalline MgB\(_2\) specimens with weaker flux pinning on the base of a modified scaling theory in which a flux creep - flux flow model is included. Equation (1) approximately reproduces the temperature dependence of the \( J_c \) as a function of \( 1-(T/T_c)^2 \) if we select appropriate pinning parameters. But, the field dependence of the \( J_c \) can be explained by Eq.(1) only in low field region. Theoretical curve deviates from the experimental points in high field region. Another mechanism for the flux pinning is necessary to overcome such discrepancy in high field region. We tried to use an exponential decay of the \( J_c \) with increasing the field proposed by Blatter et al. and successfully explained the experimental results in high field region. Consequently, two theoretical considerations are necessary to interpret the field and temperature dependence of the \( J_c \) of our polycrystalline MgB\(_2\) specimens.

One of authors (Y.M.) would like to thank Dai-ichi High Frequency CO., LTD. for financial support.

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