Critical current characteristics and history dependence in superconducting SmFeAsOF bulk

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Abstract. The superconducting SmFeAsO$_{1-x}$F$_x$ ($x=0.2$) polycrystalline bulks were prepared by the powder-in-tube (PIT) method. The magnetic field and temperature dependences of critical current densities in the samples were investigated by resistive and ac inductive (Campbell’s) methods. It was found that a fairly large shielding current density over $10^9$ A/m$^2$, which is considered to correspond to the local critical current density, flows locally with the perimeter size similar to the average grain size of the bulk samples, while an extremely low transport current density of about $10^5$ A/m$^2$ corresponding to the global critical current density flows through the whole sample. Furthermore, a unique history dependence of global critical current density was observed, i.e., it shows a smaller value in the increasing-field process than that in the decreasing-field process. The history dependence of global critical current characteristic in our case can be ascribed to the existence of the weak-link property between the grains in SmFeAsO$_{1-x}$F$_x$ bulk.
1. Introduction

Since the discovery of the first iron-oxypnictide superconducting material, LaFeAs(O,F), in the early
2008[1], many new materials have been discovered and found to be superconducting, such as
REFeAsO (RE-1111, RE denotes rare earth), AEFe$_2$As$_2$ (AE-122, AE denotes alkali or alkali earth)[2],
a-FeSe[3] and so on. The relatively high upper critical field and high critical temperature of these
materials gave rise to many wide and enthusiastic studies on their superconducting properties, electro-
магнит properties and so on. Although the chemical composition of REFeAsO is comparatively
complicated, the critical temperature of over 50K undoubtedly raises the expectation of applications.
In fact, various attempts to synthesize single crystals[4], wires[5] and other forms of superconducting
REFeAs(O,F) have been made so far. On the other hand, as one of the most important factor, the
critical current characteristics of iron pnictides were investigated under various conditions by various
methods. Many studies reported that the critical current density still remains at a very low value and is
far below the level of practical applications. Therefore, the estimation and the enhancement of the
critical current characteristic in iron pnictides is one of the most important tasks at the present stage.

In our previous study[6] and other group’s studies[7, 8], it was reported that there exist two kinds
of critical current densities in polycrystalline bulk of iron pnictides samples, i.e., the large local critical
current density ($J_{c \text{local}}$) corresponding to the shielding current in an inductive measurements flows
inside the grain, while the small global critical current density ($J_{c \text{global}}$) corresponding to the shielding
current flows through the grains for whole sample. It is necessary to clarify that what is the most major
factor that fatally deteriorates the $J_{c \text{global}}$ value from the $J_{c \text{local}}$ value which is usually shown to be at a
tolerable level, and how can the $J_{c \text{global}}$ characteristic be enhanced largely to the practicable level. As so
far, it is considered that the weak-link property that exists between the grains is the foremost element
which is deterrent to the global current through whole sample.

In this study, the polycrystalline SmFeAsO$_{1-x}$F$_x$ ($x=0.2$) bulk samples were prepared by the in situ
powder-in-tube (PIT) method. The magnetic field and temperature dependences of critical current
densities in the samples were investigated by resistive and ac inductive (Campbell’s) methods. Two
kinds of critical current densities, i.e., $J_{c \text{local}}$ and $J_{c \text{global}}$, were estimated and discussed within the
frameworks of weak-link property and history effect.

2. Experimental

The polycrystalline SmFeAsO$_{1-x}$F$_x$ ($x=0.2$) bulk samples used in this study were prepared by the in-
situ powder-in-tube (PIT) method, which was described elsewhere previously[5]. The early samples in
our previous studies contained a certain amount of unreacted iron and showed a strong ferromagnetic
behavior. By adopting many improvements in the sample preparation process, the ferromagnetism was
then dramatically decreased and could be ignored in the samples used in this study. The samples were
peeled off the Ta sheath which was used as a sheath tube in the PIT process, and formed into slabs with a typical size of 3.0 mm($w$) × 0.5 mm($t$) × 15.0 mm($l$).

The critical current characteristics of the bulk samples were measured and estimated by using Campbell’s method[9, 10] and resistive method (four terminal method). As one of the measurements dealing with the electromagnetic properties in superconductor, Campbell’s method measures the penetrating ac flux in superconductor corresponding to the applied dc and variable ac magnetic fields. By analyzing the measured ac flux profile and ac magnetic field $b_{ac}$ vs. penetration depth $\lambda'$ curve, one can derive not only the critical current density but also the relationship between the force on and the displacement of the flux lines. In this study, we focused our attention on the estimation of global and local $J_c$ in SmFeAsO$_{1-x}$F$_x$ bulk samples. In the measurements of this study, the temperature of samples was varied within the range of 18 K – 40 K, while the magnetic field was up to 0.7 T, generated by a Bi-2223 solenoid coil soaked in liquid N$_2$. The frequency and the maximum amplitude of the ac magnetic field in Campbell’s method were 97 Hz and 10 mT, respectively.

3. Results and Discussion

Figure 1 shows an example of the ac flux penetration depth $\lambda'$ vs. ac field amplitude $b_{ac}$ at $B = 0.6$ T and $T = 24$ K. The ac flux abruptly penetrates from sample surface for a small ac magnetic field, as shown in the insertion, and then gradually penetrates for a large $b_{ac}$. The abrupt penetration and the following gradual one correspond mainly to the shielding by a small global current and that by a large $b_{ac}$.

![Figure 1](image_url)

Figure 1. Ac flux penetration depth $\lambda'$ vs. ac field amplitude $b_{ac}$ at $B = 0.6$ T and $T = 24$ K. This shows a rapid flux penetration into bulk at a small $b_{ac}$ and a following gradual penetration into isolated local area, such as grains, at a large $b_{ac}$.
closed local current, respectively[10]. According to the Bean-London model, the slope of the $\lambda'$ vs. $b_{ac}$ plot gives critical current density $J_c$ as

$$\mu_0 J_c = \left(\frac{\partial \lambda'}{\partial b_{ac}}\right)^{-1},$$

where $\mu_0$ is the permeability of the vacuum. For the slope corresponding to the flux penetration to the local area, i.e., the superconducting grains in the bulk sample, $J_c$ that flows within grains can be estimated by scaling the perimeter of the shielding current path from the whole bulk sample size to the average grain size. In this study, the average of grain size was estimated to be $5.0 \, \mu m$ from the SEM micrographs of the bulk samples. Figure 2 shows the (a) magnetic field dependence and (b) temperature dependence of the local critical current density ($J_{c\text{local}}$). The values of $J_{c\text{local}}$ still hold on to the level about $10^9 \, A/m^2$ at the temperature around 30K, indicating that this material possesses a certain potential properties of critical current characteristic. The results are nearly consistent with those obtained by dc magnetization measurement in our previous study[6]. On the other hand, $J_{c\text{local}}$ decreases rapidly at a relatively large magnetic field and a temperature over 30K, seems to imply an influence due to a decreased irreversibility field.

Figure 3 shows the magnetic field dependences of the global critical current density $J_{c\text{global}}$. (a) is the result at $T = 24K$ by the estimation of the initial steep slope of the $\lambda'$ vs. $b_{ac}$ plots obtained from Campbell’s method and (b) is that at $T = 20K$ obtained from a resistive measurement (four terminal method with the electric field criterion of 1 $\mu V/cm$).

First of all, it is clear from Fig. 2 and Fig. 3(a) that the values of $J_{c\text{global}}$ are about five orders of magnitude smaller than that of $J_{c\text{local}}$, and even smaller than the “hypothetical” critical current density of copper if we define it by the electric field criterion of 1 $\mu V/cm$. The extremely low $J_{c\text{global}}$ seems to
be ascribed to the existence of the fatal weak-link property between the grains, as well as the existence of various impurities and voids which are considered to be the serious obstacles to the global super current. From the viewpoint of practical application, it is urgently necessary to eliminate the weak-link between the grains and to enhance significantly the global critical current characteristic up to the level of local ones.

Secondly, an apparent history effect was observed as shown in Fig.3, i.e., the inductively and resistively measured $J_c^{\text{global}}$ takes a smaller value in the increasing magnetic field process than that in the decreasing one. Such a history effect could not be observed in $J_c^{\text{local}}$ obtained by Campbell’s method, i.e., the values of $J_c^{\text{local}}$ in the increasing field process approximately equal to those in the decreasing one. This behavior has been also observed in some other superconductors[11, 12]. It was explained as a result caused from a superconducting micro-bridge structure, in which the super current flowing through the micro-bridge experiences a different magnetic field from the applied one, because of the demagnetizing field of the superconducting banks on each sides of the micro-bridge. In our case, the poor property of weak-link between the grains in polycrystalline SmFeAsO$_{1-x}$F$_x$ can be regarded as the superconducting micro-bridge structures, and thus causes a significant history effect.

4. Conclusion
The magnetic field and temperature dependences of critical current densities in the superconducting SmFeAsO$_{1-x}$F$_x$ ($x=0.2$) polycrystalline bulks were investigated by resistive and Campbell’s methods. It was found that a fairly large critical current density over $10^9$ A/m$^2$ in a wide range of temperature flows locally in the grains of bulk samples, while an extremely low critical current density $J_c^{\text{global}}$ of about $10^5$ A/m$^2$ flows through the whole sample. Furthermore, an apparent history effect of $J_c^{\text{global}}$ was
observed, which can be ascribed to the existence of the poor property of weak-link between the grains in polycrystalline SmFeAsO$_{1-x}$F$_x$.

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**References**

[1] Y. Kamihara, T. Watanabe, M. Hirano, H. Hosono, J. Am. Chem. Soc. 130 (2008) 3296.
[2] M. Rotter, M. Tegel, D. Johrendt, Phys. Rev. Lett. 101 (2008) 107006.
[3] F.C. Hsu, J.Y. Luo, K.W. The, T.K. Chen, T.W. Huang, P.M. Wu, Y.C. Lee, Y.L. Huang, Y.Y. Chu, D.C. Yan, M.K. Wu, Proc. Natl. Acad. Sci. 105 (2008) 14262.
[4] N. D. Zhigadlo, S. Katrych, Z. Bukowski, S. Weyeneth, R. Puzniak, J. Karpinski, J. Phys.: Condens. Matter 20 (2008) 342202.
[5] Z. Gao, L. Wang, Y. Qi, D. Wang, X. Zhang, Y. Ma, H. Yang, H. Wen, Supercond. Sci. Technol. 21 (2008) 112001.
[6] E.S. Otabe, M. Kiuchi, S. Kawai, Y. Morita, J. Ge, B. Ni, Z. Gao, L. Wang, Y. Qi, X. Zhang, Y. Ma, Physica C 469 (2009) 1940.
[7] A. Yamamoto, A. A. Polyanskii, J. Jiang, F. Kametani, C. Tarantini, F. Hunte, J. Jaroszynski, E. E. Hellstrom, P. J. Lee, A. Gurevich, D. C. Larbalestier, Z. A. Ren, J. Yang, X. L. Dong, W. Lu, Z. X. Zhao, Supercond. Sci. Technol. 21 (2008) 095008.
[8] T. Tamegai, Y. Nakajima, Y. Tsuchiya, A. Iyo, K. Miyazawa, P.M. Shirage, H. Kito, H. Eisaki, Physica C 469 (2009) 915.
[9] A. M. Campbell, J. Phys. C2 (1969) 1492.
[10] B. Ni, T. Munakata, T. Matsushita, M. Iwakuma, K. Funaki, M. Takeo, K. Yamafuji, Jpn. J. Appl. Phys. 27 (1988) 1658.
[11] T. Matsushita, B. Ni, K. Yamafuji, K. Watanabe, K. Noto, H. Morita, H. Fujimori, Y. Muto, Adv. Supercond. (Springer-Verlag, Tokyo, 1989) 393.
[12] K. Watanabe, K. Noto, H. Morita, H. Fujimori, K. Mizuno, T. Aomine, B. Ni, T. Matsushita, K. Yamafuji, Y. Muto, Cryogenics 29 (1989) 263.