CHINESE JOURNAL OF PHYSICS VOL. 31, NO. 1 FEBRUARY 1993

Effects of Measuring Process on the Magnetization of High-T, Superconductors

S. W. Hsu, Y. C. Chen, and K. Chen
Material Research Laboratories,
Industrial Technology Research Institute,
Chutung, Hsinchu, Taiwan 310, R. O.C.

(Received July 8, 1992: revised manuscript received August 17, 1992)

The process-dependent magnetization of a melt-testured $YBa_2Cu_3O_{7-y}$ (YBCO) has been studied by alternately changing temperature (T) and applied field (H). Analysis on the experiments showed that the magnetization can be seperated into the reversible and irreversible components. The reversible component is independent, of process, while the irreversible component varies with the order of the operations of raising T, lowering T, increasing H, and decreasing H. Three properties related with the order of operations was found in the experiments.

I. INTRODUCTION

The magnetic measurements on high-T, superconductors (HTSC) carry informations as to the pinning-related properties, e.g., critical current density [1], irreversiblity line [2], and flux creep [3]. It was usually measured by field-cooled (FC), zero-field-cooled (ZFC), remanent (REM), or hysteresis (HYS) processes. Typical results are: (i) $M_{ZFC}(T)+M_{REM}(T) = M_{FC}(T)$ at low temperature and low field [4]; (ii) irreversiblity line obtained from the comparison of $M_{FC,H}(T)$ and $M_{ZEC,H}(T)$ [2], or $M^+_{HYS,T}(H)$ and $M^-_{HYS,T}(H)$ in the hysteresis curve [5]; (iii) giant flus creep studied by magnetic relaxation [6]; (iv) critical current density roughly estimated by Bean's model [7]; (v) equivalence of the reversible magnetizations between those measured by FC and by HYS [8]. After all, sequence of temperature and applied field is an important factor for the variation of magnetization.

To describe conveniently, let characters V, A, R and L respectively denote the operations of increasing field, decreasing field, raising temperature, and lowering temperature. Hence the processes of FC, ZFC, REM and HYS can be simply represented by $\{L\cdots L\}V, \{R\cdots R\}VL, \{R\cdots R\}ALV$, and $\{A\cdots A\}\{V\cdots V\}\{A\cdots\}\{V\cdots V\}L$ respectively. Sequence of operations should be read from right to left. In these representations, it is found that the order of temperature and field operations is the determinant factor for the distinct phenomena of various processes. However, only performing the *ZFC*, *FC*, *REM* or *HYS* processes is insufficient to find out further properties. It must be studied by other measurement processes.

For the reason, the magnetic measurements on a melt-textured YBCO sample were performed by alternately changing temperature and applied field. A simple model based on two components, four operations, and rule of order of the operations can be used to explain the experiments.

II. EXPERIMENTAL

The melt-textured YBCO sample was prepared by the method described elsewhere [10]. It was then cut and polished to a rectangle with dimensions of 3.5 x **3.2 x 3.0** mm^3. The ab-plane of this prefer-oriented sample is parallel to the 3.5 x **3.2** mm^2 face. A Quantum Design SQUID magnetometer was used to measure the magnetization. The applied field was parallel to the c-axis of the sample. To avoid any field or temperature fluctuation, the magnetization was recorded 5 minutes after changing temperature or magnetic field.

The processes in present work were performed by alternately changing field and temperature. An example is shown in Fig.1, that was shortly denoted by *RA . . . (RALA)(RALA) . . . (RVLV)(RVLV)L.* Many similar measurements with various temperatures and field have been carried out. The change of field is larger than $2H_p$ to keep the critical state in the fully "*V*" or "*A*" shape [7].

III. RESULTS AND DISCUSSION

In these experiments, the variation of magnetization is mainly determined by the last two operations, hence the magnetization can be plotted as a function of applied field at a definite temperature and distinguished with specific characters: *RA*, *AR*, *AL*, *LA*, *RV*, *VR*. *VL*, and *LV*. Typical results at 75, 80 and 85 K are shown in Figs. 2-4 respectively. For example, in Fig. 3, *VR* (denoted by open circles) at 10 kOe means that the magnetization was obtained by raising temperature to 80 K and subsequently increasing field to 10 kOe. Figs. 2-4 have three features, that may be taken as a thumb rule for any process:

(1) The reversible components (plotted in solid lines) obtained by *LA*, *AL*, *RA*, *AR*, *LV*, *VL*, *RV* and *VR* processes at definite temperature and applied field are equivalent.

(2) Magnetization obtained by $LA(LV)$ process is quantitatively different to that by $AL(VL)$. However, the irreversible magnetization obtained by $LA(LV)$ is equal to that before lowering temperature (compare $M_{LA}(M_{LV})$ in Fig. 2(3) with $M_{AL}(M_{VL})$ in Fig. 3 (4) respectively).

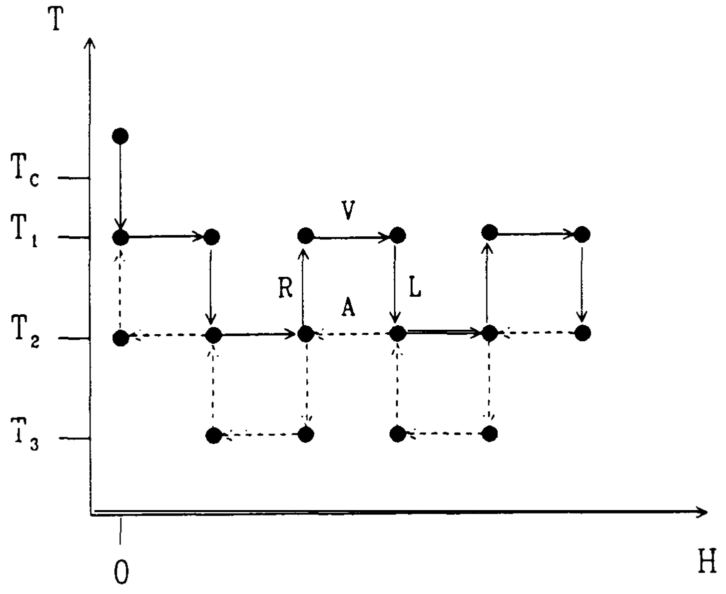

FIG. 1. A process denoted by $RA \cdots (RALA)(RALA) \ldots (RVLV)(RVLV)L$.

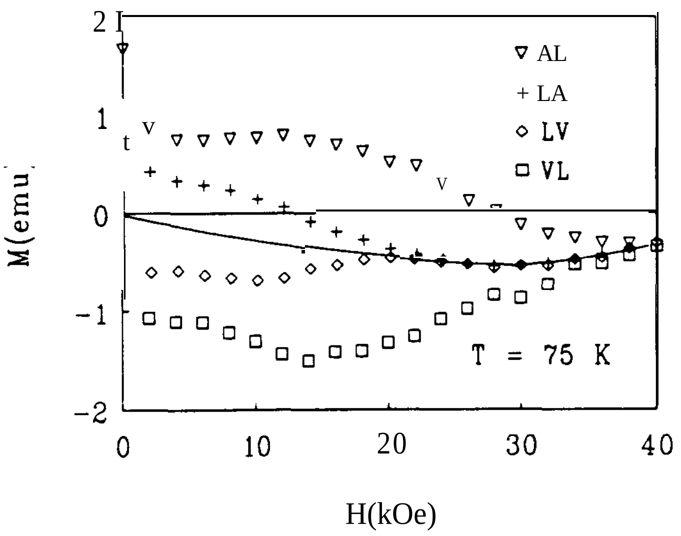

FIG. 2. Magnetization as functions of applied field and measuring process at 75 K. Solid line displays the reversible component.

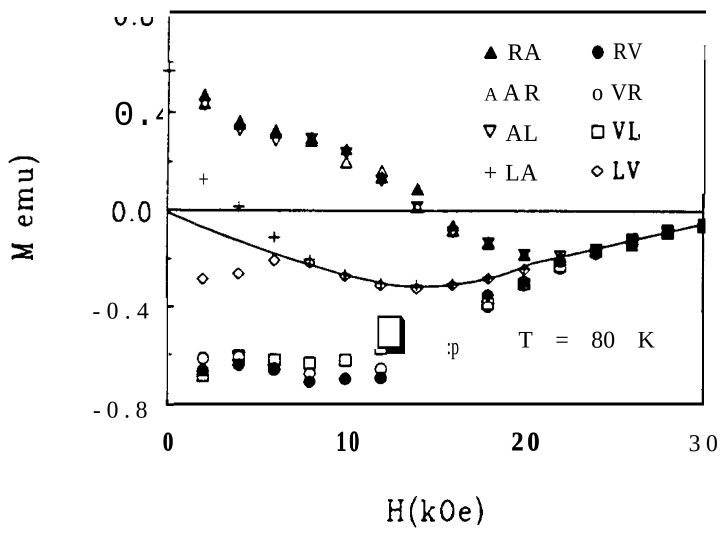

FIG. 3. Magnetization as functions of applied field and measuring process at 80 K. Solid line displays the reversible component.

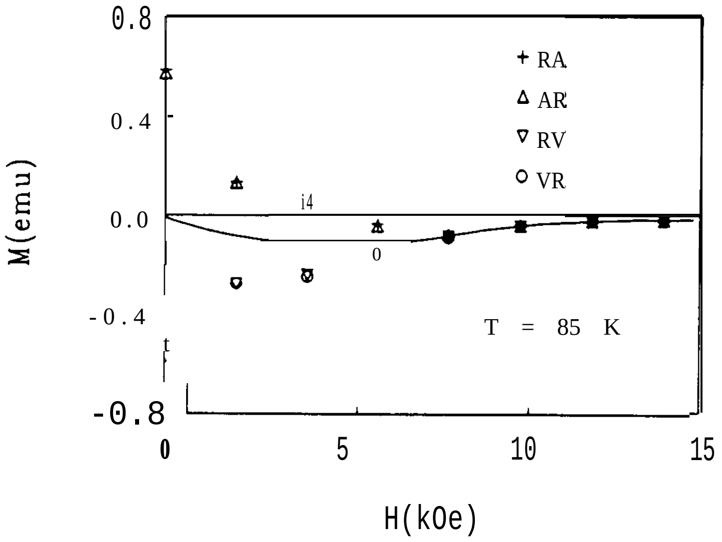

FIG. 4. Magnetization as functions of applied field and measuring process at 85 K. Solid line displays the reversible component.

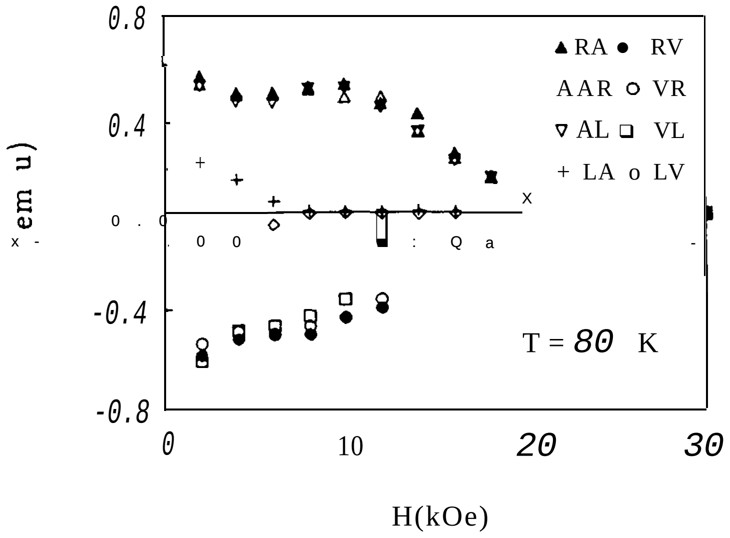

FIG. 5. The irreversible component M_i as functions of applied field and measuring process at 80 K.

(3) Magnetizations obtained by RA, AR or AL (RV, VR or VL) processes are almost equivalent at definite temperature and field, i.e., $M_{RA} \sim M_{AR} \sim M_{AL}$ ($M_{RV} \sim M_{VR} \sim M_{VL}$). The $M-H$ patterns constructed by these data are coincide with the hysteresis curves [11].

Feature (1) is obvious, because the reversible component is independent of process. As shown in Fig. 5, the irreversible component at 80 K was deduced by directly substracting the reversible component. Features (2) and (3) are caused by the variation of the irreversible component in changing temperature and applied field, and can be understood by the competition between pinning force, Lorentz force and thermal activation. Theoretical pinning energy U_0 was written as $[H_c(0)^2\xi(0)^3/8\pi]\cdot[(1-\theta^2)^2(1-\theta^4)^{-3/2}]$ or $[H_c(0)^2\xi(0)\phi_0/8\pi B]\cdot[(1-\theta^2)^2(1-\theta^4)^{-1/2}]$ [3, 12], where H,(O) is the critical field at 0 K, $\xi(0)$ is the coherence length at 0 K, Φ_0 is the flux quantum, B is the magnetic induction, and θ is defined as T/T, . Lorentz force is microscopically represented by $\vec{j} \times \vec{B}/c$, that is independent on temperature. Feature (2) can be realized by these variables. The pinning energy for the flux lines to overcome is increased as lowering temperature, while the Lorentz force is not changed. Thus the distribution of flux lines, i.e., irreversible magnetization, is retained as lowering temperature.

$M_{AR} \sim M_{AL}$ and $M_{VR} \sim M_{VL}$ in feature (3) show that the change of applied field will move flux lines to a definite critical-state regardless previous distribution. This phenomenon can be taken as an example of the Bean's or related models, in which the critical state is also definite as $\Delta H > 2H_p$. $M_{AR} \sim M_{RA}$ and $M_{VR} \sim M_{RV}$ show that the order of field and R operations are exchangible to the distribution of flux lines. Raising temperature will lower pinning energy: while changing field by V and A operations will higher Lorentz force form boundary and interior respectively. All these operations move flux lines with relatively high Lorentz force than pinning barrier. It is then qualitatively suggested that RV and VR (RA and AR) on distribution of flux lines are equivalent for the single direction of flux motions.

In conclusion, we have shown that the variation of magnetization by alternately changing of field or temperature follow features (1)-(3). The distinct effects of Lorentz force and thermal activation on flux lines is the origin of these features. For change of field less than $2H_p$, the result is $M_{irr}(H_1 \rightarrow H_2;T)+M_{irr}(H_2 \rightarrow H_1;T) = 0$ [11]. It is expected that the magnetization of high-T, superconductors by a random process can be predicted, if further investigations with the kind of process in this work are performed.

ACKNOWLEDGMENT

This research was supported by the Ministry of Economic Affairs, Republic of China, under contract number 3652100 to the Industrial Technology Research Institute.

REFERENCES

*Present address: Center for Measurement Standards, Industrial Technology Research Institute, Hsinchu 300, Taiwan, R.O.C.

[1] S. Jin, T. H. Tiefel, R. C. Sherwood, M. E. Davis, R. B. van Dover, G. W. Kammlott, R. A. Fastnacht, and H. D. Keath, Appl. Phys. Lett. 52, 2074 (1988).

[2] K. A. Müller, M. Takashige, and J. G. Bednorz, Phys. Rev. Lett. 58, 1143 (1987).

[3] Y. Yeshurun and A. P. Malozemoff, Phys. Rev. Lett. 60, 2022 (1988).

[4] A. P. Malozemoff, L. Krusin-Elbaum, D. C. Cronemeyer, Y. Yeshurun, and F. Holtzberg, Phys. Rev. B38, 6490 (1988).

[5] S. W. Hsu, K. Chen, and W. H. Lee, Solid State Commun. 75, 799 (1990).

[6] C. 'II'. Hagen and R. Griessen, in "*Studies of High Temperature Superconductors*", Vol. 3, ed. A. V. Narlikar (Nova Science Publishers Inc., Commack NY, 1991), p.84.

[7] C. P. Bean, Rev. Mod. Phys. 36, 31 (1964).

[8] S. W. Hsu, C. M. Chang, T. L. Chen, Y. C. Chen, J. J. Chu, and W. H. Lee, Solid State Commun. 80, 635 (1991).

[9] W. A. Fietz and W. W. Webb, Phys. Rev. 178, 657 (1969).

[10] K. Chen, S. W. Hsu, T. L. Chen, S. D. Lan, W. H. Lee, and P. T. Wu, Appl. Phys. Lett. 56, 2675 (1990).

[11] S. W. Hsu and Y. C. Chen, in preparation.

[12] M. Tinkham, Phys. Rev. Lett. **61,** 1658 (1988).