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TITLE: **MAGNETIC HYSTERESIS AND FLUX CREEP OF $YBa_2Cu_3O_x$ GROWN BY THE MELT-POWDER-MELT-GROWTH (MPMG) PROCESS**

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MAGNETIC HYSTERESIS AND FLUX CREEP OF $YBa_2Cu_3O_x$ GROWN BY THE MELT-POWDER-MELT-GROWTH (MPMG) PROCESS

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Abstract-- Magnetic hysteresis and flux creep of melt-powder-melt-growth (MPMG) $YBa_2Cu_3O_x$ containing nominal 0, 25 and 40 mole% Y_2BaCuO_5 (211) were measured in the temperature range of 5 to 80 K and in magnetic fields up to 5 T. With the introduced fine dispersion of second phase 211 particles, the critical magnetization current density J_c shows a weak field dependence over a wide range of temperature, and the effective pinning energy U_{eff} is much enhanced. From these results, a functional expression $U_{eff}(J, T) = - U_0\, G(T)\, (J / J_i)^n$ is obtained, where $G(T) = [1 - (T/T_x)^2]^2$ with T_x = 82.5 K near the irreversibility temperature. The observed power-law relationship of $U_{eff}(J, T)$ clearly demonstrates two of three regimes as predicted by the theory of collective flux creep, namely n = 3/2 and 7/9 for $J < J_c$ and $J << J_c$, respectively. In addition, the divergence of U_{eff} at low current densities also suggests the existence of a vortex-glass state.

I. INTRODUCTION

Since the melt-powder-melt-growth (MPMG) process [1] was proposed as an effective technique to grow polycrystalline $YBa_2Cu_3O_x$ by introducing a fine dispersion of second phase Y_2BaCuO_5 particles accompanied by the absence of weak links between the grains, a great number of experiments to understand the nature of the pinning mechanism in MPMG processed $YBa_2Cu_3O_x$ have been spurred, with the question of the role played by the 211 inclusions as strong pinning centers [2, 3]. The average grain size of the 211 particles (~ 1 μm) is significantly larger than the coherence length (2-5 Å along the c-axis and 10-30 Å in the ab-plane) of $YBa_2Cu_3O_x$ as well as the flux line lattice spacing at high magnetic fields.

Pinning by the 211 particles is thought to take place at the interface between the 211 phase and the matrix 123 phase [4]. Thus the pinning increases significantly as the size of 211 inclusions is reduced and the particles are more homogeneously distributed in the matrix of $YBa_2Cu_3O_x$. To date, although no firm conclusion about the exact pinning mechanism of the 211 phase is widely accepted by researchers, a J_c value in the order of 10^8 A/cm^2 at 77 K and 1 T has been measured on the best MPMG processed YBaCuO [5]. This observation justifies the contribution of the 211 phase to strong pinning in MPMG material.

In this paper, a comparison of magnetic hysteresis and magnetization relaxation among three MPMG samples with various nominal concentrations of 211 inclusions is, therefore, presented to study the trend of flux pinning. The main results show that (i) J_c's are much improved and (ii) higher values of the effective pinning energy U_{eff} are achieved with an increase in the number of 211 inclusions. In particular, $U_{eff}(J, T)$ follows a power-law relationship, which was previously predicted by the theory of collective flux creep [6].

II. EXPERIMENTAL DETAILS

The MPMG polycrystals containing nominal 0, 25 and 40 mole% 211 inclusions, which are hereafter called Y1.0, Y1.5 and Y1.8, respectively, were prepared for this work. The details of sample preparation have been described elsewhere [5]. Thin samples of approximately the same size used for measurements were then cut from the three pellets. The large sample surface to which the magnetic field is applied prependicularly has a cross-section of about 0.25 x 0.1 cm^2. The c-axis of the sample is parallel to the thinnest dimension (~ 0.05 cm).

A superconducting quantum interference device (SQUID) magnetometer (Model MPMS; Quantum Design) was employed to measure the superconducting transition temperature T_c, magnetic hysteresis (i.e., M (emu/cm^3) versus H (T)), and magnetization relaxation (i.e., M (emu/cm^3) versus t (sec)) of the samples. The temperatures and magnetic fields investigated are in the ranges of 5-80 K and 0-5 T, respectively. A scan length of 3 cm was used in order to minimize the nonuniformity of the applied magnetic field. The magnetic field is applied parallel to the c-axis of the sample. For the measurement of magnetization relaxation, the field was first raised to 5 T and then lowered to the measuring value to assure that the samples are fully penetrated with a monotonic flux profile. For brevity, only the relaxation data taken at 2 T are described in this work.

III. DATA ANALYSIS

The crucial information of interest to study the effect of 211 inclusions on the magnetic properties of the MPMG samples includes the magnetic irreversibility line (i.e., T_{irr} versus H_{irr}), the magnetic J_c, and the effective pinning energy U_{eff}. The irreversibility temperatures T_{irr}'s are

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obtained from the point of intersection of the zero-field cooled and field cooled curves. The corresponding magnetic field is then recorded as H_{irr}. To compare J_c's among various samples, the critical magnetization current densities are calculated from the width of the magnetic hysteresis loop using the Bean model for an orthorhombic shaped sample.

In order to analyze the relaxation data, Maley *et al.* [7] have proposed a model for the effective pinning energy U_{eff},

$$U_{eff}/k = -T\ [\ln(dM/dt) - \ln(H\omega_0 a/2\pi d)] \qquad (1)$$

where ω_0 is a characteristic attempt frequency, a is the hop distance for a flux bundle, and d is the thickness of a slab of the superconductor. U_{eff} at a constant magnetic field is obtained from $M(t)$ data by selecting the constant $C = \ln(H\omega_0 a / 2\pi d)$ to achieve the smoothest continuous curve of U_{eff} versus M ($\propto J$) for temperatures below 15 K where the intrinsic temperature dependence of U_{eff} is very small. However, for higher temperature data, this dependence must be properly taken into account as follows. Beginning with the lowest temperature data (i.e., 15 K), each isothermal set is multiplied by a scaling factor such that it forms a smooth curve along with the data sets recorded at the adjacent two lower temperatures. In other words, the scaling factor is introduced to move the high-temperature data points upwards to align with the smooth curve extrapolated from the low-temperature data. By doing so, the scaling function $G(T)$ can be determined directly from the scaling factors chosen at each temperature without selecting a functional form. The final expression for $U_{eff}(J, T)$ which includes the dependence of current density and temperature is then given as

$$U_{eff}(J, T) = -U_0\, G(T)\, F(J / J_i) \qquad (2)$$

where U_0 and J_i are scaling constants. The current density-dependent function $F(J / J_i)$ can then be modelled by an empirical expression (e.g., a power law or an exponential law) from the plot of U_{eff} versus J over the entire range of investigated temperatures.

IV. RESULTS AND DISCUSSION

Fig. 1 shows the irreversibility line as $1 - T_{irr}/T_c$ versus H_{irr} in a log-log plot. A relationship $1 - (T_{irr}/T_c) \sim H_{irr}^n$ is obtained approximately for the three different samples. These samples all exhibit extremely sharp transitions (T_c = 91-92 K) at H = 10 Oe (1 Oe = 79.6 A/m) and no significant difference in T_{irr}'s is observed as the magnetic field is increased. However, the value of n increases slightly with increasing concentration of 211 inclusions. For the sample Y1.8, n = 2/3 which was also previously reported in a YBaCuO single crystal [8].

As observed from the measurement of the hysteresis loops, the width of the loops is significantly increased by the introduction of 211 particles. The loop for Y1.0 appears almost collapsed at H = 5 T compared with the hysteresis loop of Y1.8 at 80 K which still exhibits irreversibility. For the Y1.8 sample, butterfly-shaped hysteresis loops were observed between 50 and 77 K. This anomalous behavior has been attributed to the existence of oxygen vacancies or local low-T_c phases which are quenched by the applied magnetic field at higher temperature to provide extra pinning centers [9]. In the present work, the actual key element causing the butterfly loop has not been identified yet.

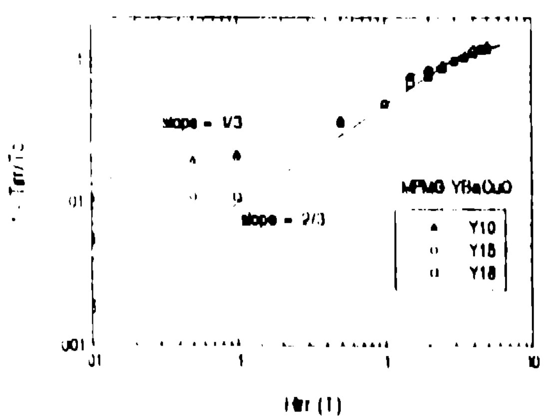

Fig. 1. Magnetic irreversibility lines of the MPMG $YBa_2Cu_3O_x$ samples.

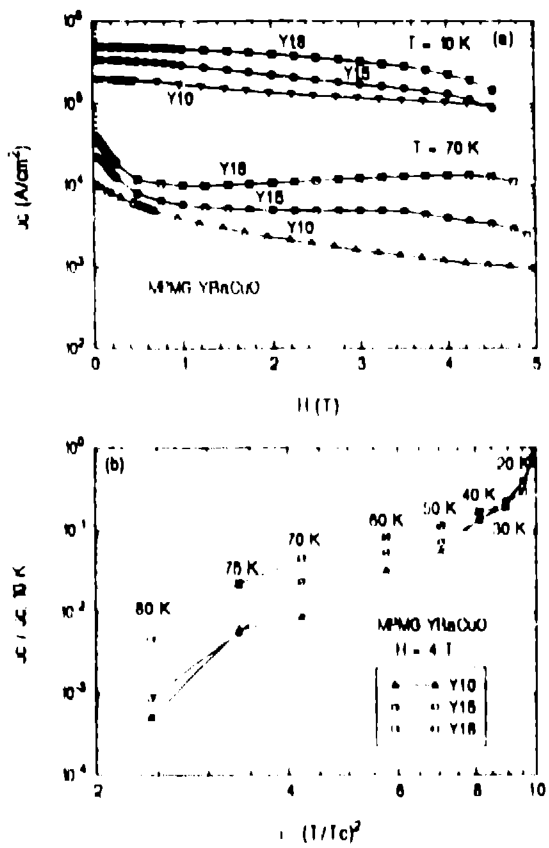

Fig. 2. (a) Magnetic field dependence and (b) temperature dependence of critical magnetization current densities J_c's.

Magnetic J_c's extracted from the hysteresis loops are shown in Fig. 2. Considering the field and temperature dependence of J_c, several points regarding the function of the 211 inclusions are notable: (i) J_c scales well with the concentration of 211 fine particles. (ii) As illustrated in Fig. 2 (b), Y1.8 has the weakest temperature dependence of J_c of the three samples, and this is even more obvious at 4 T than at lower fields (e.g., 1 or 2 T; data not shown here). In summary, these observations imply that with the presence of 211 inclusions, the samples exhibit a weak field dependence of J_c. By increasing the concentration of 211 inclusions, the regime of weak field dependence can be pushed to higher temperatures (cf. Y1.5 and Y1.8 data in Fig. 2 (b)).

Using Eq. 1, the effective pinning energy U_{eff} can be determined empirically. From the measured quantities M and t, the $\ln(dM/dt)$ term can be calculated. The constant C which gives the best smooth fit of the data below 15 K at 2 T was found to be 14 for all the samples. As shown in Fig. 3 a typical $U_{eff}(J)$ curve for the Y1.0 sample at 2 T uncorrected for the implicit temperature dependence of U_{eff}, each segment of data points represents a magnetic relaxation measurement performed at a fixed temperature. For comparison of the $U_{eff}(J)$ curves among the three samples, the value of M (emu/cm^3) has been converted to J (A/cm^2) by taking into account the sample dimensions. Notice that the data points recorded at $T > 15$ K progressively drop below the curve determined by the low-temperature data.

Fig. 4 (a) shows the curves of U_{eff}/k versus J on a log-log scale. The data were taken at 2 T between 5 and 60 K. Y1.8 has the highest values of U_{eff} as compared with Y1.0 and Y1.5 even before correcting the intrinsic temperature dependence of U_{eff}. This again provides evidence of stronger pinning achieved by the addition of 211 inclusions to $YBa_2Cu_3O_x$. Following the procedure described earlier in section III, a smooth curve of $U_{eff}/[kG(T)]$ versus J for each sample can be established over the entire range of measurement temperatures. At this stage, $G(T)$ is only a set of numerical values employed to scale the relaxation data in order to include the intrinsic temperature dependence.

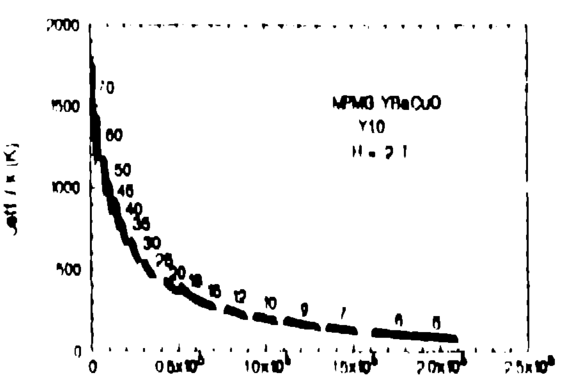

Fig. 3. U_{eff}/k versus J at 2 T for the Y1.0 sample. The number beside each segment of data represents the measurement temperature.

Another issue that draws our attention is the question: "What is the analytical dependence of U_{eff} on J at a constant magnetic field?" Therefore, a log-log plot of $U_{eff}/[kG(T)]$ versus J is shown in Fig. 4 (b) from which two linear regimes are obtained. This indicates that a power-law expression $U_{eff}(J) \sim (J/J_i)^n$ can describe the behavior of $U_{eff}(J)$ in each region. The slopes of the solid lines drawn in Fig. 4 (b) are 7/9 and 3/2 for $J << J_c$ and $J < J_c$, respectively, obtained from the theory of collective flux creep [6] for comparison. As can be seen, the experimental data agree quite well with the predictions of the theory of collective flux creep. In addition, $U_{eff}(J)$ seems to be diverging as J approaches 0, which fits within the framework of the vortex-glass model [10].

To determine the functional form for $G(T)$, the scaling numbers $G(T)$ are plotted in Fig. 5. From these data points, $G(T) = [1 - (T/T_x)^2]^n$ was found to fit best with $T_x = 82.5$ K and $n = 2$ omitting the four points from Y1.8 between 20 and 35 K which fall below every fitted curve. Since no correction is made for the implicit temperature dependence

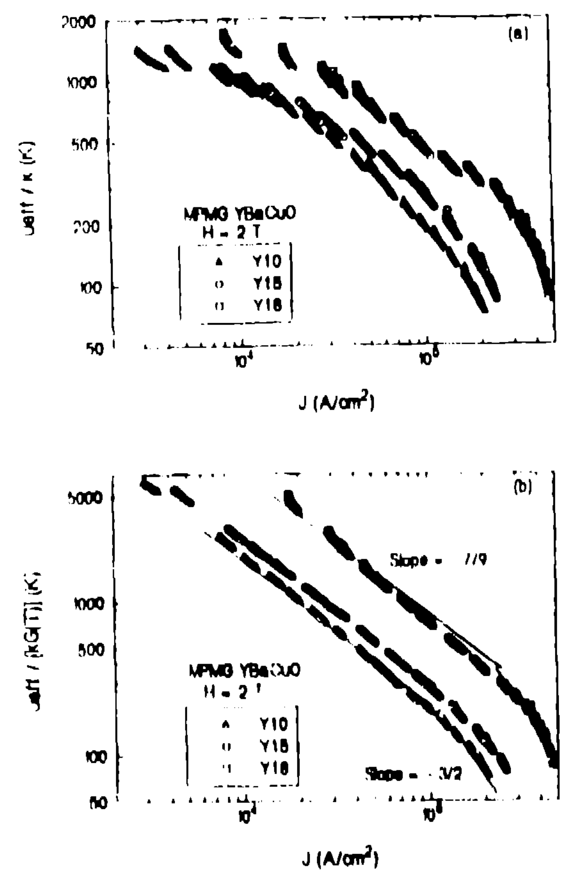

Fig. 4. U_{eff}/k versus J plotted on a log-log scale (a) with and (b) without the intrinsic temperature dependence included. (b) shows two linear regimes with the solid lines obtained from the theory of collective flux creep. The data were taken at 2 T between 5 and 60 K.

of U_{eff} below 15 K, all the scaling factors in this regime are equal to 1. T_x = 82.5 K is near the irreversibility temperature (84-85 K) of the samples in question at 2 T. Therefore, the functional form becomes $U_{eff}(J, T) = -U_0 [1 - (T/82.5)^2](J/J_i)^n$. A more rigorous treatment of temperature scaling should include a temperature dependence for $J_i(T)$, but it will not significantly change the qualitative conclusions for this study. Comparing this work with our previous measurements on other MPMG samples [11], we have found that in MPMG $YBa_2Cu_3O_x$ samples, the proper form of $G(T)$ for scaling the temperature dependence of U_{eff} obtained either from a functional form or from curve-fitting the scaling factors is basically consistent with the Ginzburg-Landau theory for $U_{eff}(T)$, and the power-law relationship derived from the theory of collective flux creep seems to accurately define the behavior of $U_{eff}(J)$. However, for a given volume of 211 inclusions, the effect of the 211 particle size on U_{eff} requires more work.

V. CONCLUSIONS

With the introduction of 211 inclusions, the $YBa_2Cu_3O_x$ samples prepared by the MPMG process exhibit a weak field dependence of J_c and an enhanced pinning strength. The 211 inclusions seem to be the dominant pinning centers especially in the high temperature regime. The observed power-law relationship between U_{eff} and J agrees qualitatively with the predictions of the collective flux creep theory. It also suggests the existence of a vortex-glass state at low J in these MPMG processed samples.

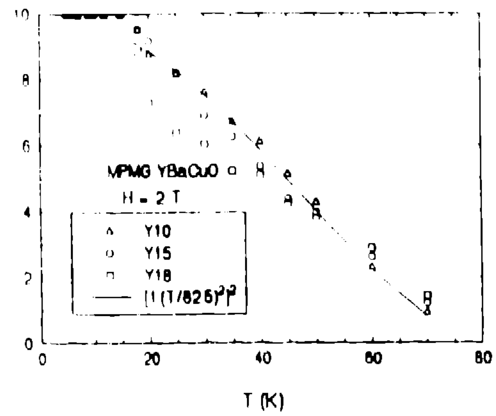

Fig. 5. Scaling function $G(T)$ determined from the data and a best fit analytical form.

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