Effects of Flux Creep in Bulk and Single Crystals of $Bi_2Sr_2CaCu_2O_{8+\delta}$ Superconductor

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Low-field AC susceptibility studies of bulk and single crystals samples of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) have been carried out in the frequency range up to 1 KHz. At constant AC field amplitude, the dissipative component of AC susceptibility shifts to higher temperatures with increasing AC field frequency. Moreover, the thermal activation energy (E_a) for flux creep in the crystals decreases with increasing AC field amplitude up to 800 Am^{-1}. These results are explained in terms of the effect of flux creep and Lorentz force ($J \times B$) in high T_c-superconductors.

1. Introduction:

The phenomenon of flux creep has received much attention in the case of high-T_c oxide superconductors. In these materials, the grain boundaries are weak links in which the flux can creep at a relatively lower field than in the grains. Furthermore, because of the higher operating temperatures of the oxide superconductors, the thermal activation responsible for creep is easier in these materials as compared to the conventional superconductors. The activation energy for flux creep in bulk and single crystals of $YBa_2Cu_3O_{7-\delta}$ (Y-123) has been estimated by variety of techniques such as DC magnetization, AC susceptibility and resistivity under applied field [1-6]. The reported values of the activation energy vary widely depending upon the measurement technique and the microstructure features of the sample.

Low field AC susceptibility has been used to determine the flux creep activation energies in bulk Y-123 system [1,4]. Several attempts have been made to explain the observed increase of T_p, the temperature corresponding to the χ'' peak, with the frequency of the AC field. Nikolo et al. [1] have been employed Anderson's flux creep model [7] and discussed the measured χ'' peak shifts with frequency in terms of an activation energy for flux vortex depinning. A similar approach was used earlier by Malozemoff et al. [8] to interpret the χ'' peak frequency dependence for Y-123 and $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) single crystals in the presence of strong DC magnetic field. Müller [9] proposed a model to determine the temperature and AC field amplitude dependence of the complex susceptibility in granular superconductors. In a further extension of Müller's model [10] which incorporated Anderson's flux creep theory [7] it was possible to explain the observed increase of T_p with the frequency of the AC field. It was further predicted that, for suitably higher magnetic fields, the smaller the grain size of the sample, the easier is the flux creep and stronger is the frequency dependence of T_p, which has also been confirmed experimentally [1,4,11-13].

2. Experimental Details:

Polycrystalline samples of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) were prepared by a solid-state reaction between Bi_2O_3, $SrCO_3$, $CaCO_3$ and CuO powders. Appropriate amounts of the powders were mixed and calcined at 820 °C for 12 h in air. The calcined powder was pulverized, cold-pressed into a disk shape, sintered at 860 °C for 24 h in air, and then furnace-cooled to room temperature. The single crystal samples of Bi-2212 were grown by the noval flux method. The crystals were having a plate-like shape with c-axis perpendicular to the surface. The sizes of the crystals were in the range 2×3 mm^2 to 3×6 mm^2. The absolute values of the real (χ') and the imaginary (χ'') components of the AC

susceptibility were measured using low field AC susceptometer based on the mutual inductance method [14]. A copper-constantan thermocouple (type T) is used to measure the sample temperature and is connected to a temperature controller R/S (Cole-Parmer) which is designed to maintain a constant, pre-set process temperature (± 0.1 °K). The Bulk samples were placed in the holder and the AC field amplitudes of 0.8, 8 and 80 Am^{-1} were applied parallel to the longest dimension of the samples. To investigate the effect of flux creep in single crystals, the magnetic field was applied parallel and perpendicular to the c-axis of the crystals, respectively. For H // to the c-axis, the AC field amplitudes were 8, 240, 600 Am^{-1}, and were 240, 600, 800 Am^{-1} for H $\perp$ to the c-axis. All the measurements were made in the temperatures between 77 °K and 90 °K at different AC field frequencies of 111.1, 333.3 and 1000 Hz, respectively. From real and imaginary components versus temperature plots, the values of the transition temperature $T_c(\chi')$ and the peak temperature T_p (corresponding to peak χ'') were estimated.

3. Results and Discussion:

Figures 1 and 2 show the real and imaginary parts of AC magnetic susceptibility for $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystal as a function of temperature with various AC field frequencies at AC field amplitude of 240 Am^{-1} with the magnetic field applied parallel and perpendicular to the c-axis of the crystal, respectively. From the χ' component of the AC susceptibility the diamagnetic onset is found to be at ~ 86.75 °K for single crystal and at ~ 87.0 °K for polycrystalline samples, respectively.

Nikolo and Goldfarb [1] defined the activation energy for flux creep (E_a) in terms of the AC field frequency f and the χ'' peak temperature T_p. The expression for E_a is given by:

$$f = f_0 \exp[-E_a / K_B T_p]$$
(1)

where K_B is the Boltzmann's constant and f_0 is a constant with dimension of frequency. By taking the logarithmic of the two sides of Eq. (1), we fined that;

$$\ln f = \ln f_0 - E_a / K_B T_P$$
(2)

Using Eq. (2), the activation energy E_a can be estimated by the slope of the $\ln(f)$ versus $1/T_p$ plots, which are straight lines.

The variation of χ with temperatures in Figs. (1 & 2) shows a small shift in the susceptibility curves to higher temperatures (T_p) with increasing the field frequency, at constant AC field amplitude. This shift in the AC susceptibility curves is arising from the effect of flux creep in the crystal [10]. Since, the AC field inside the superconductor at T_p just fully penetrates the crystals when the AC field amplitude reaches its maximum or minimum. Therefore, with increasing the AC field frequency, the vortices have less and less time to creep into the superconductor during the AC field cycle. In order to obtain full flux penetration, a weaker pinning force density is needed to compensate for less efficient creep. As the pinning force density weakens with increasing temperature, the peak temperature T_p, must increases with increasing AC field frequency. Tables (1 and 2) summarizes the values of T_c (diamagnetic onset), the χ'' peak temperature T_p, and the estimated values of E_a (the activation energy for flux creep) as a function of AC field amplitudes at various frequencies for single crystals of $Bi_2Sr_2CaCu_2O_{8+\delta}$ with H // to the c-axis and H $\perp$ to the c-axis of the crystals, respectively. For bulk samples of Bi-2212, the parameters T_c, T_p, and E_a as a function of AC field amplitudes at frequency $f = 111.1$ Hz are listed in Table (3).
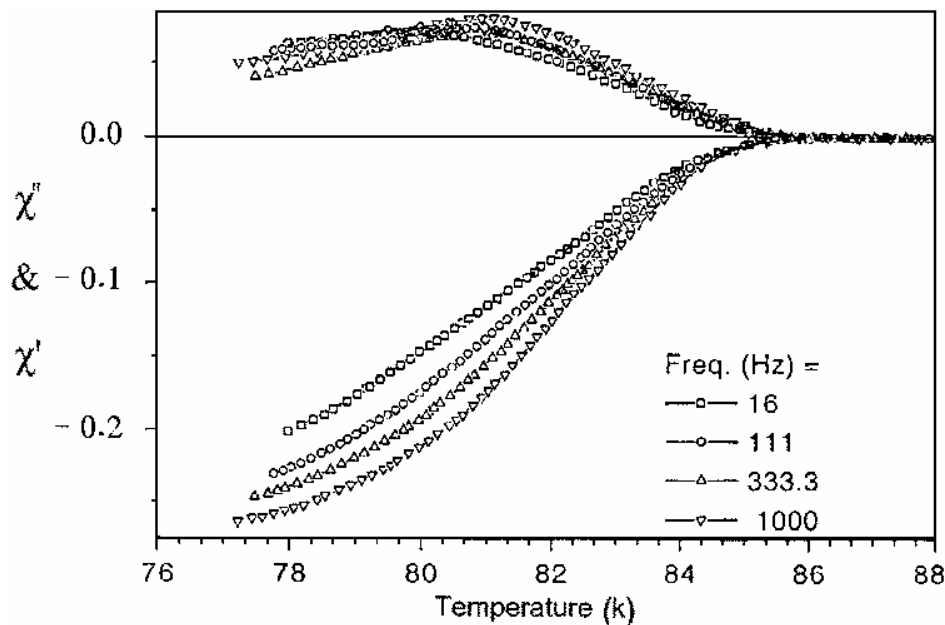
Fig. (1): AC magnetic susceptibility as a function of temperature with various AC field frequencies for single crystals of $Bi_2Sr_2CaCu_2O_{8+\delta}$ at AC field amplitude of 240 Am^{-1} with H // to c-axis of the crystal.
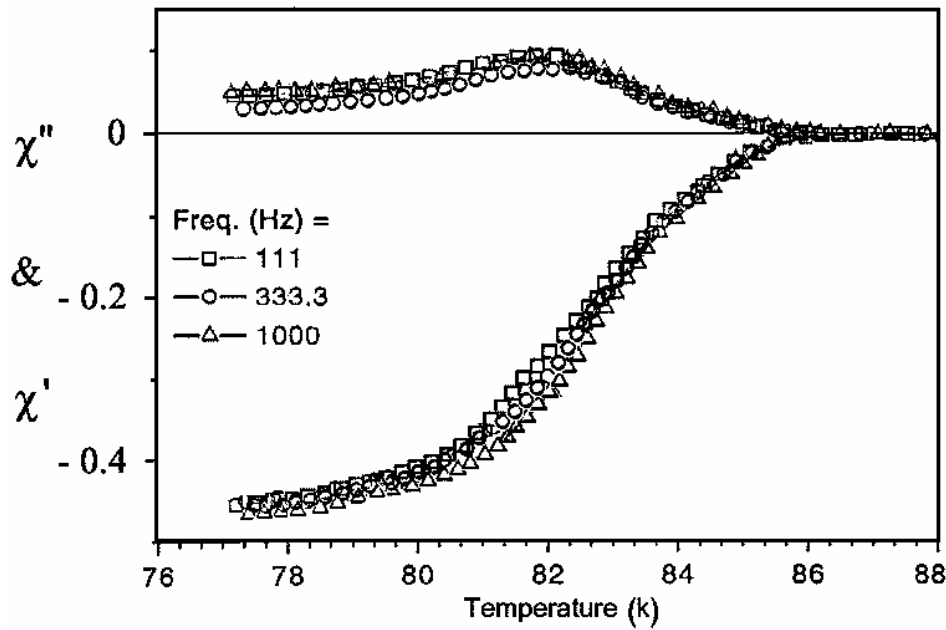
Fig. (2): AC magnetic susceptibility as a function of temperature with various AC field frequencies for single crystals of $Bi_2Sr_2CaCu_2O_{8+\delta}$ at AC field amplitude of 240 Am^{-1} with H $\perp$ to c-axis of the crystal.

Table (1). The parameters T_p, estimated values of E_a (the activation energy for flux creep), T_c (diamagnetic onset), zero-temperature pinning potential $\beta I_o(0)$, and grain sizes R_g as a function of AC field amplitudes at various frequencies for single crystals of $Bi_2Sr_2CaCu_2O_{8+\delta}$ with H // to the c-axis of the crystal.

H_a (A/m)	f (Hz)	T_p (K)	Estimated values of E_a (eV)	T_c (K)	$\beta I_o(0) \times 10^{-4}$ (Joule/Web.)	Estimated $R_g \times 10^{-6}$ (m)
8.00	111.1	83.15	2.360	86.75	11.286	0.887
	333.3	83.49				
	1000.0	83.41				
240	111.1	80.49	1.734			
	333.3	80.84				
	1000.0	81.18				
600	111.1	78.90	1.190			
	333.3	79.38				
	1000.0	79.85				

Table (2). The parameters T_p, estimated values of E_a, T_c, the zero-temperature pinning potential $\beta I_o(0)$, and R_g as a function of AC field amplitudes at various frequencies for single crystals of $Bi_2Sr_2CaCu_2O_{8+\delta}$ with H $\perp$ to the c-axis of the crystal.

| H_a (A/m)	f (Hz)	T_p (K)	Estimated values of E_a (eV)	T_c (K)	$\beta I_o(0) \times 10^{-4}$ (Joule/Web.)	Estimated $R_g \times 10^{-6}$ (m)
240	111.1	81.75	1.807	86.75	9.708	0.668
	333.3	82.04				
	1000.0	82.30				
600	111.1	80.50	1.356			
	333.3	81.00				
	1000.0	81.45				
800	111.1	80.05	1.219			
	333.3	80.50				
	1000.0	81.07				

Table (3). Values of T_p, E_a, T_c, $\beta I_o(0)$ and grain sizes R_g parameters as a function of AC field amplitudes at frequency f = 111.1 Hz for $Bi_2Sr_2CaCu_2O_{8+\delta}$ bulk superconductors.

H_a (A/m)	T_p (K)	Estimated values of E_a (eV)	T_c (K)	$\beta I_o(0) \times 10^{-4}$ (Joule/Web.)	Estimated $R_g \times 10^{-6}$ (m)
0.8	85.90	0.500	87.0	1.942	1.367
8.0	83.40	0.250			
80	83.00	0.025			

In Figs. (3 and 4), the variation of ln$f$ versus $1/T_p$ at different values of AC field amplitudes with the magnetic field applied parallel and perpendicular to the c-axis of the crystal are shown respectively. From the slope of these straight lines, the values of the activation energies at different fields were estimated.

According to Müller's critical state model [10] the shift in T_p with AC field frequency indicates flux creep. In a further extension of this model, Kumaraswamy et al. [11] have neglected the low values of AC field amplitudes (H_a) as compared to the field at the χ'' peak H_{op}. Based on this approach, he has derived an expression for the flux creep activation energies (E_a) which is simply given by:

$$E_a = \frac{\beta I_0(0)\Phi_0}{2\pi} - \frac{4H_a \overline{R}_g^{\;2} \Phi_0}{D} \tag{3}$$
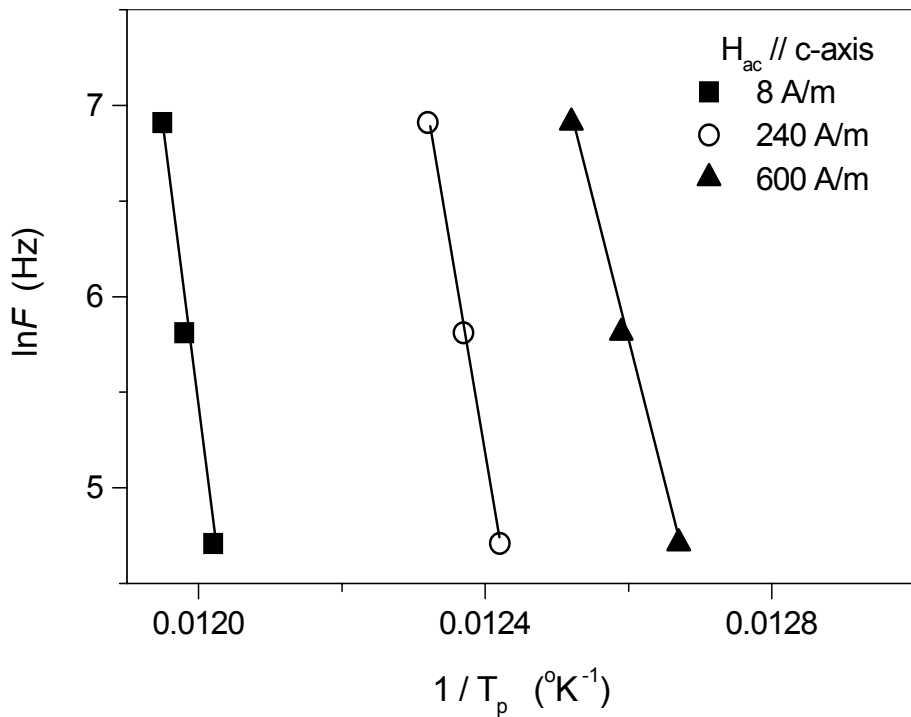
Fig. (3): Variation of ln*(F)* versus $1/T_p$ at different values of AC field amplitudes for single crystals of $Bi_2Sr_2CaCu_2O_{8+\delta}$ with H // to c-axis of the crystal.

where Φ_0 is the flux quantum ($\Phi_0 = 2.07 \times 10^{-15}$ weber), $\beta I_0(0)$ is the zero-temperature pinning potential of the sample, $\overline{R}_g$ is the average grain size of the sample, and *D* is the sample thickness (or the diameter in the case of cylindrical sample). By applying Eq. (3), the average grain size $\overline{R}_g$ can be estimated by the slope of the E_a versus H_a plots, which are straight lines. The pinning potential $\beta I_0(0)$ at zero Kelvin is calculated from the bisected part of E_a. Figure (5) shows the behavior of the activation energy as a function of the AC field amplitudes for bulk and single crystal samples of $Bi_2Sr_2CaCu_2O_{8+\delta}$ with H_a parallel and perpendicular to the c-axis of the crystal, respectively. This figure shows clearly that the activation energy E_a decreases with increasing AC field amplitude, H_a. This could be interpreted based on the fact that, with increasing AC field amplitude, the driving Lorentz force increase, and more flux can creep during the AC field cycle. From this figure together with Eq. (3), values of the average grain sizes and the zero-temperature pinning potential of single crystals and polycrystalline samples of $Bi_2Sr_2CaCu_2O_{8+\delta}$ have been calculated and listed in Tables 1, 2, and 3, respectively.

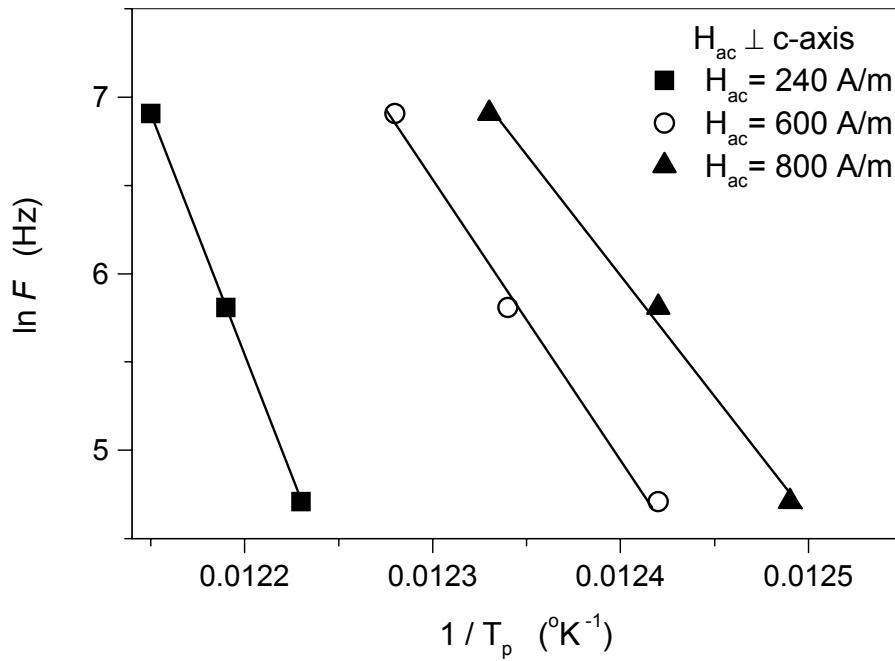**Fig. (4):** Variation of ln*(F)* versus $1/T_p$ at different values of AC field amplitudes for single crystals of $Bi_2Sr_2CaCu_2O_{8+\delta}$ with H $\perp$ to c-axis of the crystal.
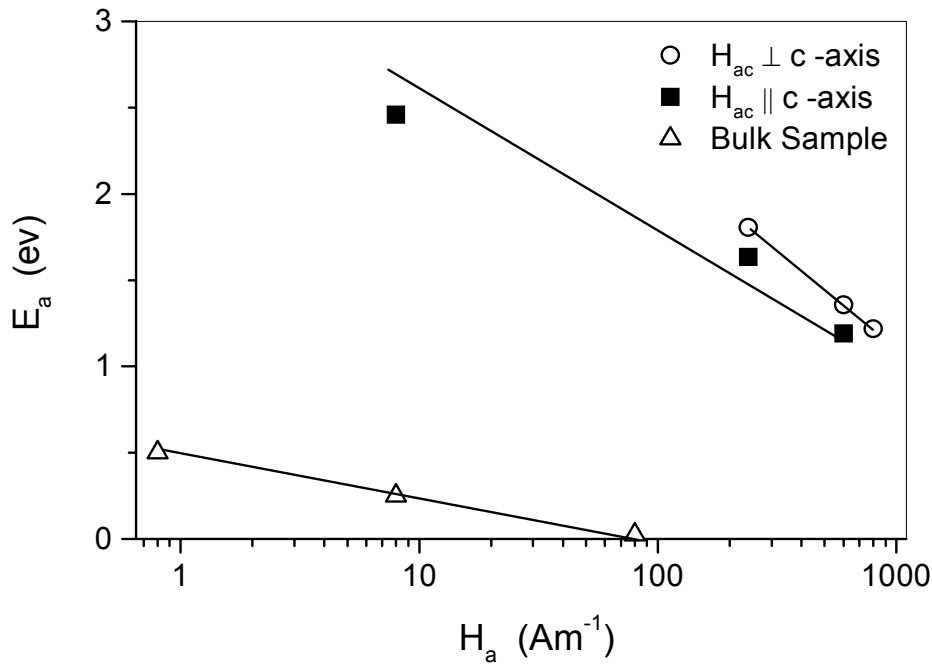

Fig. (5): The activation energy (*Ea*) versus AC field amplitudes for bulk and single crystals of $Bi_2Sr_2CaCu_2O_{8+\delta}$ with H // to the c-axis and H $\perp$ to the c-axis of the crystals.

4. Conclusions:

The phenomenon of flux creep should be considered for bulk and single crystals of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) superconductor system. At constant low AC field amplitude, the dissipative component of AC susceptibility shifts to higher temperatures with increasing AC field frequency. We have interpreted this shift in terms of flux creep in high-T_c superconductors. With increasing AC field amplitude, the Lorentz force ($J \times B$) increases and a decrease in the thermal activation energy (E_a) was observed.

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