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Irreversibility Temperatures in Oxide- and Metallic Superconductors

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ABSTRACT

We measured the irreversibility temperatures, $T_r(H)$ for both oxides [pure and alloyed Y(123) and Bi(2212, 2223)] and metallic [Nb, NbTi, and Nb_3Sn] superconductors. These results are compared and discussed in terms of $T_r(H)$ being the depinning line and/or the melting line OF the flux line (crystalline or disordered) lattice in the H-T plane.

KEY WORDS: Nb_3Sn, NbTi, Y(123), Bi(2212, 2223), flux lattice melting

INTRODUCTION

Nearly all of the applications for superconductors require high critical current densities at operating magnetic fields and temperatures. One of the major disappointments associated with the high T_c superconductors was their inability to have sufficiently high critical current densities J_c at high temperatures. Although the values of J_c in thin films have improved to the point where they are useful, the intragranular critical current densities in single crystal and ceramic oxide superconductors are still significantly lower than the desired values. It is believed that a part of this difficulty is associated with very low values of the so-called "irreversibility temperature, $T_r(H)$" (the lowest temperature at which the flux lines can be moved reversibly). Also, these low vales of $T_r(H)$ are related to very weak coupling between the conducting layers (CuO_2) in these highly anisotropic layered superconductors [1]. However, what this irreversibility line in the H-T plane represents, whether a thermodynamic phase transition in the state of the flux line lattice such as melting or a kinetic cross-over such as a depinning line, is not clear at this moment and this question is still one of the highly discussed subjects in superconductor studies. In the conventional superconductors, it is generally believed that since they are isotropic, the temperature region of the reversibility is so small that it is very difficult to measure and is not of practical importance. However, recently we have measured and reported [2] surprisingly large temperature regions where the flux lines are reversible in Nb_3Sn and NbTi multifilamentary wires. Here, we will compare these results with similarly measured values of $T_r(H)$ [3] for the oxide superconductors, Y(123) and Bi(2212, 2223), and discuss these in terms of various models for $T_r(H)$: crystalline [4] or disordered [5] flux lattice melting and thermally-assisted depinning [6].

EXPERIMENTAL PROCEDURE

For the purpose of measuring the magnetic-field-dependent irreversibility temperature $T_r(H)$ and the critical temperature $T_c(H)$, bulk sintered specimens of the desired compositions were prepared [7,8]. The specimens were powdered (~10 μm) and aligned along the c-axis. For the conventional wires, state-of-the-art multifilamentary Nb_3Sn and NbTi wires were selected. In addition, in order to study the effect of variations in the value of the Ginzburg-Landau constant κ on the irreversibility temperatures, a fine filamentary (~3 μm) cold-drawn Nb wire was also studied. These wires were cut in a length of ~6 mm segments and several lengths were placed horizontally (perpendicular to applied fields) in a superconducting quantum interference device (SQUID) magnetometer (Quantum Design, Inc.) while the aligned oxide powders were

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DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED placed in the magnetometer such that the c-axis of the oxides are parallel to the applied field. As previously described [3], a standard procedure for measuring $T_c(H)$ was used to determined, $T_r(H)$.

The results of such measurements of the magnetic moments for a Nb-Ti-alloy and a Nb wire are illustrated in Fig. 1. Also shown in the figures are the criteria which were used for determining the irreversibility temperature $T_r(H)$ and the critical temperature $T_c(H)$ [or the mean-field critical magnetic field $H_{c2}(H)$]. Here we define $T_r(H)$ at the temperature which an observable deviation is noted in the moments after the temperature cycle. It was found that by this criteria the difference in the moments for the warming and the cooling cycle was consistently ~0.1% at $T_r(H)$.

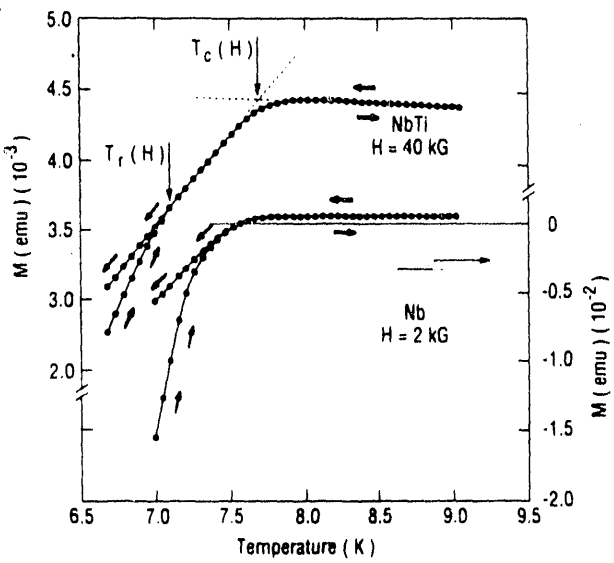

Fig. 1. The reversible temperature regions for a Nb-Ti alloy and a pure Nb wire are illustrated.

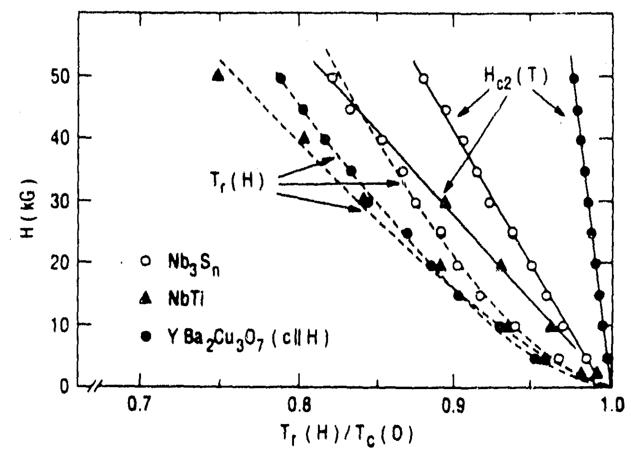

Fig. 2. A comparison of the temperature region of the reversible magnetic flux line motion in Nb_3Sn, NbTi and Y(123).

RESULTS AND DISCUSSION

The results of the magnetic field dependence of the values of $T_r(H)$ for Nb_3Sn, Nb-Ti; and Y(123) and for the Bi(2212) and Bi(2223) specimens are summarized in Figs. 2, 3 and 4. As shown in Fig. 3, the data for all of the pure and alloyed Y(123) specimens follow a relationship:

$$H = a[1 - T_r(H)/T_c(0)]n \tag{1}$$

with n ~ 1.5 and "a" is a constant of proportionality. We measured the magnetic hysteresis width ΔM [at $T/T_c(0) \cong 0.1$ and 0.5 and H = 10 kG] for each specimen. We find that "a" decreases nearly proportionally with decreasing ΔM. Thus, it is clear that the pinning strength of a specimen has a strong correlation with the irreversibility temperature in the case of alloyed $YBa_2Cu_3O_7$. Also, it was found that the data above do not fit the predicted dependence of $T_r(H)$ on H predicted on the basis of flux-lattice melting by Houghton et al. [4]. In the case of the Bi-oxides, the relationship in Eq. (1) does not fit at all as shown in Fig. 4. However, the relationship between the strength of the flux pinning and the width of the reversible temperature region is similar to that of Y(123), i.e. the stronger the pinning, the higher the values of $T_r(H)$. Thus, these results indicate that the $T_r(H)$ lines in these oxides are not likely to be a thermodynamic melting temperature of the crystalline flux line lattice unless the melting temperature depends upon the state of flux pinning.

Since both the flux creep model and Fisher's glass-to-liquid transition model [5] for $T_r(H)$ depend on the strength of the pinning, we have to study other

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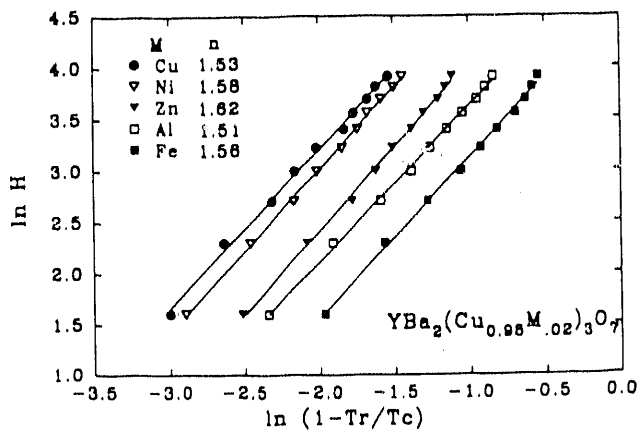

Fig. 3. The irreversibility temperatures for a pure and alloyed Y(123) as a function of applied fields.

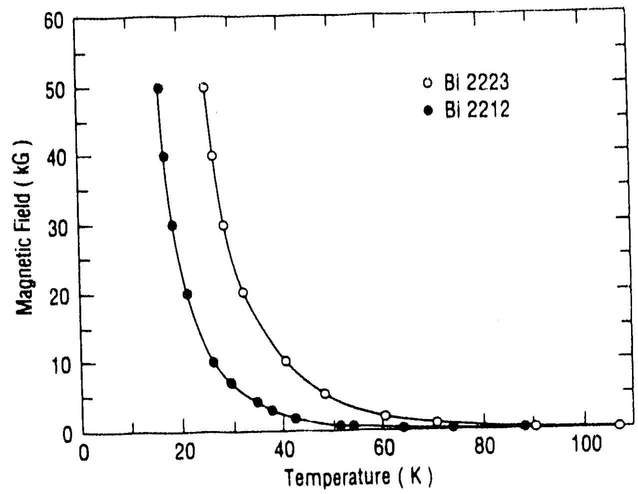

Fig. 4. The irreversibility temperatures for a Bi(2212) and a Bi(2223) as a function of applied field.

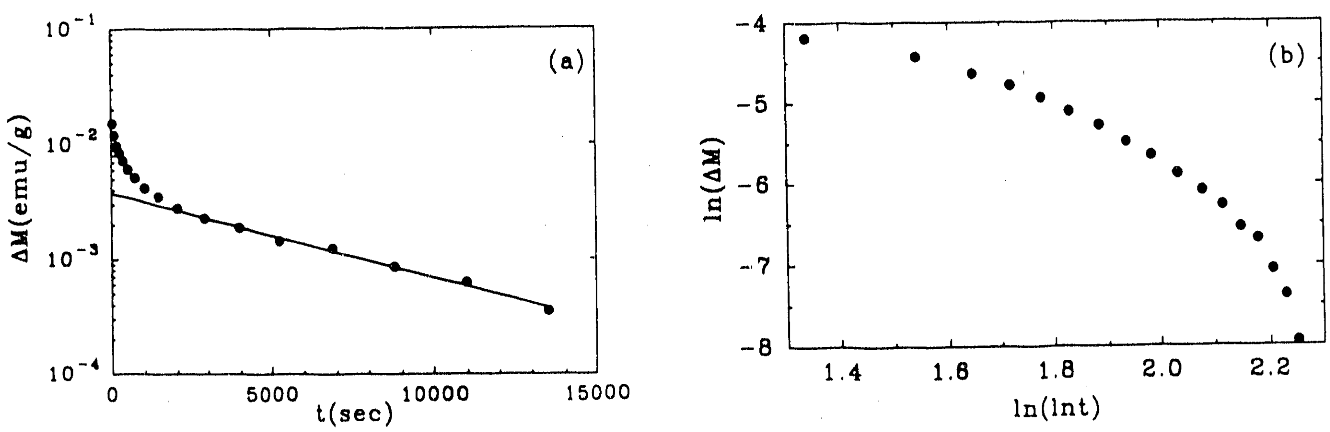

Fig. 5. The temporal dependence of the hysteresis width (the critical current) for a Bi(2223).

properties of these materials in order to distinguish these models. In order to do this, we note that only in the limit of $t \to \infty$, the predictions of the temporal dependence of the flux creep are distinguishable i.e. Fisher's model predicts,

$$\Delta M \sim (\ell n\ t)^{-1/\mu} \qquad \text{where } \mu < 1 \tag{2}$$

while the creep model [6] predicts

$$\Delta M \sim e^{-\alpha t} \text{ where } \alpha \text{ is a constant.} \tag{3}$$

If we assume that the regime $\Delta M \to o$ is equivalent to $t \to \infty$, we can achieve this condition in the Bi-oxides at low fields (1-3 kG) and at temperatures very close to T_r. The result for the Bi(2223) specimen is shown in Fig. 5. This clearly shows that the creep in this specimen follows an exponential temporal dependence for $t \to \infty$ [Fig. 5(a)] and does not follow the $(\ln t)^{-1/\mu}$ dependence [Fig. 5(b)]. Thus, we conclude that in these materials, $T_r(H)$ is more likely to be a depinning line in the H-T plane rather than a glass-to-liquid phase transition line.

The present interest in studies of the magnetic state of the oxide superconductors als prompted reexamination of the conventional superconductors to seek clarification of some of the observed phenomena in the oxides. As shown in Fig. 1, state-of-the-art Nb-Ti wires exhibited rather large reversibility regions. Also, in Fig. 2 a comparison of the sizes of the reversibility temperature regions is illustrated for Nb_3Sn, Nb-Ti, and pure Y(123) on a reduced temperature scale, $T_r(H)/T_c(O)$. The regions, $[T_c(H) - T_r(H)]$, for Nb_3Sn and Nb-Ti are nearly 1/3 as large as that for Y(123). This is quite surprising, but what is more surprising is the fact that the field dependence of $T_r(H)$ for both the Nb_3Sn and Nb-Ti wires fits the predicted dependence of the melting temperature calculated with the theory of Houghton et al. [2]. In addition, the predicted κ dependence was also founded to follow the theory as illustrated in Fig. 1, i.e. smaller the value of κ, the smaller the reversibility region and κ for Nb is an order of magnitude smaller than Nb-Ti. Furthermore, a large reduction in J_c (~5 times) or in the size of filaments in Nb-Ti wires did not result in observable difference in the size of $[T_c(H) - T_r(H)]$. Thus, all these results point toward flux lattice melting in the high-κ and high-Jc conventional soperconductors. The only experimental observation which raises a question about this interpretation, is the fact that when the irreversibility temperature is measured by the cycling magnetic field at a constant temperature, this temperature $H_r(T)$ is significantly closer to $H_{c2}(T)$ than $T_r(H)$. At present, the reason for this discrepancy is not clear and further study is required to confirm the possible observation of flux-lattice melting in Nb_3Sn and Nb-Ti.

In summary, it appears that the irreversibility lines are flux-line depinning lines in the oxides and are possibly flux-line-lattice melting lines in the conventional superconductors. Particularly, the latter is very unexpected and further study is needed to understand the nature of flux line motion in these materials.

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