Pinning of vortices in superconductors at high critical temperature

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I. INTRODUCTION

Due to problem identification and enumeration of defects in HTC superconductors, the correlation between current density and the transition of vortex pinning volume is not completely mastered. However, many theoretical and experimental studies have been developed to better understand the problem of dissipation due to vortices in type II superconductors.
When a current is applied to a superconductor sample, the flux lines are set in motion above a critical current threshold below which the flux lines are pinning.
This is attributed to competition between the number of vortices and pinning centers whose action determines the critical current density and other properties of superconducting vortex lattice. These pinning centers are more efficient than the nature of defects which is limited to the presence of very specific defects (intrinsic structure, plans of twins ...).
Moreover, in thin films of YBaCuO, the main sources of pinning defects are due to the growth mode of thin films such as dislocations, grain boundaries, impurities.
These pinning centers are often associated with default zones in the volume, but many experimental and theoretical work have studied the effects of surfaces [1-2] on the critical current density, suggesting that they are of especially important that surfaces are large, by reason of their geometry or roughness.
In this article we will discuss the volume density of pinning force of vortices in a superconductor type 2. We will examine its variation with the applied magnetic field and we will try to determine its expression based on the Kramer model for weak magnetic field and on the model of flux creep in the case of strong magnetic fields.

II. EXPERIMENTAL

The studied sample is a single crystal of $YBa_2Cu_3O_{7-\delta}$ thin film deposed by the ablation laser method on the surface (001) of a $SrTiO_3$ substrate. In zero magnetic field the resistance begins to disappear at a temperature T_c = 90K, called critical temperature [3].

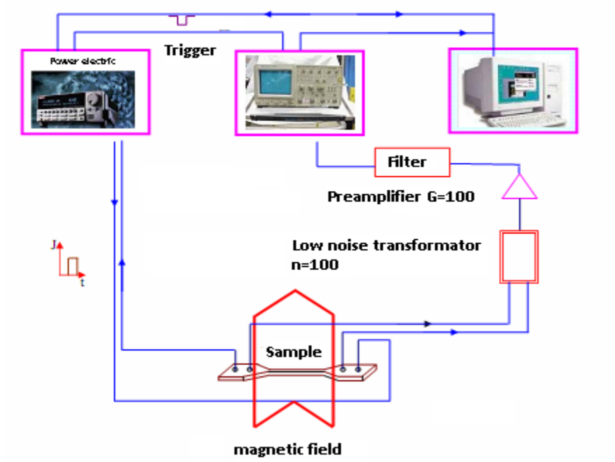

Figure 1: Schematic diagram of transport measures to pulsed current.

The c-axis of the single crystal of $YBa_2Cu_3O_{7-\delta}$ is perpendicular to the surface of the film. Electrodes of measurement are in gold and deposited on the surface of the sample in situ by evaporation. The film has a thickness of 400 nm and a width of 7.53 µm. The distance between electrodes of power measurement is 1.35 µm. Contact resistances were less than 1Ω [3].

2. DETERMINATION OF THE VOLUME DENSITY OF PINNING FORCE.

J_c is defined as the current density for which the volume density of Lorentz force is equal to the average volume density of pinning force F_p. This is determined experimentally by equation (1):

$$F_p = \mu_0 H.J_c \qquad (1)$$

Using the measurements of J_c (H), one can infer variations in the volume density of the pinning force F_p as a function of applied magnetic field H [4].
Figure (2) shows the variations in F_p (H) if the applied field H is parallel to the crystallographic c axis and the temperature T = 77K

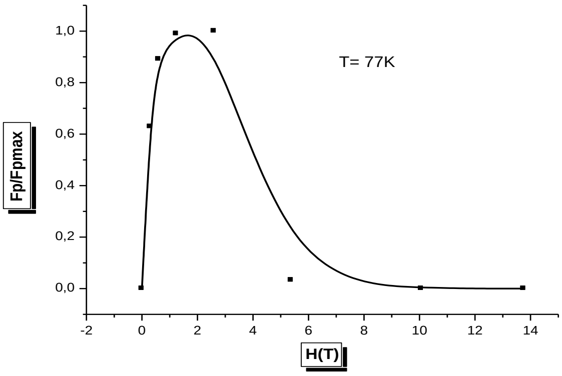

Figure 2: Variations in the volume density of pinning force as a function of applied magnetic field H / / c for a temperature T = 77K

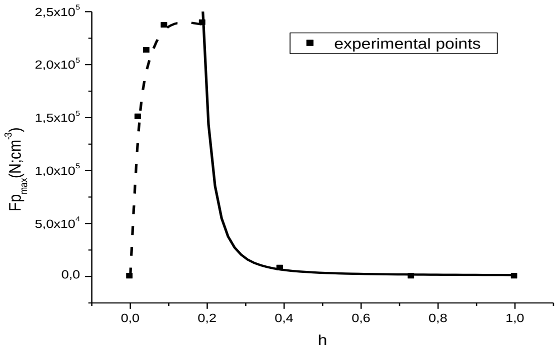

Figure 3: The volume density of pinning force F_p as a function of reduced magnetic field h = H / H *, for a temperature of 77K, and the two adjustments obtained with two models.

It is observed that the volume density of pinning force F_p has two types of behaviour:

• In the first, it increases with the magnetic field H to a maximum, f_{pmax} = $2,35.10^5$ $N.cm^{-3}$ corresponding to a magnetic field H=1.71 T , this behaviour is predicted by the model of Kramer [5-6]

• In the second, F_p decreases to approach zero for high magnetic fields predicted by the model of flux creep [7]. This pinning of flux lines in type II superconductor is derived from the interaction of vortices with defects in the material. The pinning force per unit volume F_p, defined as the force that equalizes the Lorentz force per unit volume when the critical current density J_c is reached, is given by the expression (1).

In the case of HTC superconductors, for which there is an irreversibility line below Hc_2 where J_c is zero, the trapping of magnetic field lines is usually performed for H = Hc_2 or to the field where we obtain the maximum of pinning force H_{max} [8] or to another value of the magnetic field H* characteristic curve F_p (H) which can be related, for example, with the irreversibility line, so that H* is defined by F_p (H*) = 0 [9].

This force can be determined from measurements of critical current density, it follows a scaling law of type:

$$F_p = f(T)\, g(h) \qquad (2)$$

Where f (T) is a function that depends only on the temperature T and g(h) a function that depends only on the reduced value of the applied magnetic field. This function is strictly null for h = 0 and h = 1, passes by a maximum for an intermediate value h= h_p and its form is very sensitive to the microstructure of the material [10].

An example of adjustment of our results concerning variations in the pinning force density F_p as a function of reduced magnetic field h=H/H* is shown in Figure3. This adjustment was carried out in the case where H is parallel to the crystallographic c axis to a temperature of 77 K by adopting the two previous models: The squares represent the experimental data. The dotted lines represent fit with the Kramer model for the domain of low fields. The solid line represents fit with the flux creep model for the domain of high fields.

- Squares: experimental data.
- The dotted line: it is done with the Kramer's model.
- The solid line: it is done with the flux creep model

As shown in figure 3, F_p following two types of scaling law based on the domain of applied magnetic fields:

• In the domain of low magnetic fields (h < 0.2) F_p can be adjusted with the model given by Kramer's scaling law of type (3):

$$F_p = k.h^m.(1-h)^q \qquad (3)$$

The fit gives $k = 1,05.10^6$ $(N.cm^{-3})$, m = 0.47 and q = 3.28. In the literature m ≈ 0.5 - 1 and q ≈ 1 in the superconducting Nb-Ti type and m ≈ 0.5 and q ≈ 2 in Nb_3Sn superconducting type [11].

• For high magnetic fields (h> 0.2) the volume density of pinning force can be described by the law of motion derived from the flow model by thermal activation: this is the creep flow. In this case where it is considered that the dissipation produced by the movement of packets volume vortex can overcome the potential barrier U by thermal activation and produce, in the presence of a transport current J, an electric field E by relationship [12]:

$$E = \left(\frac{2a_0 B \Omega_0 U J}{J_0 k_B T} \right) \exp\left(-\frac{U}{k_B T} \right)$$

Where:

Ω_0 represents the vibration frequency of the lattice of flux lines;

U is the difference in Gibbs energy when the flux line interacts with the pinning center and when it is outside the center.

a_0 is the distance of displacement by the flux line,

J_0 is the critical current density per unit volume in the absence of flux creep

J is the volume density of transport current.

T is the absolute temperature in Kelvin

k_B is the Boltzmann constant

B is the magnetic field applied

The current density in flux creep conditions is given by the equation:

$$J = \frac{J_0 k_B T E}{2a_0 B \Omega_0 U} \exp\left(\frac{U}{k_B T}\right)$$

Substituting U by U_0/H and U_0/k_BT by H^0 the critical current density in these conditions is expressed by (4):

$$J_c = \frac{J_0 E_c}{2a_0 \mu_0 \Omega_0 H^0} \exp(\frac{H^0}{H}) \qquad (4)$$

The pinning force density is defined by Eq (1). Its expression then becomes (5):

$$F_P = F_{P0}.\frac{H^*}{H^0}.h.\exp(\frac{H^0}{H^*}\frac{1}{h}) \qquad (5)$$

Where $F_{P0} = \frac{J_0 E_c}{2a_0 \Omega_0}$ is a prefactor and coefficient h = H/H* is the reduced magnetic field so F_p is written:

$$F_p = p_1.h.\exp(\frac{p_2}{h})$$

with p_1 and p_2 two constants. The solid line in figure 3 corresponds to an adjustment of our data with equation (5), we find:

$p_1 = 290.37$ ($N.cm^{-3}$) and $p_2 = 1.58$.

The good agreement between experimental data and the fit with the model of flux creep in figure 3 provides a confirmation of the fact that the pinning of magnetic flux has a dominant role in determining the critical current in the presence of the magnetic field.

III. CONCLUSION

We analyzed the mechanisms of vortex pinning by studying the volume density of pinning force F_p and its variation with temperature and applied magnetic field.

This force is derived from the critical current density, J_c in samples of superconducting materials with high critical temperature (YBaCuO), determined from transport measurements and characteristics E (J). It is observed that F_p has two types of behaviour:

In the first, it increases with the magnetic field to a maximum, f_{pmax} corresponding to a magnetic field H_{max}, this behaviour is predicted by the model of Kramer.

In the second, it decreases to zero for high magnetic fields predicted by the model of flux creep.

The pinning elastic theory was developed by several authors to explain the observed facts on variations of F_p in high critical temperature superconductors. It provides that the maximum of F_p occurs when the pinning through the lattice of flow lines (FLL) dominates.

This model predicts that for low values of the magnetic field the force of pinning and the Lorentz force F_L are dominated by the force exerted by the defects.

F_L increases when H increases. For large values of H the shear vortex lattice is very important around the pinning centers. This shearing process in high fields dominates the pinning force.

Competition between these two processes produces a maximum of F_p for a magnetic field where the two effects are approximately equal in force.

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