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Angular dependence of the critical current density and the temperature scaling of the flux pinning force in YBCO thin film

Abdelhalim Hafid[a,*], Ahmed Taoufik[a], Abella Bouaaddi[a], Hassan Elouaddi[a], Ahmed Tirbiyine[a,b], Brahim Lmouden[a], Mustapha Bghour[a], Habiba El hamidi[a], Youssef Ait Ahmed[a]

[a] Laboratory of Materials Superconductors at High Critical Temperature, Ibn Zohr University, Agadir, Morocco
[b] Equipe de recherche MSISM, Faculté Poly-disciplinaire, Université Cadi Ayyad, B. P. 4162, Route Sidi Bouzid, Safi 46000, Morocco

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ABSTRACT

In this paper, the critical current $J_c(\Theta)$ have been investigated as a function of magnetic-field angle Θ. Θ is the angle between the c-axis and the applied magnetic field direction. This investigation concerned three temperature values (60 K, 78 K and 81 K). The normalized pinning force f_p versus the normalized magnetic field h was also studied ($f_p = F_p / F_{pmax}$ and $h = H / H_{max}$). The F_p expression was determined based on the Kramer model.

The studied sample was a single crystal of YBaCuO thin film deposited by the ablation laser method on the surface (100) of a $SrTiO_3$ substrate.

The results of this work show the existence of point core pinning of the normal centers in the low field regime and the occurrence of the flux creep in high field regime.

1. Introduction

The anisotropic magnetic properties of high temperature superconductors have been extensively studied since the discovery of superconductivity [1]. This work is focused on the YBCO superconductor. Owing to its upper critical magnetic field, possibility of large critical current density (J_c) and relatively high transition temperature T_c, this superconductor is an ideal material for promising applications like current limiters, energy storage systems and magnetic bearings…

It is therefore very important from the viewpoints of both fundamental research and practical application to understand the critical current density (J_c) and the flux pinning properties of high-temperature superconducting (HTS). In particular, the dynamics of vortices in YBCO superconductors. This is why we have made a systematic study of the angular dependence of the critical current density and pinning force at various temperatures and magnetic fields.

An important general property of a superconducting material is the flux pinning behavior. Indeed, the flux pinning will rule the achievable critical current densities, the position of the irreversibility line and hence, effects of flux motion and creep. Originally, the collective creep theory and glassy vortex dynamics were developed based on the magnetic behavior of YBCO [2]. In this latter, the perfect diamagnetic state is maintained up to a lower critical field ($H > H_{c1}$), beyond which the flux begins to penetrate and vortex formation takes place.

When a transport current is applied in the vortex superconducting state, the situation becomes complex because of the Lorentz force ($F_L = J * H$) acting on vortices. The motion of these vortices induces a dissipative energy in the sample, which is responsible for

* Corresponding author.
E-mail address: asskti@gmail.com (A. Hafid).

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the finite resistance measured in the superconductor.

Flux pinning can be achieved by number of ways. Nevertheless, one of the simple methods of achieving flux pinning is to add the non-superconducting nano-inclusions over the dimensions of coherence length. In order to improve the pinning efficiency, many researchers have found that the nature of this non-superconducting nano-inclusion can be magnetic, non –magnetic, or ferroelectric material [3,4]. In recent years, many efforts have been made in order to increase pinning efficiency of vortex lines of high temperature superconductors in general and YBCO in particular [5,6].

The analysis of the pinning force unambiguously reveals that the low field contribution to the pinning force is due to the presence of correlated defects. It is for this reason that we studied the normalized pinning force $f_p = F_p / F_{pmax}$ as a function of the reduced magnetic field $h = H/H_{max}$ at various temperatures.

2. Experimental procedure

The studied sample was a high quality single crystal $YBa_2Cu_3O_{7\text{-}\delta}$ thin film deposited by the laser ablation method on the surface (100) of a $SrTiO_3$ substrate. In zero magnetic field, the resistance vanished at T_c = 90 K. The c-axis was perpendicular to the surface of the film. Electrodes of measurements were in gold and deposited on the surface of the sample by in situ evaporation. The film thickness and width were 400 nm and 7.53 µm respectively. The distance between electrodes of measurements was 135 µm. A contact resistance is very small [7].

Measurements were realized by using the DC four–probe method. J_c was defined as the critical current density where an electric field of 1 µV/cm appears. The film was oriented with respect to the magnetic field direction from 0° to 180°. The current was reversed to simulate the range from 180° to 360° [8].

In order to rule out distortions of the E-J curve by extensive heating that could be induced by the very high dissipation levels employed here, a pulsed current power supply was used with a time duration τ = 10 ms, a waveform repeat time of 2 s, and an average over 64 pulses at the same fixed J, T and H. The microstructure of several of these thin films was studied extensively, using Transmission Electron Microscopy (T.E.M). These T.E.M observations together with X-ray Energy Dispersion Spectroscopy (E.D.S.) as well as usual X-ray spectra show that the films are highly homogeneous and have essentially a single YBCO (123) phase.

Transmission electron microscopy (T.E.M.) observations performed on our samples revealed not only the presence of the usual twin boundaries as the major visible defect but also, a set of columnar-like defects. In addition, the sample certainly contains also point defects in articular oxygen vacancies [9].

3. Results and discussion

3.1. The critical current density and the vortex pinning

The critical current density (J_c) in a superconductor is the maximum current density that a superconductor can carry without power dissipation, and it is considered as one of the most important factors for applications of superconducting materials. The J_c in magnetic fields usually shows an angular dependence due to the anisotropy of materials, this angular dependence $J_c(\theta)$ was measured from the current–voltage(I–V) curve by using the1 µV criteria. And the angle θ is defined between the applied field and the c-axis of the CuO_2 (perpendicular to the surface).

The critical current density $J_c(\Theta)$ behavior is shown in detail inFig. 2 for three values of magnetic field (0.3 T, 0.6T and 10T) at 60 K. As can be seen in this figure, J_c increases as Θ increases, it reaches its maximal value at Θ = 90° corresponding to the configuration where the applied magnetic field is adjusted parallely to the ab planes of the sample. After the maximum value, $J_c(\Theta)$ decreases and reaches its initial value.

We also found that the critical current density for each angle is not very sensitive to the high magnetic field (B = 10 T), while it has higher values for low fields.

$$J_{c,90^\circ}\ (0.3T) > J_{c,90^\circ}\ (0.6T) > J_{c,90^\circ}\ (10T)$$

Fig. 3 shows the angular dependence of the critical current density $J_c(\Theta)$ at 0.3 T for three values of temperature (60 K, 78 K and 81 K).

At low temperature, flux lines preferentially penetrate into the weakly superconducting layers because they are stabilized the most. Since the loss of the superconducting energy due to the inclusion of the flux lines is least in this case.

The peak in $J_c(\Theta)$ at Θ = 90° corresponding to the configuration where the magnetic field is parallel to the ab planes can be explained by the following pinning mechanism which is characteristic for the layered oxide.

As the crystalline defects present in YBCO films, point defects like Y_2O_3 precipitates, and linear and planar defects such as dislocations, twin boundaries and stacking faults have been identified [10–16]. Among them, linear and planar defects cause strong correlated pinning in particular orientations but are not enough to account for the high value of J_c observed in YBCO films.

On the other hand, researchers in superconductivity field confirmed that the size of nano-precipitates is one of the main factors determining the angular dependence of J_c on external magnetic fields [17], and the weakly superconducting layers then work as natural pinning centers. The pinning strength is considerably high, and thus the critical current density becomes very high.

The critical current density is strongly dependent on the direction of the applied magnetic field [18].