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Peak effect in the MTG-$YBa_{2-x}Na_xCu_3O_y$ single crystals

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Abstract

We have measured the magnetic hysteresis loop of the melted-textured-growth $YBa_{2-x}Na_xCu_3O_y$ ($x = 0.1$, 0.2) crystals in a wide range of temperature from 25 to 80 K ($0.27 \leqslant T/T_c \leqslant 0.89$). The field dependence of the critical current density for a fixed temperature shows a peak effect. The field dependence of the pinning force density F_p for all measured temperatures can be scaled into a single curve for the magnetic field H below the peak field H_p. The dominant pinning mechanism in this low field regime is presumed to be normal-point-pinning. Above the peak field H_p and near T_c, an exponential H decay behavior of the critical current density was observed. The characteristic field H_0 can be deduced from the formula $J_c(H) = J_c(0)\exp(-H/H_0)$ and can be presented as: $H_0 \propto (1 - T/T_c^w)/\alpha$, in which α is 0.22 and 0.19 and T_c^w is 88.92 and 88.20 K, for $x = 0.1$ and 0.2, respectively. A percolation-like network of inhomogeneous regimes induced by Na addition is discussed.

Keywords: Peak effect; Magnetization; Na addition; Inhomogeneity; Percolation-like network

1. Introduction

Many superconductors display a maximum in the critical current density J_c as a function of the applied magnetic field H or of the temperature T. The shape of the peak is material dependent. For example, YBCO crystals [1] the peak is broad and temperature dependent, while for BSCCO [2] it happens in low magnetic field, sharp and independent of temperature. And peak effects happening in crystals of full [3–5] or partly [6,7] substitution of other elements for Y have also been extensively researched.

Here we study the peak effect in the MTG-$YBa_{2-x}Na_xCu_3O_y$ out of following reasons. (a) Chemical modification of certain elements in YBCO is an effective way to induce disorders and to influence J_c. (b) Since the ionic radius of Na is comparable to that of Y or Ba, Na favors partially Y or Ba site [8] and its peak effect may help to investigate the origin. (b) Alkali doping can improve the oxygen diffusion [8] and may rule out the influence from oxygen deficiency inhomogeneous distribution. (c) It is much easier to control alkali doping than to control oxygen.

2. Sample and experimental

The Na-doping YBCO ($YBa_{2-x}Na_xCu_3O_y + 40$ mol% Y_2BaCuO_5, $x = 0.1$ and 0.2) crystals were

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prepared by the MTG method. The details of the fabrication were reported in Ref. [9]. These samples with platelet were split from the cleaved plane of the MTG processing bulk with a single domain. The size of $x = 0.1$ and 0.2 are $3.12 \times 2.64 \times 0.4$ and $2.68 \times 2.46 \times 0.34$ mm^3, respectively. All our measurements were done on vibrating sample magnetometer (VSM). The zero resistance temperature of the sample is 89.3 K at zero magnetic field and the critical current density J_c are 1.70×10^4 A/cm^2 and 3.75×10^4/cm^2, respectively, at 70 K.

In order to rule out the effect of oxygen deficiency and inhomogeneous distribution, we put the crystal into an oven at 400 °C in flowing oxygen gas at 1 atm for more than 50 h. And also due to more rapid diffusive rate of oxygen in the Na addition than pure YBCO, we regard a homogeneous oxygen distribution.

Temperature ranges from 15 to 85 K with sweeping field up to 8 T. J_c values were determined with the extended Bean critical model.

$$J_c = 20\ \mathrm{dM}/[a(1 - a/3b)]$$

where J_c is in A/cm^2, dM is the magnetization hysteresis width in emu/cm^3 and a and b are cross-sectional sample dimensions in cm ($a < b$).

3. Results and discussion

Fig. 1 gives the field dependence of J_c values in different isotherms. From 25 to 85 K, critical current density experiences the same features as YBCO [1] that the peak moves regularly to higher field along with decreasing temperature. At the same time, the peak becomes broader and J_c values larger. Somebody regarded the peak field $H_{\max}$, in which maximum of J_c value occurs, is correlated to the formation of a percolating network of normal zones and others related it to irreversible zones. And we here discussed the relationship between $H_{\max}$ and T. In Fig. 2, we exhibit double logarithmic scale. If assuming the irreversibility relation exponent is 1.5, tentative fit between $H_{\max}$ and T needs a scaling temperature T_0 (95.1 K). However, this T_0 is larger than T_c (89.3 K) in sample and so we do not regard the peak effect out of the irreversible properties of inhomogeneity from Na doping.

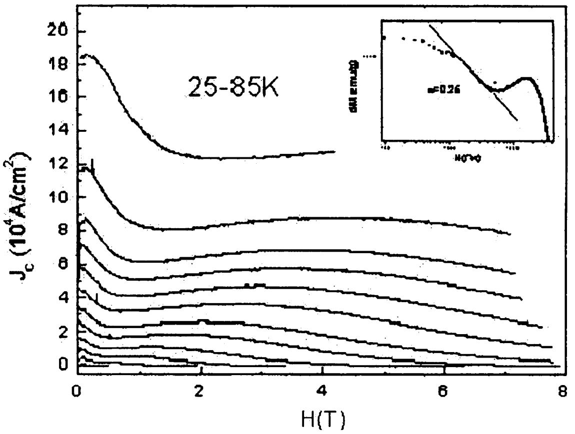

Fig. 1. The field dependence of J_c values in different isotherms from 25 to 85 K.

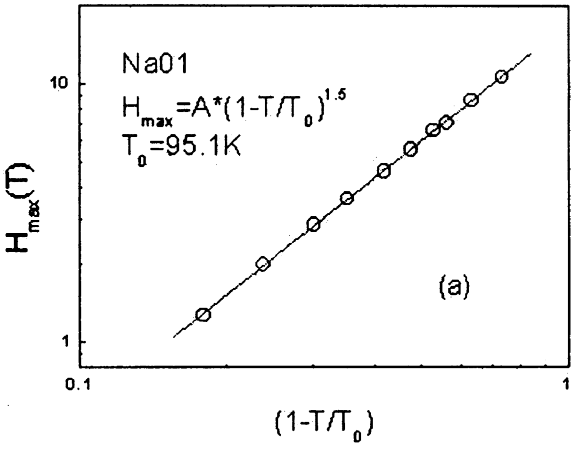

Fig. 2. The relationship between $H_{\max}$ and T can be fitted as $H_{\max} \propto (1 - T/T_0)^n$ with $T_0 = 95.1$ K.

Feitz and Webb showed that a scaling technique can be applied to the magnetic field dependence of the pinning force density, $F_p = J_c \times H$. Since zero at $H = 0$ and at H_{c2}, F_p must have a maximum at some intermediate field H_p. Fig. 3a exhibits F_p as a function of H. With the decrease of temperature, F_p increases and H_p is shifted to higher fields. Plotting $f(b)$ $[= F_p(H)/F_p(H_p)]$ as a function of b $[= H/H_{c2}]$ can cause the curves for different temperature to collapse. It can be seen that below

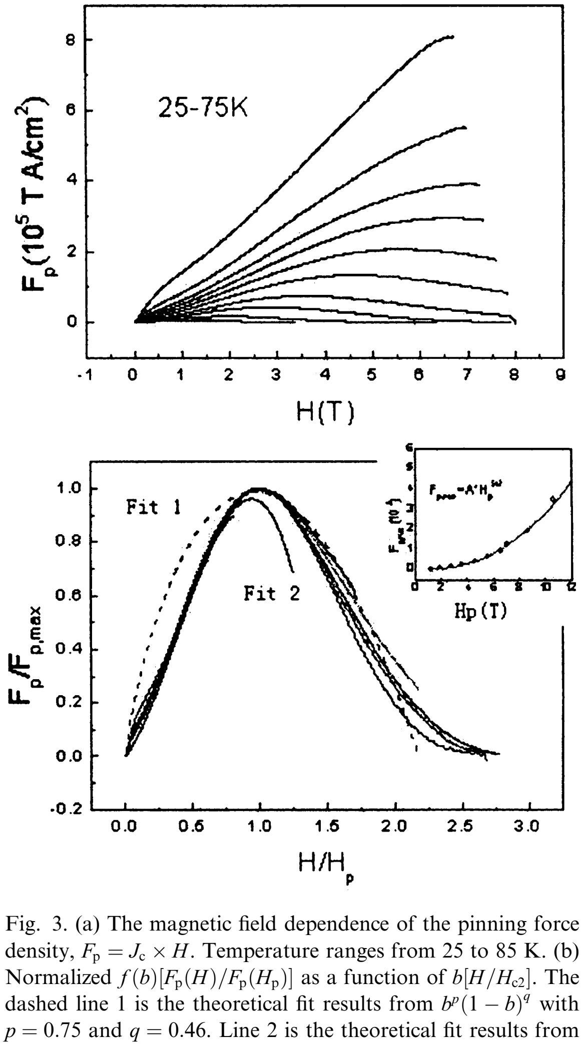

Fig. 3. (a) The magnetic field dependence of the pinning force density, $F_p = J_c \times H$. Temperature ranges from 25 to 85 K. (b) Normalized $f(b)[F_p(H)/F_p(H_p)]$ as a function of $b[H/H_{c2}]$. The dashed line 1 is the theoretical fit results from $b^p(1-b)^q$ with $p = 0.75$ and $q = 0.46$. Line 2 is the theoretical fit results from $f(b) \propto b(1 + 2.67b - 2.26b^2)$. Inset: the value of $F_p(H_p)$ as a function of H_p. The solid line is a fit to $F_p(H_p) \approx AH_p^{2.5}$.

H_p all isotherms superpose perfectly while above H_p they do not. Dew-Hughes [10] has presented that, assuming strong pinning, $f(b)$ can be written in the form of $b^p(1-b)^q$ and p and q depend on the nature of pinning. For the normal-surface-pinning, $p = 1/2$, $q = 2$ and for the normal-point-pinning, $p = 1$, $q = 2$. At low field, $(1-b)^q$ can be regarded as unity. So $J_c \propto f(b)/H \propto H^{p-1}$. Thus we can firstly get the parameter p. From inset of Fig. 1, we got p is 0.75 which lies between 0.5 and 1 and maybe implies pinning mechanism from both point and surface contributions. However, we have been unable to find suitable q value to reproduce the experimental behavior. In Fig. 3b, the dashed line "fit 1" is the theoretical fit results from $b^p(1-b)^q$ with $p = 0.75$ and $q = 0.46$. The inset of Fig. 3b exhibits the value of $F_p(H_p)$ as a function of H, H_p. The solid line is a fit to $F_p(H_p) \approx AH_p^{2.5}$, different from Ref. [11].

However, we can fit the low field part (below H_p) well with $f(b) \propto b(1 + 2.67b - 2.26b^2)$, as the solid line "fit 2" in Fig. 3b. It has some similar part as the $b^p(1-b)^q$ and the dominant pinning mechanism in this low field regime is presumed to be normal-point-pinning. The Na inhomogeneous was proposed to play an important role in normal inclusions. Also we have examined the behavior of critical current density J_c above H_p at a sequence of temperature in Fig. 4. From this figure, critical current density begins to fall off with the elevated magnetic field. It is obvious that at low temperatures, not only is the critical current density increased, but the suppressions of J_c with increasing field becomes weaker. At high field part we find that J_c vs H follows an exponential behavior, namely, $J_c(H) = J_c(0)\exp(-H/H_0)$, which has also been observed on many crystal samples [1,12]. Except for the results at 65 K which have some deviation from fit, the exponential behavior between J_c and H has a good precision. The absolute value of slope $(1/H_0)$ in linear fit on the semi-logarithmic picture, as

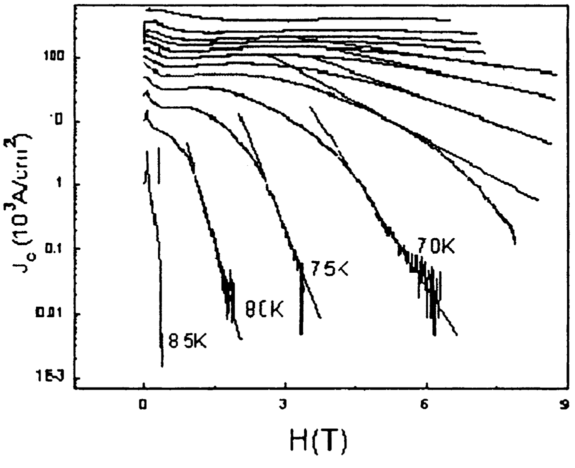

Fig. 4. The field dependence of J_c above H_p. J_c vs H follows an exponential behavior, namely, $J_c(H) = J_c(0)\exp(-H/H_0)$.

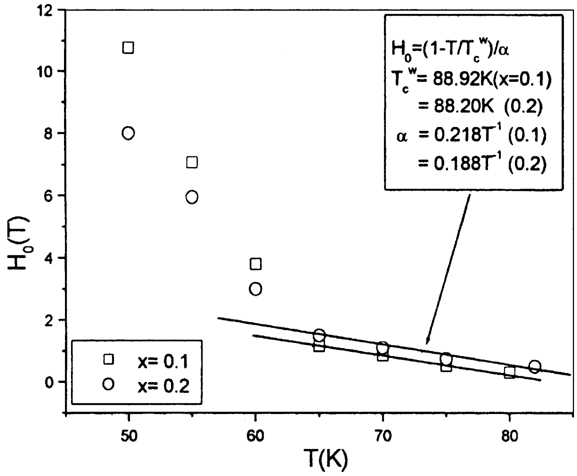

Fig. 5. The temperature dependence of characteristic field H_0 in both samples, $H_0 \propto (1 - T/T_c^w)/\alpha$.

described above, decreases with the descending temperatures and makes out the high-field and current density applications. From Fig. 4, we got the value of characteristic field H_0 at different temperatures. And in Fig. 5 we give out the changing of H_0 with T in two different samples: $x = 0.1$ and 0.2, respectively. Both samples show the same behavior that H_0 follows a good linear relation with T above 65 K, and some minor difference from the different doing of Na as well. We can write down the formula as $H_0 \propto (1 - T/T_c^w)/\alpha$, in which α is $0.22T^{-1}$ and $0.19T^{-1}$ and T_c^w is 88.92 and 88.20 K, for $x = 0.1$ and 0.2, respectively. The zero resistance temperature of the sample is 89.3 K at zero magnetic fields and a little greater than T_c^w. Here we can see that T_c^w varies with the doping of Na and more doing leads to less value. T_c^w may be supposed to reflect the Na inhomogeneous normal region, α has a similar value as reported in Ref. [12] and it is not certain whether α is related to the Na doping or not. It is supposed that a percolation-like network of inhomogeneous regimes of Na addition formed.

4. Conclusion

We measured the peak effect in the magnetic hysteresis loop of an MTG-$YBa_{2-x}Na_xCu_3O_y$ ($x = 0.1$, 0.2) crystal in a wide range of temperature, $0.27 \leqslant T/T_c \leqslant 0.89$. The pinning force density F_p can be scaled into a single curve for all measured isotherms before peak field H_p and its functional form reflects the observed peak effect. We regard the peak effect out of the normal properties of inhomogeneity from the Na addition. Above peak field H_p and near T_c, $J_c(H) = J_c(0)\exp(-H/H_0)$. The characteristic field H_0 can be presented as: $H_0 \propto (1 - T/T_c^w)/\alpha$. It is supposed that a percolation-like network of inhomogeneous regimes of Na addition formed.

Acknowledgements

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