Pinning in Nd-based 123-superconductors

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Abstract: By means of a scaling analysis of the volume pinning forces, F_p, normalized by the maximum value, $F_{p,max}$, versus the reduced field $h = H_a/H_{irr}$, where H_{irr} denotes the irreversibility field, we analyze the pinning properties of various Nd-based superconductors of the 123-type. $NdBa_2Cu_3O_{7-\delta}$ (NdBCO) samples show a peak in the scaled F_p-graphs above 0.4, and the ternary compounds $(Nd_{0.33}Eu_{0.33}Gd_{0.33})Ba_2Cu_3O_y$ (NEG) even at ≈0.5. This high peak position provides strong evidence for a dominant pinning caused by spatial variations of the transition temperature, T_c, throughout the samples. In NdBCO single crystals, two peaks are observed in the magnetization loops. Angular dependent measurements clarified that this extra peak is due to twin plane pinning.

Key words: Pinning forces, Scaling, $NdBa_2Cu_3O_{7-\delta}$, δT_c-pinning

INTRODUCTION

Flux pinning is one of the crucial problems in the development of technical high T_c superconductors, especially because of the high operating temperature aimed for in applications. The LRE-123 (LRE=light rare earths) superconductors, processed in controlled oxygen partial pressure [1], provide a novel approach yielding samples with unique pinning properties. In this paper, we analyze the pinning properties of $NdBa_2Cu_3O_{7-\delta}$ (NdBCO) single-crystals and melt-processed samples, and of the newly developed ternary compounds $(Nd_{0.33}Eu_{0.33}Gd_{0.33})Ba_2Cu_3O_y$ (NEG). Single crystals of NdBCO exhibit magnetization loops (MHLs) with three peaks. By means of the angular dependence of the MHLs we found that the 'intermediate' peak is due to pinning provided by the twin plane structure.

EXPERIMENTAL

MHLs are measured using a commercial SQUID magnetometer[2] with a maximum field of ± 7 T; $H_a \parallel c$ axis. To minimize field inhomogeneities, the scan length is set to 1 cm. For measurements with $\Theta \neq 0$ (i.e. $H_a \parallel c$), a special sample holder ('rotator option') is used. The sample preparation is described in detail elsewhere [1, 3] The homogeneity of the samples was ensured by investigating them by means of magneto-optic imaging. Critical current densities, $j_c(H_a, T)$, are obtained from the MHLs by means of the extended Bean formalism. Due to the large paramagnetic moment of Nd (and mainly Gd in NEG), corrections to the MHLs have to be carried out carefully.

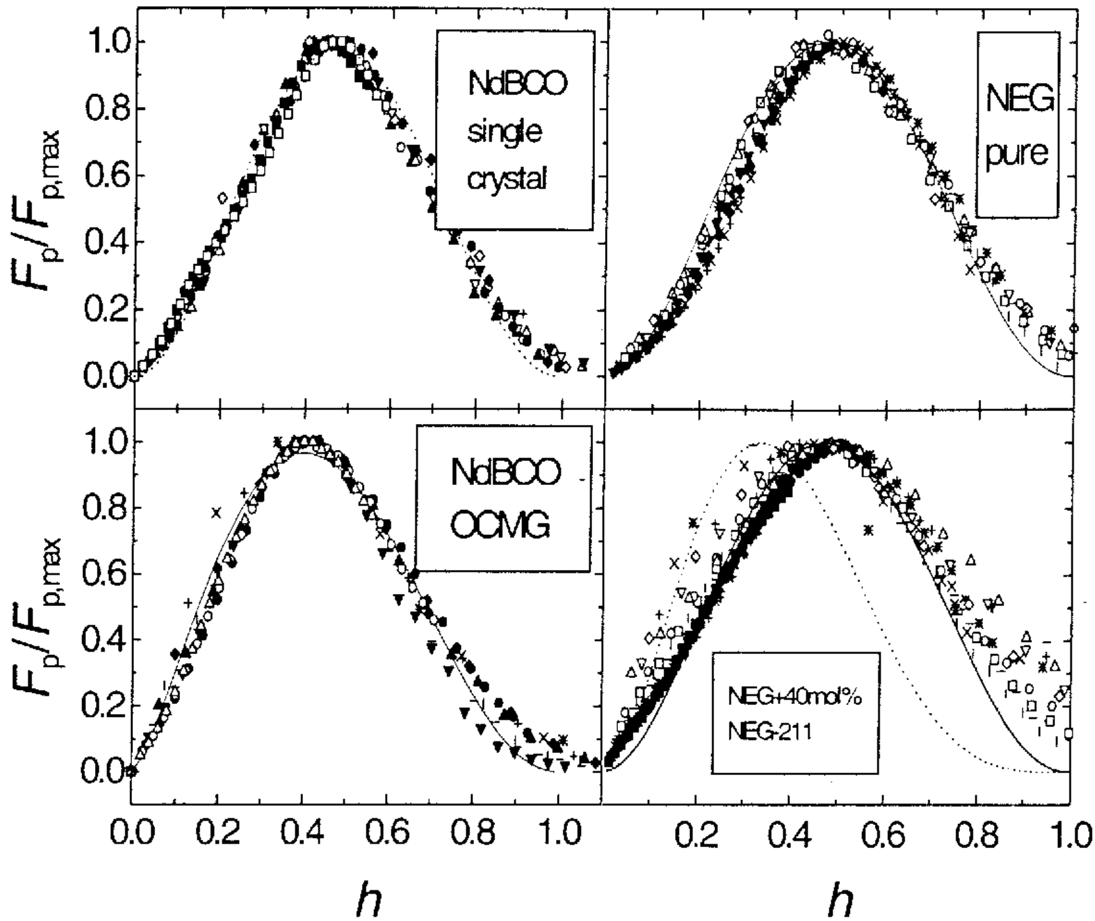

Fig. 1. Plots of the scaled volume pinning forces, $F_p/F_{p,max}$, versus the reduced field, $h = H_a/H_{\rm irr}$. (a): NdBCO single crystal, (b): NdBCO OCMG processed, (c): pure NEG, (d): NEG + 40 mol% NEG-211. Data are taken in the temperature range 65 K $\leq T \leq$ 92 K. The bold and dashed lines are theoretical curves corresponding to δT_c-pinning and δl-pinning, respectively.

RESULTS AND DISCUSSION

As a tool to deduce the microscopic pinning mechanism, we use the model by Dew-Hughes [4] for conventional superconductors, which is a direct summation model of the elementary pinning forces. This approach ignores effects of flux line elasticity and flux creep. However, this model may predict many forms of pinning functions and can describe various pinning types. Therefore, as shown earlier [5, 6], it is well suited for the analysis of F_p data for an unknown pinning mechanism.

In Fig. 1, we present the result of the scaling analysis of F_p, normalized by its maximum value, $F_{\rm p,max}$, and plotted versus the reduced field, $h = H_a/H_{\rm irr}$. In the temperature range 65 K $\leq T \leq$ 92 K, all parameters are directly accessible to our experimental field range.

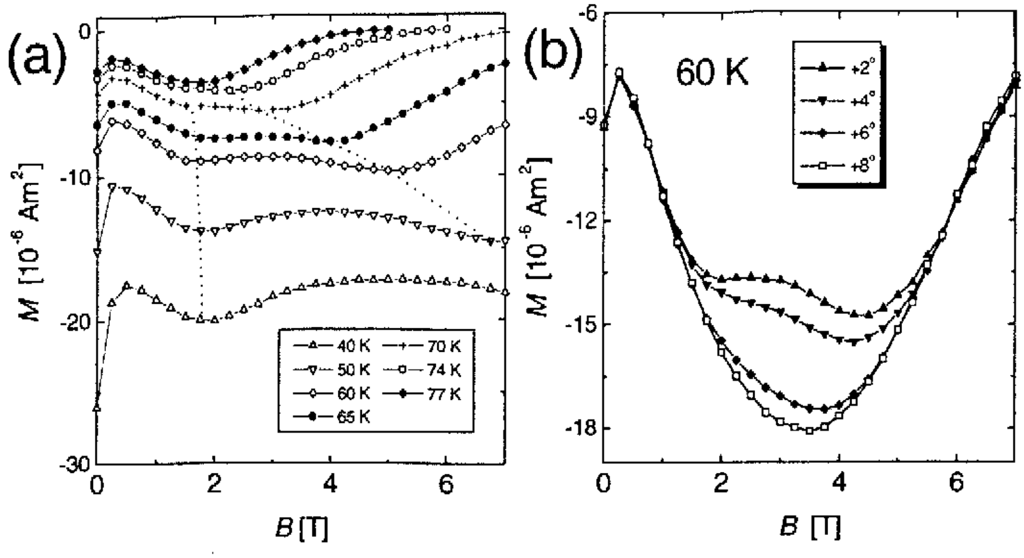

Fig. 2. The intermediate peak of NdBCO single crystals. In (a), MHLs are shown at temperatures between 40 K and 77 K. (b) shows MHLs obtained for various angles Θ at 60 K. This clearly shows that the intermediate peak exists only in a narrow angular window around 0°.

H_{irr} is determined from the MHLs using a criterion of 10^5 A/m^2. The resulting scaling is found to be excellent in all cases; necessary corrections to H_{irr} by means of the scaling were within the experimental error. The peak in the F_p diagram is located at $h_0 \approx 0.5$. In Refs. [6, 7] it was shown that such a high peak position can only be explained assuming a dominant pinning provided by *superconducting* defects with a pinning interaction volume $V_{pin} \sim \xi^2 d$ (ξ denotes the coherence length and d the intervortex spacing), instead of the usual normal-conducting inclusions like Y_2BaCuO_5 particles [7]. These latter particles lead to a peak at $h_0 = 0.33$, commonly found in Y-based 123-superconductors [7, 8]. The high position of the peak in the NEG superconductors ($h_0 \approx 0.52$) is evidently due to an increased disorder, which strengthens the δT_c pinning [9]. For the NEG-123 sample with addition of 40 mol% NEG-211 particles, the scaling does only work up to 77 K. At temperatures above, the data deviate towards a lower peak position. This behaviour indicates a change of dominant pinning mechanism, which is also clearly reflected in the $j_c(B)$ curves.

The MHLs of NdBCO single crystals revealed another interesting feature: At temperatures between 40 K and 77 K, another peak is observed ('intermediate' peak [10]). The position of this peak is practically independent of temperature [fig. 2 (a)]. Angular dependent measurements show that this peak only exists in a narrow window $-5° \leq \Theta \leq +5°$. If Θ is increased beyond 5°, only the fishtail peak is observed; however, the position of the fishtail peak is always affected by the presence of the intermediate peak [11]. We ascribe the origin of the intermediate peak to the onset of twin plane pinning. Furthermore, the twin plane pinning can be effective only for 3D vortices. As the twin structure effect is observed in the whole temperature range up to 90 K, we can conclude that the vortices exist in the 3D state practically up to T_c [11]. These measurements also reveal that the pinning centers responsible for the fishtail peak are randomly distributed point-like defects, which is consistent with the results of the pinning force analysis.

CONCLUSIONS

As a conclusion, we may state that the peak positions in the F_p-diagram close to 0.5 are a strong indication that indeed pinning at composition fluctuations providing a scatter of T_c is active in Nd-based superconductors. This pinning is even strengthened in the NEG compunds due to an increased disorder ('constant pinning wavelength'). The intermediate peak found in MHLs of NdBCO single crystals is identified with the onset of twin plane pinning. As this effect is observed up to 90 K, vortices in the Nd-based superconductors have 3D character nearly up to T_c.

ACKNOWLEGEMENTS

This work was partially supported by the New Energy and Industrial Technology Development Organization (NEDO) for the R & D of Industrial Science and Technology Frontier Program. MRK and MJ are grateful for support from Japanese Science and Technology Agency (STA), MMD is thankful to the Iwate Techno Foundation, Iwate, Japan for the providing the financial assistance.

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