Journal of Alloys and Compounds, 195 (1993) 431–434
JALCOM 7499

Angular Dependence of Creep in YBCO Single Crystals Investigated by Torque Magnetometry

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Abstract

Investigations by means of torque magnetometry at 77K reveal different torque contributions in YBCO single crystals due to intrinsic anisotropy as well as several types of crystal defects. The angular dependence of the irreversible part of the magnetization shows remarkable peculiarities in comparison with other HTSC materials. In contrast to earlier results with Bi- and Tl-type materials, scaling of the magnetization component parallel to the c-axis with the corresponding flux density component is only roughly fullfilled indicating deviations from twodimensionality in YBCO. Torque relaxation measurements reveal that, depending on the field orientation, different relaxation laws may occur. Effective pinning barriers extracted from the decay curves depend strongly on the field orientation. This dependence is clearly different from that found in BSCCO investigated previously. Results are discussed with respect to the "butterfly" shape observed commonly for magnetization curves of YBCO.

1. Introduction

High-T_c superconductors differ from conventional low-T_c ones by two remarkable features: anisotropy and giant flux creep. Besides, there are essential differences of these properties among the various high-Tc materials which are related to the different level of anisotropy, for instance between YBCO on the one hand and the BSCCO- or TBCCO-type materials on the other. At 77K the latter ones clearly behave as layered materials the most essential properties of which are determined by the dynamics of so called pancake vortices (e.g.[1,2]). Especially, pinning forces and activation energies are monotonous functions of the pancake area density B_z/Φ_0 [2]. Contrary, in the case of YBCO one observes deviations from the scaling behaviour with the component B_z and butterfly shaped torque curves are observed [3]. The latter ones indicate an increase of the volume pinning force with increasing field in similar way as butterfly shaped magnetization curves (e.g.[4]). For an explanation of that effect several models were suggested in the literature (e.g.[3] and references therein). Krusin-Elbaum et al.[4] suggest that the butterfly shape is related to a change of the relaxation dynamics with increasing flux density. Hojaji et al.[5] report a corresponding change of relaxation and explain the butterfly shape by an uncoupling of pinning centers from the superconducting matrix at high fields. The results of Ref. [4] and [5] refer to the symmetrical case of the external field being parallel to the crystal c-axis. In the present paper we have extended the investigations to arbitrary orientations of the field with respect to the crystal axes. For this aim we apply torque magnetomety which has been proved as a useful tool for investigations of all kinds of anisotropy.

2. Experimental

Experiments were carried out with a single crystal $YBa_2Cu_3O_{7-x}$ which was selected in order to demonstrate clearly the typical effects to be discussed below. The crystal has dimensions of (2.35x2.35x0.08) mm^3 the shortest one being parallel to the c-axis. It was grown from an oxidic solution near to the eutectic composition. The crystal contains only twin planes of one of the possible two [110] orientations. The transition temperature is T_c=90.5K as determined by means of ac-susceptibility. Measurements were performed by means of a sensitive torque magnetometer as described earlier (e.g. [6]). Torque was measured after cooling the crystal in zero field to the measuring temperature of 77K. The torque G exerted on the sample by a rotating external magnetic field H (rotation rate 0.3 deg/s) was measured as a function of the field direction θ. The field was turned with forward (G_f) and reverse rotational sense (G_r) in order to get information

0925-8388/93/$06.00

on rotational hysteresis losses. The rotation plane was parallel to the twin planes containing the c-axis direction (θ=0). From the measured torque data reversible (G_{rev}) and irreversible torque contributions (G_{irr}) were separated according to

$$G_{rev}=1/2(G_f+G_r) \qquad (1a)$$

$$G_{irr}=1/2(G_f-G_r). \qquad (1b)$$

Relaxation of the torque after stopping the field rotation was measured for several values of H and various sample directions.

3. Results

3.1 Anisotropy

Typical torque results are shown in Fig.1 for various values of the external magnetic field. All torque curves show a typical butterfly shape which is most pronounced for the highest field. The reversible torque contribution is negligibly small in comparison to the irreversible one.

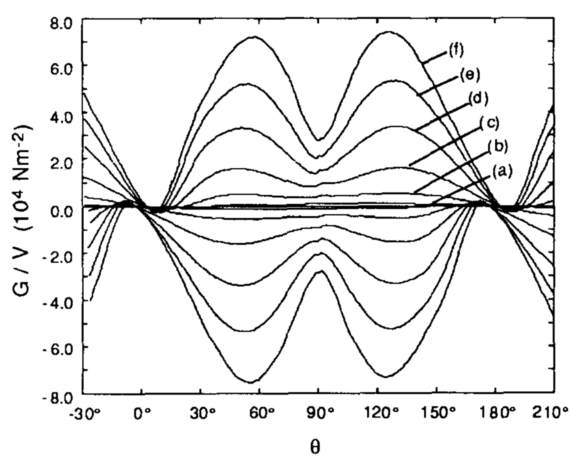

Fig.1 Dependence of torque on the field direction θ for external magnetic fields of 24kA/m (a), 80kA/m (b), 160kA/m (c), 240kA/m (d), 320kA/m (e), 400kA/m (f).

In principle, with torque magnetometry one measures the magnetization component transverse to the magnetic field. Due to the anisotropy of the present samples screening currents flow mainly in planes perpendicular to the c-axis. Accordingly, the irreversible magnetization has only a component along the c-axis which may be calculated from the irreversible torque contribution according to (cf. e.g. /7/)

$$M_{irr}=G_{irr}/(\mu_o VH\sin\theta) \qquad (2)$$

(V sample volume)

For a square shaped platelet one may approximately calculate the critical current density according to $j_c=4M_{irr}/D$ (D platelet edge). In Fig.2 we have plotted M_{irr} and j_c versus the component B_z of the flux density parallel to the c-axis. There the demagnetization is taken into account with a demagnetization factor of N_z=0.94 for the present sample. In the vicinity of θ=0 Eq.(2) is not applicable. Therefore, B_z values corresponding to $\theta<15°$ are omitted in Fig.2. Note that there is a rough scaling with the flux density component B_z.

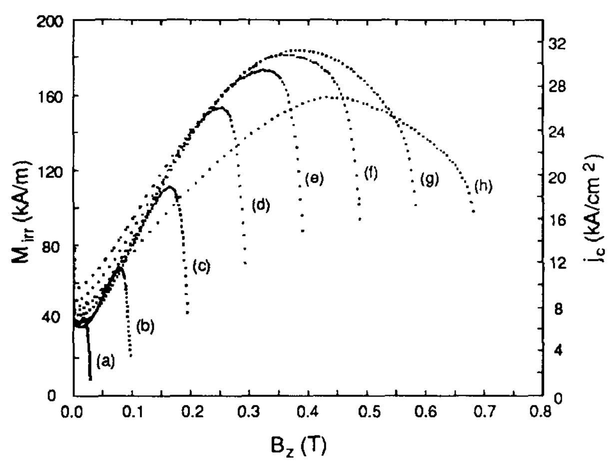

Fig.2 Dependence of the irreversible magnetization and of the critical current on the component B_z of the flux density for external magnetic fields of 24kA/m (a), 80kA/m (b), 160kA/m (c), 240kA/m (d), 320kA/m (e), 400kA/m (f), 480kA/m (g) and 560kA/m (h)

3.2 Relaxation

Decay curves of the irreversible torque after stopping field rotation at different orientations θ are shown in Fig.3. There are large differences of the amount of decay as well as of the shape of the decay curves. In Fig.4 we compare the orientation dependence of M_{irr} for stationary rotation with relaxed values of M_{irr} at fixed time intervals after stopping field rotation. In the high field region there is an increase of the relaxation rate in a similar way as for BSCCO [2]. The relaxation has a minimum at the low field side of the magnetization peak. At very low fields relaxation again increases. The torque data resemble the observations reported by Hojaji et al.[5] for magnetization curves. Remarkably, the minimum of relaxation found for torque as well as for magnetization curves [5] does not coincide with the maximum of M_{irr}. Obviously, the maximum of M_{irr} is not simply caused by a reduced decay rate due to an elevated barrier U_0. The results show that the volume pinning force and the effective pinning barrier have different dependence on the orientation of the mean flux density.

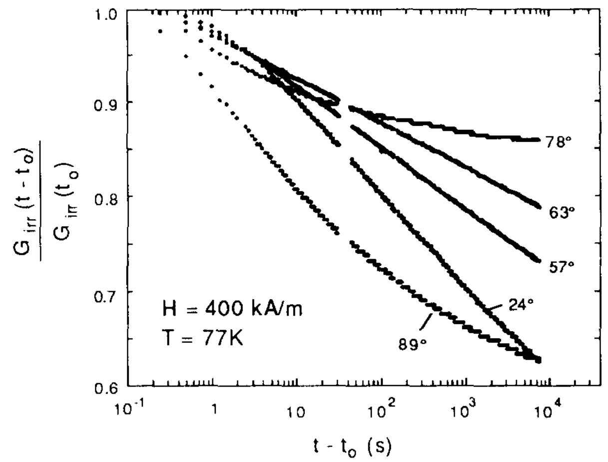

Fig.3 Relaxation curves for different directions of the external field θ=24°, 57°, 63°, 78°, 89°

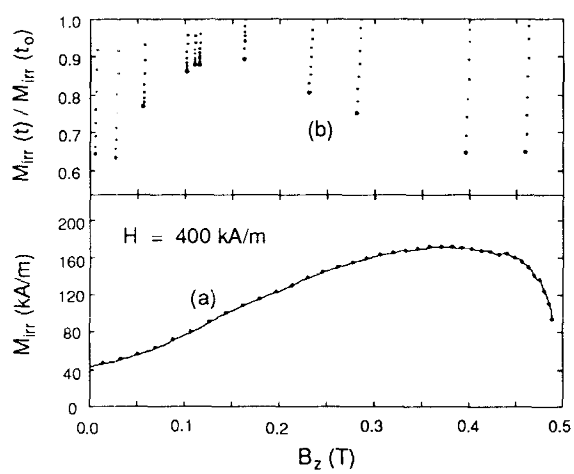

Fig.4 Magnetization curve (a) and relaxed magnetization values (b) after a period of 0s , 3s , 10s , 30s , 100s , 300s , 1000s and 3000s

4. Discussion

Relaxation results (Fig.3) show that there are deviations from the logarithmic decay law commonly observed for high values of U/kT. For lower values the nonlinear dependence of the pinning barrier on the current density has to be taken into consideration. Then, according to the collective creep [8] and the vortex glass models [9] the decay is reasonably described by the interpolation formula

$$M_{irr}(t)=M_o/[1+(pkT/U_o)\ln(t/t_{eff})]^{1/p} \quad (3)$$

which contains as special cases the logarithmic decay for p=-1 as well as the power law decay for the limit p=0 [2]. By fitting the relaxation data with Eq.(3) one finds p=-1 (i.e. logarithmic decay) for a wide angular range θ<70° (Fig.5). For field inclinations above θ=70° a decrease of the effective pinning barrier U_o/kT occurs which is connected with an increase of p up to a maximum at the point of steepest slope of the torque curve G(θ). Obviously, a drastic change of the relaxation mechanism occurs when the field inclination exceeds a critical value θ_{cr}. Considering the above reported rough scaling of the irreversible magnetization with the component H_z of the field, θ_{cr}=70° corresponds to roughly H_z=80kA/m. At higher fields, Anderson-Kim behaviour is observed while below the crossover a more complicated vortex dynamics occurs.

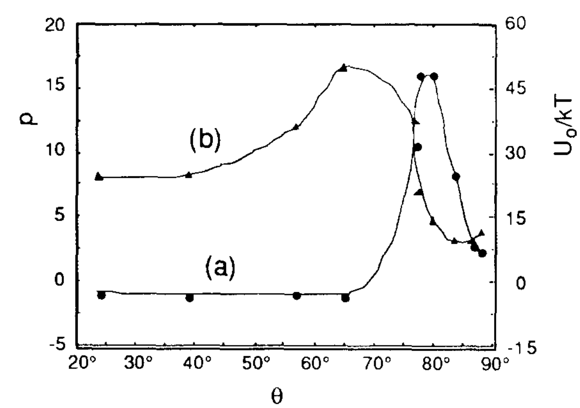

Fig.5 Dependence of the power p (a) and of the effective pinning barrier (b) of the interpolation formula Eq.(3) on the field orientation.

A change of the relaxation mechanism was also suggested by Krusin-Elbaum et al. [4] for an explanation of the butterfly shape of magnetization curves of YBCO single crystals. These authors assume that at the low field side of the magnetization maximum, the current is controlled by collective creep. At much higher fields j_c decreases as H^{-3}. Torque measurements differ from common magnetization measurements insofar as only the component B_z is varied while the amount of |**B**| remains constant during the experiment. For inclination of **B** with respect to the c-axis a folding of vortex lines due to the layered structure may be expected as discussed in Ref.[3]. Within this picture the decrease of torque above a certain angle θ (i.e. the butterfly shape, cf. Fig.1) may be understood by displacement of vortex segments being parallel to the CuO planes ("strings") while at lower angles i.e. higher values of B_z only vortex segments being parallel to the c-axis ("kinks") move. The present relaxation results show that the creep of kinks is well described by the Anderson/Kim mechanism. The corresponding barrier U_o increases with decreasing B_z as already reported for BSCCO [2]. Contrary, creep due to displacement of string segments occurring in the present case at high inclination angles is governed by a different mechanism. A displacement of the relatively tightly pinned strings may occur only if kinks experience a comparatively strong pinning. Then, the Lorentz force component acting on strings for high inclination angles θ may be large enough.

5. Conclusions

The present experimental results show that for strongly pinning YBCO single crystals butterfly shaped torque curves occur when the external field is inclined towards the CuO planes. In contrast to recent observations at BSCCO [2] only rough scaling of the irreversible magnetization with the flux density component B_z is found in YBCO. The observed maximum of the irreversible magnetization i.e. of the critical current density is shown to be related to a sudden change of the relaxation mechanism. Relaxation changes from collective creep at low field components H_z (or high inclination angle) to Anderson-Kim behaviour at high H_z (orientations near the c-axis). The high field behaviour of YBCO single crystals for large H_z is governed by the motion of kink segments of vortices in the same way as for BSCCO [2]. However, for large field inclinations from the c-axis (low H_z) under conditions of large enough Lorentz force density, displacements of string segments of vortices occur. This induces a change of the relaxation mechanism.

Acknowledgement

The present work was supported by the Bundesministerium für Forschung und Technologie under contract No.13N5928. The authors thank Dr. T. Klupsch for valuable discussions.

References

1 P.H.Kes, J.Aarts, V.M.Vinokur, C.J. van der Beek, Phys.Rev.Lett. 64 (1990) 1063
2 R.Hergt, R.Hiergeist, J.Taubert, H.W.Neumueller, W.Ries, 2.Beijing Int. Conf. HTSC, Beijing 1992
3 R.Hergt, R.Hiergeist, phys. stat. sol. (a) 133 (1992)
4 L.Krusin-Elbaum, L.Civale, V.M.Vinokur, F.Holtzberg 2.Beijing Int. Conf. HTSC, Beijing 1992
5 H.Hojaji, S.Hu, A.Barkatt, D.D.Davis, A.N.Thorpe, Physica C 195 (1992) 135
6 R.Hergt, W.Andrä, R.Hiergeist, J.Taubert, phys. stat. sol. (a) 129 (1992) 237
7 C.W.Hagen, M.R.Bom, R.Griessen, B.Dam, R.Veringa, Physica C 153-155 (1988) 322
8 M.V.Feigelman, V.M.Vinokur, Phys. Rev. B 41 (1990) 8986
9 M.P.A.Fisher, Phys. Rev. Lett. 62 (1989) 141