ISSN 1063-7834, Physics of the Solid State, 2006, Vol. 48, No. 5, pp. 826–832. © Pleiades Publishing, Inc., 2006.
Original Russian Text © D.A. Balaev, S.I. Popkov, K.A. Shaĭkhutdinov, M.I. Petrov, 2006, published in Fizika Tverdogo Tela, 2006, Vol. 48, No. 5, pp. 588–593.

METALS AND SUPERCONDUCTORS

Mechanisms of Dissipation in a Josephson Medium Based on a High-Temperature Superconductor in a Magnetic Field

D. A. Balaev, S. I. Popkov, K. A. Shaĭkhutdinov, and M. I. Petrov
Kirensky Institute of Physics, Siberian Division, Russian Academy of Sciences, Akademgorodok, Krasnoyarsk, 660036 Russia
e-mail: smp@iph.krasn.ru
Received June 3, 2005

Abstract—This paper reports on the results of an investigation into the influence of magnetic fields (0–60 kOe) on the temperature dependences of the electrical resistance $R(T)$ of the $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7$ + CuO composites. The structure of these composites is considered to be a network of tunnel-type Josephson junctions in which a nonsuperconducting component (CuO) forms boundaries (barriers) between high-temperature superconducting crystallites. The temperature dependence $R(T)$ of the composites has two steps characteristic of granular superconductors: (i) an abrupt change in the electrical resistance at the critical temperature of high-temperature superconducting crystallites and (ii) a smooth transition to the superconducting state under the influence of the boundaries between the crystallites. The experimental dependences $R(T)$ are analyzed within the Ambegaokar–Halperin model of thermal fluctuations in Josephson junctions and the flux creep model. An increase in the magnetic field leads to a crossover from the Ambegaokar–Halperin mechanism to the flux creep mechanism. The temperature dependences $R(T)$ in the range of weak magnetic fields (from 0 to 10^2 Oe) are adequately described by the relationship following from the Ambegaokar–Halperin model. In the range of strong magnetic fields (from 10^3 to 6×10^4 Oe), the dissipation obeys the Arrhenius law $R \sim \exp(-U(H)/T)]$, which is characteristic of the flux creep model with a temperature-independent pinning energy $U(H)$. The effective Josephson coupling energies and the pinning energies corresponding to the Ambegaokar–Halperin and flux creep mechanisms are determined.

PACS numbers: 74.81.Fa, 74.50.+r

DOI: 10.1134/S1063783406050039

1. INTRODUCTION

Since the discovery of high-temperature superconductors [1–5], the effect exerted by a magnetic field on their transport properties has been continuing to attract the particular attention of researchers (see, for example, [6–15]), because the numerous processes of dissipation and suppression of superconductivity by a transport current and a magnetic field in high-temperature superconducting materials can have different origins and proceed through a variety of mechanisms [16]. In high-temperature polycrystalline superconductors, the resistive transition occurs in two stages [1, 8–12, 17]: (i) the first stage is characterized by an abrupt jump in the temperature dependence of the electrical resistance R, which considerably broadens only in strong magnetic fields (10–60 kOe) and corresponds to a transition of high-temperature superconducting crystals to a superconducting state; and (ii) the second state is characterized by an extended tail in the dependence $R(T)$, which increases even in weak magnetic fields (tens of oersteds) and is associated with the flow of the transport current through a three-dimensional network of grain boundaries. These boundaries are weak links of the Josephson type. This circumstance is responsible for the high sensitivity of the electrical resistance of high-temperature superconducting polycrystals to weak magnetic fields. The network of Josephson junctions formed in high-temperature granular superconductors can be referred to as a Josephson medium [18].

The transport properties of high-temperature granular superconductors in magnetic fields have been described in the framework of a number of mechanisms (see, for example, [16]). In the present paper, we analyze the ranges of applicability of two mechanisms, namely, the Ambegaokar–Halperin (AH) mechanism [19] and the mechanism of magnetic flux creep [20]. Within the Ambegaokar–Halperin model [19], thermal fluctuations in a Josephson junction bring about a loss of phase coherence between the two superconductors forming this junction. In this case, the difference between the phases of the wave functions of the superconductors changes abruptly; i.e., there occurs a phase slip by 2π. This leads to a nonzero voltage drop across the junction. As was first shown by Tinkham [3], a similar result follows from analyzing the thermally activated motion of vortices in a Josephson medium. Vortex jumps through potential barriers also lead to a phase slip by 2π and give rise to an additional resistance, which can also be described in the framework of the

Ambegaokar–Halperin model [3]. The ratio of the Josephson coupling energy

$$E_J(T) = \hbar I_C(T)/e \quad (1)$$

to the product k_BT is a measure of suppression of the superconducting properties of the Josephson junction. Here, $I_C(T)$ is the function describing the temperature dependence of the critical current of the Josephson junction in the absence of fluctuations. For a low transport current ($j \ll I_C$), the Ambegaokar–Halperin model predicts the following relationship for the resistance caused by the thermal fluctuations [19]:

$$R = \{I_0(E_J(T)/2k_BT)\}^{-2}, \quad (2)$$

where I_0 is the modified Bessel function. Relationship (2) can be rewritten as

$$R = \{I_0(C(H)J_C(T)/2T)\}^{-2}, \quad (3)$$

where $J_C(T) = I_C(T)/I_C(0\text{ K})$, and $C(H)$ is the parameter characterizing the Josephson coupling strength, which depends on the applied magnetic field. This parameter is given by the formula

$$C(H) = \hbar I_C(H, 0\text{ K})/k_Be = E_J(H, 0\text{ K})/k_B. \quad (4)$$

The Ambegaokar–Halperin model has been used to describe the transport properties of single Josephson junctions [21, 22], high-temperature polycrystalline superconductors [8, 23–25], and high-temperature superconducting composites [16, 26] in magnetic fields. In the last two cases, the three-dimensional network of Josephson junctions is replaced by an effective junction. The validity of this approach was discussed in [16, 23, 25].

Apart from the Ambegaokar–Halperin model, the thermally activated motion of vortices can be described within the model of magnetic flux creep [20]. In this model, the dependence $R(H, T)$ obeys the Arrhenius law [2]

$$R = R_0\exp(-U(H, T)/k_BT), \quad (5)$$

where R_0 is the preexponential factor, and $U(H, T)$ is the function describing the field and temperature dependences of the pinning potential, i.e., the mean height of the energy barrier that has to be overcome by a vortex (or a bundle of vortices) of the magnetic flux during its motion in an intergranular region, which eventually gives rise to an electrical resistance. The results obtained from a number of experiments with high-temperature polycrystalline superconductors [corresponding to the second portion of the dependence $R(T)$] have been interpreted in the framework of the aforementioned approach [4, 11, 12, 27]. In some cases, the pinning potential exhibits classical temperature-independent behavior $U(H, T) = U(H)$ [4, 27].

However, in our opinion, the field ranges used in the above studies of polycrystals and composites are not sufficient to provide a comprehensive description of the transport properties of Josephson media in magnetic fields. The temperature dependences of the electrical resistance $R(T)$ were measured and analyzed in the following ranges: 0–130 Oe [23], 0–75 Oe [25], 0–3.5 kOe [26], and 1–17 kOe [8] in the framework of the Ambegaokar–Halperin model; and 0.3–20.0 kOe [11], 0–10 kOe [12], and 0–300 Oe [27] in the framework of the flux creep model.

This paper reports on the results of the measurements and interpretation of the temperature dependences of the electrical resistance $R(T)$ for composites prepared from the high-temperature superconductor $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7$ and copper oxide CuO in the range of magnetic fields from 0 to 60 kOe. The structure of two-phase composites based on high-temperature superconductors is considered to be an artificially produced network of Josephson junctions [28, 29]. In these composites, the nonsuperconducting component is a material forming barriers between superconducting grains (i.e., Josephson junctions). It should be noted that the Josephson coupling strength (energy) can be controlled by varying the volume ratio of the components. Since the resistance of CuO at temperatures below 100 K is relatively high ($>10^8\ \Omega$ cm), the composites based on high-temperature superconductors and CuO have a network of tunnel-type junctions.

2. SAMPLE PREPARATION AND EXPERIMENTAL TECHNIQUE

The composites were prepared according to the fast backing technique described in our previous paper [28]. The temperature–time conditions of heat treatment were as follows: heating at 910°C for 2 min and, after cooling, repeated heating at 350°C for 3 h. The transport properties of the composites in the absence of magnetic fields were investigated in [28]. Hereafter, the composites will be designated as YBCO + *V*CuO, where *V* is the CuO content (in vol %) in the composite and the superconductor content is equal to 100 vol % – *V*.

The temperature dependences of the electrical resistance $R(T)$ were measured by the standard four-point probe method during heating of the sample preliminarily cooled to 4.2 K. The magnetic field H was applied perpendicular to the direction of the electric current. The samples were cooled in a zero magnetic field. The transport current density $j \sim 0.03$ A/cm^2 was less than 1% of the critical current density for the samples at 4.2 K [$j_C(4.2\text{ K}) = 3$–6 A/cm^2] and, in our opinion, satisfied the condition $j \ll j_C$. Decreasing the transport current density had virtually no effect on the dependence $R(T)$. By contrast, an increase in the transport current density j led to a smearing of the resistive transition.

3. RESULTS AND DISCUSSION

Figures 1 and 2 present the temperature dependences of the electrical resistance $R(T)$ of the YBCO +

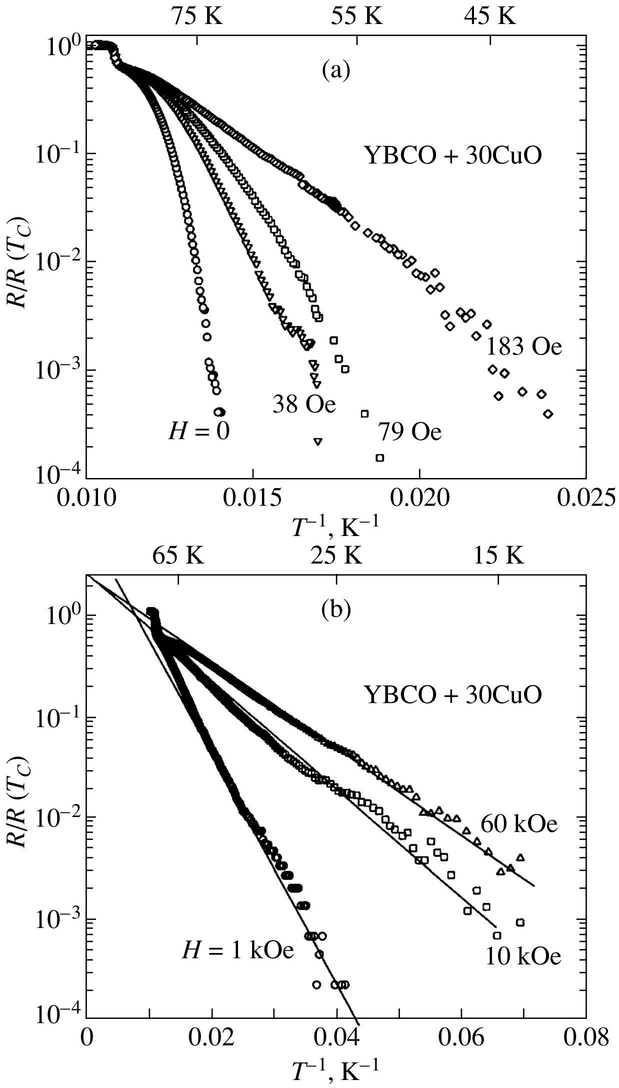

Fig. 1. Temperature dependences of the electrical resistance of the YBCO + 30CuO composite in the magnetic field ranges (a) 0–183 Oe and (b) 1–60 kOe.

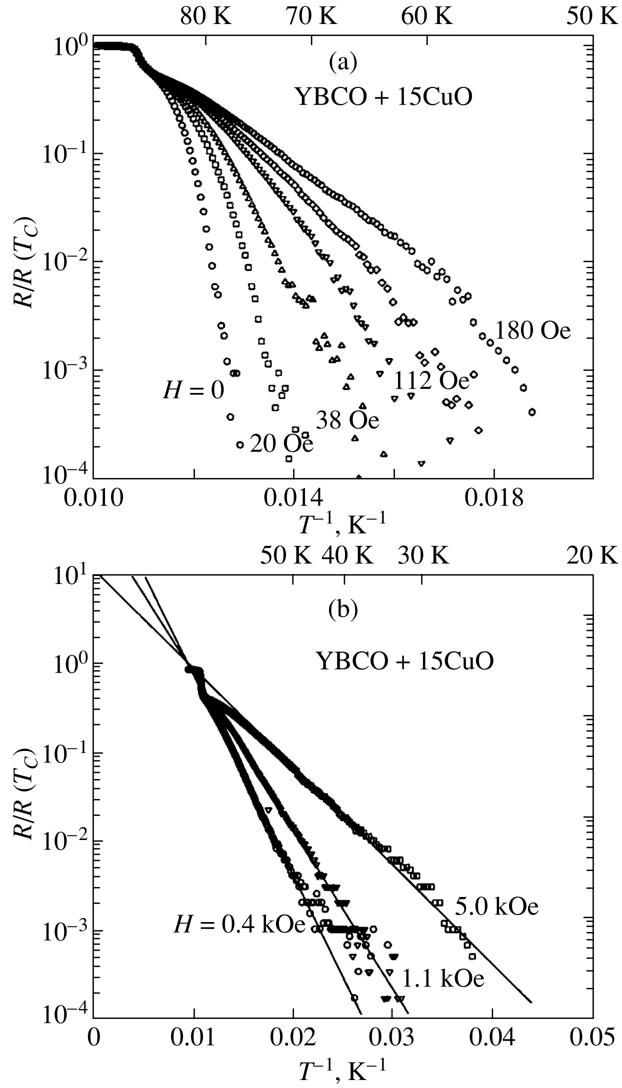

Fig. 2. Temperature dependences of the electrical resistance of the YBCO + 15CuO composite in the magnetic field ranges (a) 0–180 Oe and (b) 0.4–5.0 kOe.

30CuO and YBCO + 15CuO composites in the T^{-1}–$\log R$ coordinates. It can be seen that these dependences have no linear portions in magnetic fields weaker than ≈200 Oe (Figs. 1a, 2a) but, contrastingly, are linear over a wide range of temperatures in strong magnetic fields; i.e., $H = 1$, 10, and 60 kOe for the YBCO + 30CuO composite (Fig. 1b) and $H = 0.4$, 1.1, and 5.0 kOe for the YBCO + 15CuO composite (Fig. 2b). This suggests that the Arrhenius law (5) holds at an approximately temperature-independent pinning energy. As was done by the authors of a number of papers (see, for example, [11, 25]), the functional temperature dependence of the pinning energy $U(T)$ in weak magnetic fields can be found in the form $U(T) = (1 - T/T_C)^q$. Indeed, the exponent q is estimated to be $q \approx 2.9$ for $H = 0$ Oe, $q \approx 2.3$ for $H = 38$ Oe, $q \approx 2.2$ for $H = 79$ Oe, and $q \approx 1.6$ for $H = 180$ Oe. (Note that, within this approach, it is impossible to describe the low-resistance range $R/R(T_C) < 10^{-2}$). However, it will be shown below that there is another approach to describing the temperature dependence of the electrical resistance $R(T)$ for composites in the range of weak magnetic fields (<200 Oe).

In order to describe the experimental dependences $R(T)$ in the framework of the Ambegaokar–Halperin model, it is necessary to determine the dependence $J_C(T)$. For this purpose, we used the classical Ambegaokar–Baratoff dependence [30] for a tunnel-type Josephson junction. This dependence was already used in our previous study [28] for describing the dependences $R(T)$ of high-temperature superconductor + CuO composites in the absence of magnetic fields within the Ambegaokar–Halperin model. Therefore, apart from weakly varying parameters, such as the resistance $R(T_{CJ})$ of the barriers separating high-tem-

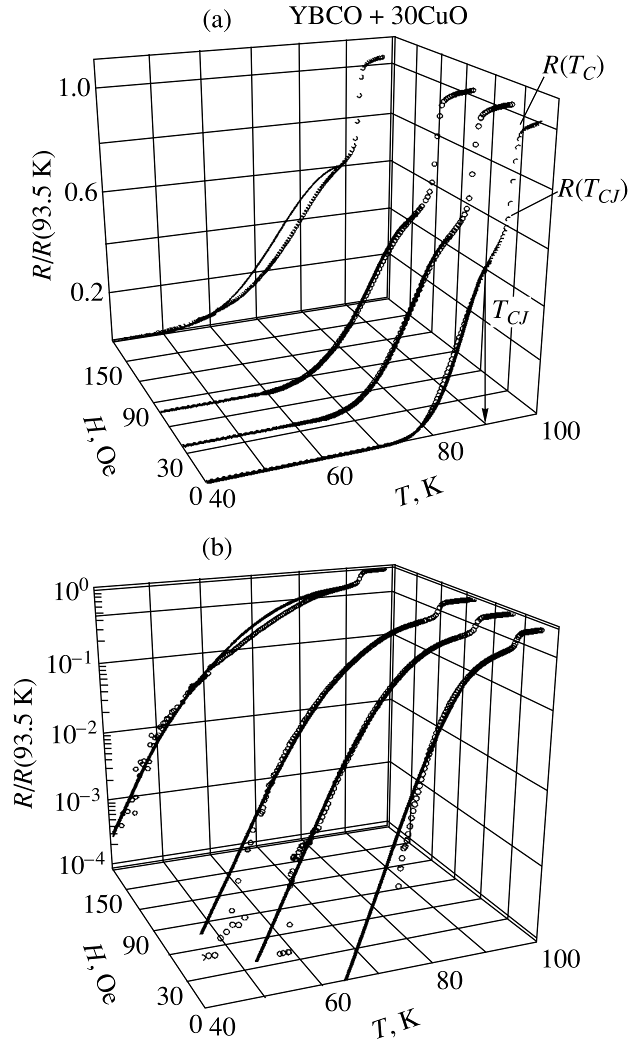

Fig. 3. (a) Electrical resistance of the YBCO + 30CuO composite as a function of the temperature and the applied magnetic field (points). Solid lines indicate the results of the best fit within the Ambegaokar–Halperin model [19] using relationship (3) for the parameters $C(H)$ = 1760, 1080, 860, and 620 (corresponding to an increase in the magnetic field). (b) The same as in panel (a) with the electrical resistance R plotted on a logarithmic scale. $R(T_{CJ})$ and T_{CJ} are the parameters used for constructing the theoretical dependences $R(T)$.

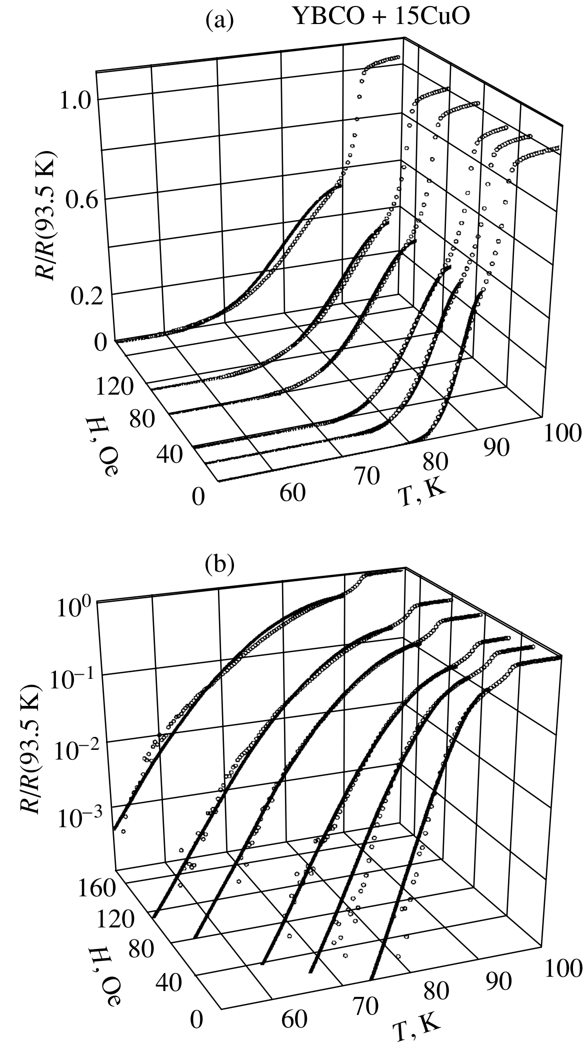

Fig. 4. (a) Electrical resistance of the YBCO + 15CuO composite as a function of the temperature and the applied magnetic field (points). Solid lines indicate the results of the best fit within the Ambegaokar–Halperin model [19] using relationship (3) for the parameters $C(H)$ = 3000, 1980, 1500, 1150, 1000, and 820 (corresponding to an increase in the magnetic field). (b) The same as in panel (a) with the electrical resistance R plotted on a logarithmic scale.

perature superconducting crystallites [corresponding to the second step in the dependence $R(T)$] and the critical temperature T_{CJ} at which all high-temperature superconducting crystallites have already transformed into the superconducting state, there is only one adjustable parameter $C(H)$ defined by expression (4). The results of fitting the experimental temperature dependences of the electrical resistance $R(T)$ in the framework of the Ambegaokar–Halperin model with the use of relationship (3) for the YBCO + 30CuO and YBCO + 15CuO composites in magnetic fields are presented in Figs. 3 and 4, respectively. The abscissa X, the ordinate Y, and the applicate Z are respectively the temperature, the magnetic field, and the electrical resistance normalized to the resistance R that corresponds to the temperature of the onset of the transition of high-temperature superconducting crystallites ($T_C = 93.5$ K) and is identical for all the composites. The dependences $R(T)$ exhibit two steps (see above). The Ambegaokar–Halperin theory adequately describes the second (smooth) portion of the temperature dependence of the electrical resistance $R(T)$. It can be seen that the experimental and theoretical dependences $R(T)$ are in good agreement in magnetic fields of up to ≈150 Oe. Moreover, as is clearly

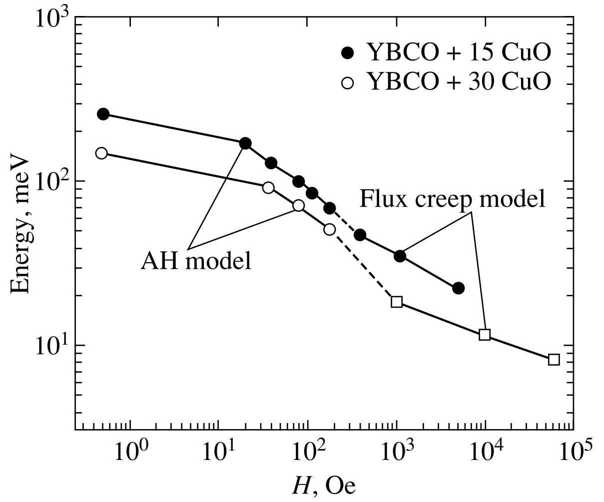

Fig. 5. Magnetic-field dependences of the effective Josephson coupling energy $E_J(H, 0\ K)$ calculated from the results of the best fit within the Ambegaokar–Halperin model (Figs. 3, 4) using the parameters $C(H)$ defined by expression (4) and the vortex pinning energy $U(H)$ determined from the slopes of the curves $\log R(T^{-1})$ (Figs. 1b, 2b) according to relationship (5) for the YBCO + 15CuO and YBCO + 30CuO composites.

seen from Figs. 3b and 4b (in which the electrical resistance is plotted on a logarithmic scale), this agreement is retained in the range of low resistances R, i.e., the resistances three orders of magnitude lower than the resistance $R(T_{CJ})$. It is worth noting that the experimental results are inconsistent with the Ambegaokar–Halperin theory in magnetic fields stronger than ≈150 Oe [see the dependences $R(T)$ for H = 180 Oe in Figs. 3a and 4a]. In magnetic fields H = 0.4, 1.0, 5.0, 10.0, and 60.0 kOe, this discrepancy for the samples under investigation increases and reaches ≈100%.

The above results allow us to make the inference that the dissipation in a network of Josephson junctions occurs through the mechanism described by the Ambegaokar–Halperin model in magnetic fields of up to ~10^2 Oe and the mechanism of magnetic flux creep in fields stronger than ~10^3 Oe, in which the resistance R is determined by relationship (5). In the authors' opinion, this situation is quite realistic. There are a few possible qualitative explanations for this behavior of the dissipation. First, according to the commonly accepted model of a Josephson medium [18], the Meissner state in the subsystem of grain boundaries is destroyed even in a zero field: the magnetic field penetrates into the sample in the form of slow network hypervortices whose sizes decrease and whose number increases with increasing field strength. As the magnetic field increases to a strength H_J, the hypervortices transform into Josephson vortices [7, 18]. In [7], the magnetic field H_J was compared with the field H_{irr}, in which the dependence of the magnetization on the magnetic field strength in magnetic measurements changed irreversibly. The magnetic fields H_{irr} obtained in [7] and in other experiments with high-temperature yttrium superconductors [9, 31] at temperatures close to 77 K are equal to tens of oersteds. It is clear that the field dependence of the magnetoresistance of a network of weak links should also change in magnetic fields close to the field H_J or H_{irr}, in which the vortex structure undergoes a transformation. For the samples under investigation, the magnetic field H_{irr} at T = 77 K is approximately equal to 38 Oe according to the results obtained from the electrical [$R(H)$] and magnetic measurements. Possibly, the change in the behavior of the magnetoresistance is difficult to determine reliably because of the distribution in the geometric parameters of the network of Josephson junctions in the YBCO + CuO composites.

Second, the magnetic field begins to penetrate into superconducting grains at a strength H_{C1g}. It should be noted that the magnetic field strength H_{C1g} at temperatures close to 77 K can also amount to tens or hundreds of oersteds [9, 13, 15, 18]. Therefore, interaction of the two vortex subsystems becomes probable: Josephson vortices in the form of Abrikosov vortices pass from weak links into grains (and vice versa). These processes can also affect the temperature dependence of the electrical resistance of the network of weak links.

Finally, as was noted in [16], the Ambegaokar–Halperin and flux creep mechanisms formally differ only in the choice of the pinning potential. The potential used in the Ambegaokar–Halperin model is periodic (the equation describing the behavior of a Josephson junction is equivalent to that for the motion of a Brownian particle at a periodic potential [19]), whereas the flux creep model does not impose stringent restrictions on the arrangement of pinning centers with respect to each other. An increase in the magnetic field leads to an enhancement of the Lorentz force and, hence, to a change in the coordinate function of the pinning potential and a decrease in the pinning force as the potential gradient. As a result, only the deepest pinning centers remain in strong fields. Consequently, in strong magnetic fields (>10^3 Oe), there arise conditions similar to those used in the flux creep model. In the field range 10^2–10^3 Oe, either both mechanisms coexist or there occurs a crossover from the Ambegaokar–Halperin mechanism to the flux creep mechanism.

The pinning energy $U(H)$ of Josephson vortices in the intergranular region can be determined from the slopes of the curves $\log R(T^{-1})$ (Figs. 1b, 2b). Moreover, the mean Josephson coupling energy $E_J(H, 0\ K)$ can be obtained from the results of the best fit of the experimental dependences $R(T)$ within the Ambegaokar–Halperin theory; i.e., it can be determined from the parameters $C(H)$. From relationship (4), we obtain $E_J(H, 0\ K) = k_B C(H)$. The quantities $E_J(H, 0\ K)$ and $U(H)$ for the composites under investigation are plotted on a log–log scale in Fig. 5. As can be seen from this figure, the points obtained in the framework of the Ambegaokar–Halperin and flux creep models fall on straight lines. This indicates that the dependences $U(H)$ and $E_J(H)$ obey a power law; i.e., $U(H)$ and $E_J(H) \sim H^{-n}$. The calculations performed for magnetic fields in the range from ~10 to 2×10^2 Oe lead to the following relationships: $E_J(H) = H^{-0.38}$ for the YBCO + 30CuO composite and $E_J(H) = H^{-0.39}$ for the YBCO + 15CuO composite. For stronger magnetic fields, we have $U(H) = H^{-0.2}$ for the YBCO + 30CuO composite in the field range from ~10^3 to 6×10^4 Oe and $U(H) = H^{-0.25}$ for the YBCO + 15CuO composite in the field range from 0.4×10^3 to 5×10^3 Oe. The exponents obtained in the framework of the Ambegaokar–Halperin model are close to those determined by processing the dependences $R(T)$ within this model for polycrystals $YBa_2Cu_3O_7$ [25, 26] (n = 0.3–0.5) and $Bi_{1.7}Pb_{0.2}Sb_{0.1}Sr_2Ca_2Cu_3O_{10}$ [23] (n = 0.33) (also in weak fields up to ~200 Oe). It should be noted that the exponent determined in [23] was explained in terms of the averaging of the Fraunhofer dependence $J_C(H)$ for Josephson junctions with due regard for the distribution in the physical parameters of grain boundaries in high-temperature superconducting polycrystals [32]. The revealed change in the exponent n in the above relationships also indicates a crossover between the dissipation mechanisms in the transition field range 10^2–10^3 Oe.

In a number of works [8, 21–23, 25, 26], the experimental dependences $R(T)$ were fitted within the Ambegaokar–Halperin model by using the phenomenological relationship $E_J(T) = (1 - T/T_{CJ})^\alpha$ for the energy E_J [and, hence, a similar expression for the quantity $J_C(T)$]. According to our calculations within this approach, the experimental and theoretical data are in somewhat worse agreement (than those presented in Figs. 3 and 4) for α = 0.65–0.75; i.e., in the case when the function $a(1 - T/T_{CJ})^\alpha$ (where a is a constant) in the high-temperature range $0.7T/T_{CJ} \le T \le 1T/T_{CJ}$ can approximate the Ambegaokar–Baratoff dependence (in the immediate vicinity of the temperature T_{CJ} at $0.93T/T_{CJ} \le T \le 1T/T_{CJ}$, the Ambegaokar–Baratoff dependence is linear, $\alpha = 1$ [30]). However, the electrical resistance of the YBCO + 45CuO composite even at $H = 0$ becomes nonzero already at a temperature of ≈12 K ≈ $0.13T/T_{CJ}$ and the tail of the temperature dependence of the electrical resistance $R(T)$ is adequately described in the framework of the Ambegaokar–Halperin theory with the use of the dependence $J_C(T)$ derived within the Ambegaokar–Baratoff model (Fig. 6). Consequently, the discrepancy between the experimental and theoretical data in the low-temperature range ($0.1T/T_{CJ} \le T \le 0.5T/T_{CJ}$) in magnetic fields stronger than ≈150 Oe cannot stem from the fact that, in this range, the dependence $J_C(T)$ obeys another law. Therefore, we can make the inference that the dependence $J_C(T)$ obtained within the Ambegaokar–Baratoff model can be used for describing the resistive transition of the network of tunneling Josephson junctions in the framework of the Ambegaokar–Halperin theory.

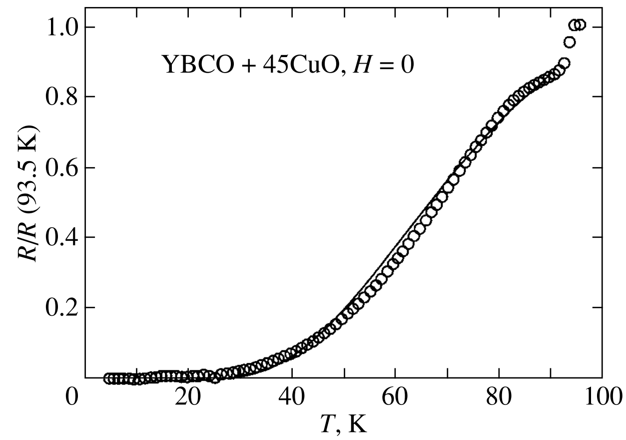

Fig. 6. Temperature dependence of the electrical resistance of the YBCO + 45CuO composite at H = 0 and j = 0.003 mA/cm^2 (points). The solid line indicates the results of the best fit within the Ambegaokar–Halperin model using relationship (3) for the parameter C = 280 with the temperature dependence $J_C(T)$ in the Ambegaokar–Baratoff model.

4. CONCLUSIONS

Thus, the temperature dependences of the electrical resistance $R(T)$ of the $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7$ + CuO composites were measured in weak (H ~ 0–200 Oe) and strong (H ~ 10–60 kOe) magnetic fields. The results obtained from these measurements made it possible to draw the conclusion that the mechanism of dissipation in a network of Josephson junctions undergoes a crossover with an increase in the magnetic field. Earlier, only one dissipation mechanism was considered in similar investigations into the resistive state of Josephson media in magnetic fields (most likely, due to the use of narrower ranges of magnetic fields) [8, 11, 12, 23–25, 27]. We analyzed the experimental dependences $R(T)$ in the framework of the Ambegaokar–Halperin and flux creep models. The results of the analysis performed have demonstrated that the dissipation proceeds through the Ambegaokar–Halperin mechanism in the range of weak magnetic fields from ~0.5×10^{-1} to 10^2 Oe, the crossover of the dissipation mechanisms occurs in the range 10^2–10^3 Oe, and the electrical resistance is caused by the magnetic flux creep in strong magnetic fields from ~10^3 to 6×10^4 Oe.

ACKNOWLEDGMENTS

We would like to thank A.V. Mitin for his participation in discussions of this study. D.A. Balaev acknowledges L.P. Ichkitidze for helpful discussions of the results.

REFERENCES

1. M. A. Dubson, S. T. Herbet, J. J. Calabrese, D. C. Harris, B. R. Patton, and J. C. Garland, Phys. Rev. Lett. **60**, 1061 (1988).
2. T. T. M. Palstra, B. Batlogg, R. B. van Dover, L. F. Schneemeyer, and J. V. Waszczak, Appl. Phys. Lett. **54**, 763 (1989).
3. M. Tinkham, Phys. Rev. Lett. **61**, 1658 (1988).
4. J. D. Hettinger, A. G. Swanson, J. S. Brooks, Y. Z. Huang, L. Q. Chen, and Zhong-Xian Zhao, Supercond. Sci. Technol. **1**, 349 (1989).
5. B. A. Aronzon, Yu. V. Gershanov, E. Z. Meĭlikhov, and V. G. Shapiro, Sverkhprovodimost: Fiz., Khim., Tekh. **2**, 83 (1989).
6. S. I. Volkov, Yu. E. Grigorashvili, and L. P. Ichkitidze, Izv. Vyssh. Uchebn. Zaved., Élektron., Nos. 4–5, 128 (2000).
7. N. D. Kuz'michev, Fiz. Tverd. Tela (St. Petersburg) **43** (11), 1934 (2001) [Phys. Solid State **43** (11), 2012 (2001)].
8. H. Shakeripour and M. Akhavan, Supercond. Sci. Technol. **14**, 234 (2001).
9. D. Daghero, P. Mazzetti, A. Stepanescu, and P. Tura, Phys. Rev. B: Condens. Matter **66**, 184514 (2002).
10. L. Burlachkov, E. Mogilko, Y. Schlessinger, Y. M. Strelniker, and S. Havlin, Phys. Rev. B: Condens. Matter **67**, 104509 (2003).
11. M. R. Mohammadizadeh and M. Akhavan, Supercond. Sci. Technol. **16**, 234 (2003).
12. H. Khosroabadi, V. Daadmehr, and M. Akhavan, Physica C (Amsterdam) **384**, 169 (2003).
13. V. V. Derevyanko, T. V. Sukhareva, and V. A. Finkel', Fiz. Tverd. Tela (St. Petersburg) **46** (10), 1740 (2004) [Phys. Solid State **46** (10), 1798 (2004)].
14. A. A. Sukhanov and V. I. Omel'chenko, Fiz. Nizk. Temp. **30** (6), 604 (2004) [Low Temp. Phys. **30** (6), 452 (2004)].
15. P. Mune, F. C. Fonesca, R. Muccillo, and R. F. Jardim, Physica C (Amsterdam) **390**, 363 (2003).
16. R. J. Soulen, Jr., T. L. Francavilla, W. W. Fuller-Mora, and M. M. Miller, Phys. Rev. B: Condens. Matter **50**, 478 (1994).
17. A. V. Mitin, Sverkhprovodimost: Fiz., Khim., Tekh. **7**, 62 (1994).
18. E. B. Sonin, Pis'ma Zh. Éksp. Teor. Fiz. **47** (8), 415 (1988) [JETP Lett. **47** (8), 496 (1988)].
19. V. Ambegaokar and B. I. Halperin, Phys. Rev. Lett. **22**, 1364 (1969).
20. P. W. Anderson, Phys. Rev. Lett. **9**, 309 (1962).
21. R. Gross, P. Chaudhari, D. Dimos, A. Gupta, and G. Koren, Phys. Rev. Lett. **64**, 228 (1990).
22. J. Gao, Yu. M. Boguslavskij, and B. B. G. Klopman, J. Appl. Phys. **72**, 575 (1992).
23. A. C. Wright, K. Zhang, and A. Erbil, Phys. Rev. B: Condens. Matter **44**, 863 (1991).
24. A. C. Wright, T. K. Xia, and A. Erbil, Phys. Rev. B: Condens. Matter **45**, 5607 (1992).
25. C. Caffney, H. Petersen, and R. Bednar, Phys. Rev. B: Condens. Matter **48**, 3388 (1993).
26. H. S. Gamchi, G. J. Russel, and K. N. R. Taylor, Phys. Rev. B: Condens. Matter **50**, 12950 (1994).
27. E. Babic, I. Kusevic, S. X. Dou, H. K. Liu, and O. Y. Hu, Phys. Rev. B: Condens. Matter **49**, 15312 (1994).
28. M. I. Petrov, D. A. Balaev, K. A. Shaĭkhutdinov, and K. S. Aleksandrov, Fiz. Tverd. Tela (St. Petersburg) **41** (6), 969 (1999) [Phys. Solid State **41** (6), 881 (2002)].
29. M. I. Petrov, D. A. Balaev, K. A. Shaĭkhutdinov, and S. I. Popkov, Pis'ma Zh. Éksp. Teor. Fiz. **75** (3), 166 (2002) [JETP Lett. **75** (3), 138 (2002)].
30. V. Ambegaokar and A. Baratoff, Phys. Rev. Lett. **10**, 486 (1963); Phys. Rev. Lett. **11**, 104 (1963).
31. K. Y. Chen and Y. J. Quian, Physica C (Amsterdam) **159**, 131 (1989).
32. R. L. Peterson and J. W. Ekin, Phys. Rev. B: Condens. Matter **37**, 9848 (1988).

Translated by O. Borovik-Romanova