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ABSTRACT

Magnetization of high T_c superconductors logarithmically decreases with time. There is a maximum in the temperature dependence of the coefficient at this logarithm. If one assumes that there do exist two kinds of pinning centers, then this dependence can be described in the Anderson theory of thermal creeps of Abrikosov's vortices. The temperature dependence of the critical current is also discussed.

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It was found that in a new high temperature conductor, the magnetization slowly, logarithmically, decreases with time [1-5]. This decay follows from Anderson's model of flux creep [6]. An alternative explanation is that the twinning boundaries are the Josephson weak links between the twins [7]. This model is like a spin glass model. In spin glasses the logarithmic time-dependence of magnetization is also observed. In experiments they usually find a ratio

$$\tau = -\frac{1}{M}\frac{dM}{d\,\ln t} \qquad (1)$$

where M is a magnetization of a superconductor. The temperature dependence of this ratio has a characteristic maximum at 30-40K in a field 500 G. In weak fields a position of this maximum shifts to higher temperatures. In spin glasses this maximum is not observed. Anderson's model also predicts monotonous growth of r with temperature. So the authors of [3] claim that the decrease of r with temperature definitely disagrees with the flux creep model.

We show below that after certain generalizations the Anderson model can explain this peak in the temperature dependence of r. This generalization consists in an assumption that there exists two kinds of pinning centers: many weak centers with rather low activation energy, and few strong centers with high activation energy. At low temperatures weak centers give the main contribution into pinning and creep and the ratio r monotonously rises with temperature. At high temperatures the vortex lattice near weak centers comes to thermal equilibrium during experiment, the weak centers are excluded and the critical current is determined by strong centers, on which creep is much more weak.

If there is a current lower than the critical in superconductor then the vortex lattice is in a metstable state. Due to the thermal fluctuations small areas of the lattice make thermal jumps. If the current is close to critical then the height of the barrier is equal to

$$E = U_m\left(1-\frac{J}{J_c}\right)^{\alpha} \qquad (2)$$

where $\alpha > 0$ is some index which depends upon energy distribution of the barriers. Experiments are usually described by the phenomenological Anderson formula with $\alpha = 1$.

If we assume that the potential energy for each area which makes jumps can be approximately described by one co-ordinate g then near the critical current this energy is cubic parabola:

$$U(g) = \frac{Um}{4}\ \frac{g}{gm}\ \left(3\left(1 - \frac{\mathcal{J}}{\mathcal{J}_c}\right) - \left(\frac{g}{gm}\right)^2\right) \qquad (3)$$

and the height of the barrier is determined by the formula (2) with $\alpha = \frac{3}{2}$.

The probability of the thermal jump through such a barrier is proportional to exp(-E/T). As a result of these jumps the current in the sample decreases

$$\frac{d\mathcal{J}}{dt} = \beta\ e^{-E/T} \qquad (4)$$

where coefficient β depends upon the size of the sample. Solving this equation with logarithmic accuracy, we obtain

$$E = T\ \ell n\ \omega t \qquad (5)$$

where $\omega = \beta\frac{dE}{d\mathcal{J}}/T$. Rough estimations give $\omega \sim 10^5 - 10^{10}(s^{-1})$.

After switching on a sufficiently strong field, the critical current will flow through the sample. This current decreases with time. From (3) and (5) we obtain

$$\mathcal{J} = \mathcal{J}_c\left(1 - \left(\frac{T\ \ell n\omega t}{U_m}\right)^{1/\alpha}\right) \quad . \qquad (6)$$

Magnetization of the sample is proportional to the current. Then we obtain

$$r = -\frac{1}{M}\frac{dM}{d\ \ell n\ t} = \frac{1}{\alpha}\left(\frac{T}{U_m}\right)^{1/\alpha} \ell n^{1/\alpha - 1} \qquad (7)$$

Because the effective size of a potential well is likely to decrease with increasing temperature, the formula (7) gives a monotonously increasing temperature. It is true if all pinning centers have approximately equal value of U_m . If there are two kinds of pinning centers: with high barrier $U_m=U_1$ and with low $U_m=U_2$ then (7) is valid only at low temperature when $E = T\ \ell n\ \omega t << U_2$. Near the critical current Eq.(7) should be rewritten as

$$r = \frac{T^{1/\alpha}}{\alpha\ \ell n\ \omega t^{1-1/\alpha}}\ \frac{\sum_i \rho_i\ U_i^{-1/\alpha}}{1 - \sum_i \rho_i\left(\frac{T\ell n\ \omega t}{U_j}\right)^{1/\alpha}} \quad , \qquad (8)$$

where ρ_i is a relative contribution of the i-th pinning centers to the current.

At temperature $T > U_2/\ell n\ \omega t$ weak pinning centers do not contribute and we can again use Eq.(7), in which we must substitute U_1 for U_m . If $U_1 >> U_2$ then ratio r at high temperature will be smaller

than at low temperature, where formula (8) works. In this model r exhibits a sharp jump at temperature T-$U_2/\ell n\omega t$. In experiments there is rather a maximum and smooth decreasing.

There may be three reasons for this smooth decreasing. The first is that there can be some scattering of magnitudes of U_i of weak centres so that the centers with the lower U_i are excluded first. Then we can still use formula (8), but including only the centers with $U_i > T\ \log(wt)$, so that eventually with increasing temperature U_m will increase and r decrease. The second reason is that the magnetic field in a sample is inhomogeneous. If U_m depends upon the magnetic field then the pinning centers are excluded gradually. A distribution of the magnetic field depends upon history. So r may depend upon history too. Third reason is that when the current is much smaller than the critical one, then the height of the barrier is not U_m but goes to infinity. Indeed, at $\mathcal{J} << \mathcal{J}_c$ the vortex lattice must be strongly reconstructed for passing into the state with energy lower than the initial. There may be a high barrier between these states. For field near M_c, where we can ignore the interaction between vortices, Vinokur and Feigelman proposed that $E = U_m(\mathcal{J}_c/\mathcal{J})^{1/4}$.

It is based on the result [8] for distributions. Taking into account (5) we obtain

$$\mathcal{J} = \mathcal{J}_{c1} + \mathcal{J}_{c2}(U_m/T\ \ell n\omega t)^4 \quad ,$$

where $\mathcal{J}_{c1}$ is a contribution from strong centers which weakly depends upon time. At higher temperature the second term is small and the ratio $r \sim T^{-4}$. A quantitative theory of creep is still lacking, especially for the case of collective pinning so that it is difficult to say which of the above mechanisms gives the main contribution to rather smooth decrease of r with temperature increasing.

In any case, the peak of r is near the temperature $\sim U_m/\ell n\omega t$. It is possible that with the rise of magnetic field the effective U_m decreases and position of the maximum shift towards low temperature region in correspondence with experiment. The value of ratio r in maximum is equal to const/$\ell n\omega t$. For characteristic experimentation time of 1 min. we have $\omega t \sim 10^6$-10^{10}, $\ell n\omega t \sim 10$-20. Hence $r_{max} \sim 10^{-1}$ is in agreement with experimental value.

The physical reason for pinning of the vortices in oxygen superconductors may be randomly placed oxygen atoms. An isolated atom weakly interacts with the vortice lattice and cannot form a metastable state. But high concentration of randomly placed atoms destroys the long range order in the vortex lattice [9]. The size of the area with short range order depends upon pinning force and elastic modulus of the lattice and is much larger than spacing of the pinning centers. The number N of pinning centers in the area with short range order is large. Such areas are weakly correlated under thermal jumps independently. Therefore, the height of the potential barrier when such an area propagates across the randomly placed pinning centers, is proportional to $\sqrt{N}$ and may be rather large, although the critical current under such collective pinning is usually small [10, 11].

Another reason for pinning may be the intersection of twinning boundaries [12]. In this case critical current must depend upon the number and structure of such boundaries. Such centers cause a plastic deformation of vortex lattice and for them the Labusch criteria [13] is fulfilled. In this case, single-particle pinning when the mean force is proportional to the number of centers will take place. Large clusters of oxygen atoms in an area with size ξ, or some other defects which can be formed, for instance, by irradiation of sample by fast particles [14] can act as centers of this kind. It is not yet understood for which centers the pinning energy is high and for which it is low.

Above we have considered the picture of thermal creep of Abrikosov's vortices. It is possible that the twinning boundaries are weak links [7]. In this case relaxation is determined by the motion of Josephson vortices. A qualitative picture in this case is the same as in the motion of Abrikosov's vortices. But the quantitative dynamics of random Josephson medium has not been studied extensively enough. The thermodynamical properties of granular superconductors were studied in many works (for example [15, 17]. Dynamical properties were studied in [18]. But the authors of this work considered the model of the Josephson contacts with large interaction radius and temperatures close to T_c. Mathematically, a model of the granular superconductor in a magnetic field is like the spin glass model. But a direct comparison of experimental results on superconductor and spin glasses and with theoretical results [19] is impossible because the magnetic moment and the magnetic field in those systems have different physical meaning.

It is known [20,21] that in high temperature superconductor the critical current obtained from magnetic measurements rapidly drops with increasing temperature. For example, at $T \approx 45k \approx T_{c/2}$ the current is by a factor of 10 smaller than at 4.2K [20]. Some authors [21] have reported exponential dependence of magnetization with temperature. Usually all parameters of superconductors tend to constant values at $T \ll T_c$, so that an origin of such a strong temperature dependence of the current in this region is not clear. Anderson [8] had shown that creep lead to decreasing of magnetization with temperature. This is due to decrease of the current

in sample during the measurement ($\sim$1min) because of the creep. For usual superconductors estimates show that this decrease is negligibly small [22] and creep very weakly affects the temperature dependence of the current. For high temperature superconductors we have different values of all the parameters and all the estimations must be repeated again. From (6), (7) we have

$$\frac{\mathcal{J} - \mathcal{J}_c}{\mathcal{J}_c} \sim r(T)\ln\omega t ,$$

Usually $\ln\omega t \sim 10\text{-}20$. For the high temperature superconductors at $T \sim 10\text{-}20K$ $r(T) \sim 0.05$ thus from the simple approximation we see that at $T \sim 10\text{-}20k$ the difference between the measured current and critical is of the order of the critical current itself. Here and above under the critical current we mean the maximal current without fluctuations. This current determines magnetization at initial moment (about 10^{-5}S). One can measure this current from current-voltage curves. In such experiments the current is determined from appearance of the threshold voltage V_c which is usually rather high what corresponds to small time interval $\sim 10^{-5}$S. Direct resistive measurements of the current are less sensitive to creep than magnetic measurements. We do not know of any resistive measurements of critical current in single crystals of high temperature superconductors (the results of measurements on polycrystals are governed by weak lings between granulas). The current measured on films (from curves I-V) has the same order of magnitude than that in single crystals and weakly depends on temperature at $T \ll T_c$. It agrees with hypothesis of strong creep, but we do not know of any results of magnetic measurements on the films. The fact that the current decreases during experiments and can be much smaller than critical does not contradict the fact that the observed change of the current is rather small, because the time dependence of the current is logarithmic. Analogous reasons for strong creep in high T_c superconductors were discussed in [23].

At creep the activation energy $E = U_m(T) \cdot E_1(J/J_c(T))$ where $E_1(J/J_c)$ at $J \to J_c$ is determined by (2). But at small currents this dependence may be different. The problem for theory is to determine current dependence of activation energy at any currents. As we have discussed above, $E(J/J_c)$ may go to infinity when $J/J_c \to 0$. If we know the dependence of energy on current from Eq.(5) we can find temperature and time dependence of the measured current. For instance

$$r = - \frac{T}{\mathcal{J}\frac{\partial E}{\partial \mathcal{J}}} = - \frac{E(\mathcal{J})}{\frac{\partial E}{\partial \mathcal{J}} \ln\omega t} . \qquad (9)$$

Assuming that at low temperatures, $T \ll T_c$, U_m and J_c are temperature independent, the temperature dependence of measured current is determined by the creep only. In this range we can connect the time and temperature dependence of measured current. Differentiating (5) over time and temperature we obtain

$$T \frac{\partial J}{\partial T} = \ln \omega t \frac{\partial J}{\partial \ln t} \quad . \tag{10}$$

In this formula all derivatives are taken at the same time. We may neglect the temperature dependence of ω in logarithm because of the large value of this logarithm itself. For the same reason it is not important whether magnetization is measured in a minute or in an hour and $\ln \omega t$ may be considered as a constant. There is only one paper in which we can find the time and temperature dependence of critical current for one and the same sample [2]. This data agrees with (10). Further investigations are necessary to estimate the role of creep in high T_c superconductors.

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