Critical current, magnetic irreversibility line and relaxation in a single Tl-O layer 1223 superconductor*

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We have carried out systematic studies on the critical current, magnetic irreversibility line and magnetic relaxation for a c-axis orientated powdered (Tl0.5Pb0.5)Sr2Ca2Cu3O9 (Tl-1223) sample. This single Tl-O layer compound, in comparison with the double Tl-O layer compound Tl2Ba2CaCu2O8+4 (Tl-2223), exhibited a high irreversibility line, less temperature and magnetic field dependent critical currents and a smaller flux creep rate. The substantially greater flux pinning ability of Tl-1223 can be understood in terms of its structural characteristics; in Tl-1223, there is only one insulating Tl-O layer between superconducting CuO2 blocks while there are two in Tl-2223. The increase in the number (and distance) of insulating layers weakens the Josephson coupling between CuO2 blocks along the c-axis and the results in a decrease in the value of Jc. This decoupling between blocks causes the vortex lattice to break into pancake-like vortices which are easily thermally activated.

Keywords: critical currents; flux creep; irreversibility

Among high Tc superconductors, the thallium based high Tc compounds are thought to be attractive for applications because they show the highest Tc. In terms of structural characteristics, the thallium based superconductors can be distinguished into two series with chemical formulae of Tl1-Ba2-Cu1-x-y(CuO2)n+4 and TlBa2CaCu2-x,CuO2n+3 (n = 1, 2, 3 and 4), in the latter, Ba can be replaced by Sr. The major distinction between these two types of superconductors is that in the former compounds the copper perovskite-like blocks containing 1, 2, 3 or 4 CuO2 planes (which are believed to be responsible for the superconductivity) are separated by two insulating Tl-O layers, while the latter have only one Tl-O layer separating the CuO2 blocks.

The Tl1-Ba2-CaCu2O10 (Tl-2223) compound, which shows the highest Tc at 125 K among high Tc superconductors, has been studied extensively. At 4.2 K Jc is high and comparable to other high Jc superconductors. However, with increasing temperature Jc drops rapidly and becomes even worse when a magnetic field is applied. This has been explained in terms of the very pronounced thermally activated flux flow or decoupling of pancake-like vortices existing in the highly anisotropic superconductors.

It has been shown recently that at 77 K (Tl,Pb)Sr2CaCu3O9 (Tl-1223) or compounds with the same structure but slightly different compositions (Tl-1223) has a much higher Jc in the presence of a magnetic field. The short separation between superconducting CuO2 blocks along the c-axis has been noticed and was believed to result in an enhancement of the CuO2 inter-block coupling, leading to the high value of Jc at 77 K. However, the previous work was carried out on multiphase and polycrystalline films or multiphase partially melted samples. Here we present a systematic study on the irreversibility line, the temperature and magnetic field dependence of Jc, and the flux creep based on the aligned monophase (Tl0.5Pb0.5)Sr2CaCu3O9 compound and compare them with the results of Tl-2223. The goal is to show that the Tl-1223 has an intrinsically good supercurrent carrying capability.

Experimental

The samples were made through a solid state reaction. For the Tl-2223 sample, the introduction of Pb in the Tl site is found to be helpful for the formation of the Tl-223 phase. In order to prevent loss of thallium at elevated temperatures, the samples were sealed in Au foil during synthesis. The sintering temperatures were 910°C and 950°C for Tl-2223 and Tl-1223, respectively.

Based on X-ray diffraction (XRD) and energy dispersive X-ray spectrometry (EDS) analyses, single phase
samples of both materials were obtained. Bar-shaped samples (1.5 x 2 x 10 mm) were cut from the sintered pellets and used for resistivity and a.c. susceptibility measurements to define $T_c$. Resistivity measurements were made using a four-probe a.c. method at 77 Hz.

In order to focus on the intrinsic intragrain properties and not to be confused by the intergrain contribution to the magnetization, the sintered bulk specimens were carefully ground into fine grains. The grains were then mixed with liquid wax and placed in a magnetic field of 6.5 T. The liquid was hardened and held grains aligned with their c-axis parallel to the field. The average grain size was around 2 and 4 μm as measured by scanning electron microscopy (SEM) for the Tl-1223 and Tl-2223 samples, respectively.

Magnetization data were taken with a vibrating sample magnetometer (VSM3001, Oxford Instruments) at different fixed temperatures. The applied magnetic fields were parallel to the c-axis in all measurements. The irreversible field $H_{irr}$ was defined as the field over which the magnetic hysteresis became undetectable. $J_c$ was determined from magnetization hysteresis loops using the Bean critical state model. The time relation (flux creep) measurements were performed at $H = 1$ T and various temperatures. Careful procedures were made to avoid overshoot of the applied field which is small but sometimes can give rise to rather confused results. The magnetization $M(t)$ was then recorded over a period of 10 to 3600 s.

Results and discussion

In Figure 1 we show the temperature dependence of the resistivity of the Tl-1223 and Tl-2223 samples. The transition is fairly sharp. $T_c$ is 115 and 118 K for Tl-1223 and Tl-2223 respectively, corresponding to zero resistances. The temperature dependence of $H_{irr}$ (irreversibility line) of Tl-1223 and Tl-2223 is shown in Figure 2. The dashed line roughly represents the upper critical field $H_{c2}$. It is clear that Tl-1223 has a much steeper irreversibility line and, therefore, a much larger irreversible region in the $H-T$ plane than does Tl-2223, although their $T_c$'s are very close. This means that the Tl-1223 material can still carry supercurrent under high temperature and magnetic field conditions and the Tl-2223 material, in contrast, can carry no current under the same conditions, so becoming useless for practical applications under these conditions. In fact the rather low irreversibility line of Tl-2223 may set very severe limits to the applications of Tl-2223 at liquid nitrogen temperature.

As mentioned previously, we determined $H_{irr}$ by choosing the field over which the magnetization hysteresis disappears. In this case the value of $H_{irr}$ might rely on the criteria that we used in the experiment and the sensitivity of the instruments. However, we found that the scatter of the experimental data had little effect on our conclusions about the Tl-1223 and Tl-2223 samples. Also for YBa$_2$Cu$_3$O$_y$ (YBCO), the result obtained on the aligned powdered sample seems in agreement with the results in the literature. The actual criterion we used was equivalent to the value of $J_c$ of 100 A cm$^{-2}$.

The difference between Tl-1223 and Tl-2223 can be understood according to their structural characteristics and the thermally activated flux flow or pancake vortex decoupling. In Tl-1223 and Tl-2223 compounds, the superconducting CuO$_2$ blocks are separated by one or two insulating Tl-O layers along the c-axis. The coupling between adjacent CuO$_2$ blocks is Josephson coupling whose strength is exponentially reduced with increasing separation distance. Thus an increase in the number (and distance) of insulating layers greatly weakens the Josephson coupling between superconducting CuO$_2$ blocks along the c-axis. When the coupling energy is comparable to $k_BT$, the CuO$_2$ blocks will be decoupled. This decoupling causes the 3D vortex lattice to break into 2D pancake vortices which are easily thermally activated or melted.

$J_c$ has been estimated from the Bean critical state model. Assuming the grains are spherical, then

$$J_c \text{ (A cm}^{-2}\text{)} = \frac{30 \Delta M d}{\rho}$$

where $\Delta M$ (emu cm$^{-3}$) is the difference in magnetization for field ramping up and down, and $d$ (cm) is the
average diameter of the grains. In Figure 3, we show the magnetic field dependence of \( J_c \) at 4.2 K and 77 K. At low temperature \( J_c \) for both samples is very similar. This is due to the enhancement of the inter-block coupling and the reduction of thermal activation energy \( k_B T \). However, on increasing the temperature to 77 K, \( J_c \) for Tl-2223 decreases quickly and becomes strongly field dependent; the Tl-1223 sample, however, still shows a large value of \( J_c \). At \( T = 77 \text{ K} \) and \( H = 1 \text{ T} \), the values of \( J_c \) for Tl-1223 and Tl-2223 samples are estimated to be \( 1.24 \times 10^5 \text{ A cm}^{-2} \) and zero, respectively. \( J_c \) for both samples roughly decreases exponentially as the temperature increases, as shown in Figure 4. It drops far more quickly for the Tl-2223 material.

The time relaxation of magnetization at 1 T and 30 K is shown in Figure 5. The equilibrium magnetization, which is the average of the magnetization for increasing and decreasing field, has been backed off. Within the period of data recording, magnetizations showed a logarithmic decay in most cases, as expected by Anderson theory. An effective pinning potential \( U_{eff} \) was obtained by using the formula

\[
M(t) = M(0)(1 - k_BT/U_{eff} \ln t)
\]

Although \( U_{eff} \) may not represent the true height of the pinning well, comparison of the results obtained under similar conditions can still be meaningful. For the Tl-1223 and Tl-2223 samples, the values of \( U_{eff} \) were 13 and 14 meV respectively at 4.2 K and 1 T. The values increased to 70 and 43 meV at 30 K and the same field. The values of \( U_{eff} \) are very close to each other for the two samples at 4.2 K. However, with increasing temperature the difference becomes significant. This seems to be consistent with the results for \( J_c \).

Conclusions

In summary, we have studied the irreversibility line, the critical current and the flux creep for a single Tl-O layer (Tl-1223) superconductor. All the results show that in comparison with the double Tl-O layer (Tl-2223) superconductor, the single Tl-O layer (Tl-1223) superconductor exhibits a higher irreversibility line, a higher \( J_c \), and a larger pinning energy at high fields and temperatures. An explanation based on the thermally activated decoupling of pancake-like vortices in different CuO2 blocks in combination with their structural characteristics has been given.

Apart from this explanation based on their intrinsic structural characteristics, the possible introduction of pinning centres by non-superconducting phases, for instance (Ca,Sr)2CuO3 and BaPbO3, has also been proposed in connection with the multiphase partially melted sample. However, since similar results have been obtained for single phase grains, it is unlikely that the non-superconducting grains can provide extra pinning centres that are substantially stronger. Additionally, the size of these impurity grains seems too large in comparison with the coherence length of the material; although they may make some contribution to the pinning it is not essential.
References