Magnetic irreversibility and zero resistance in granular Y358 superconductor

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Abstract. We report on magnetization and magnetoresistance measurements of polycrystalline $Y_3Ba_5Cu_8O_{18}$ superconductor (Y358), prepared by solid state reaction in order to study the correlation between the magnetic irreversibility line and the zero electric resistance as a function of applied field. The magnetization measurements were performed using a MPMS-XL SQUID magnetometer and the magnetoresistance measurements were made using a PPMS, both from Quantum Design, up to 1 T. The granular microstructure was confirmed by scanning electron microscopy. In this case the grain junctions are weaker than in the Y123 system and the effect of the applied field on the grain couplings is much stronger. Consequently, in our sample the zero resistance line shifts away from the irreversibility line and is lower by more than 15 K at 1 T. We explain our results in terms of the superconducting glass model and in comparison with results obtained in other materials from the YBaCuO family.

1. Introduction

The discovery of the new member of the YBaCuO-family, the $Y_3Ba_5Cu_8O_{18}$ superconducting system [1], or simply Y358, has allowed the access to new and important results about the phenomenology of the superconducting cuprates, however, there are some differences between the family members. While the $YBa_2Cu_3O_{7-\delta}$ superconducting (Y123), one of the most studied superconducting systems, has two CuO_2 planes and one CuO chain, the $Y_3Ba_5Cu_8O_{18}$ system has five CuO_2 planes and three CuO chains. This difference reflects in some important superconducting characteristics, such as the critical temperature (T_C), for example.

The Y358 has been prepared under different growth techniques, such as conventional sintering [1,2,3,4,5,6], sol-gel [7,8], biopolymer-mediated [9] and melt-texturing [10], resulting in different specimens from polycrystalline samples to superconducting nanowires [9]. Different compounds has been derived from the Y358 system, such as $Yb_{1.8}Sm_{1.2}Ba_5Cu_8O_{18}$ [11], $RE_3Ba_5Cu_8O_{18}$ (RE = Sm and Nd) [12], $Y_3Ba_5Ca_2Cu_8O_{18}$ [13], $Y_3Ba_5Cu_8O_{y-x}F_x$ [14,15] and $Y_3Ba_5Cu_{8-x}Zn_xO_{18-\delta}$ [16]. Several studies between YBaCuO-family members have been carried out in order to compare structural, magnetic and electric properties [2,5,8]. On the other hand, there are many and important aspects and fundamental properties to be investigated in the Y358 system.

In this work we have performed magnetization and magnetoresistance measurements up to 1 T in a polycrystalline $Y_3Ba_5Cu_8O_{18}$ sample to study the magnetic irreversibility line and the zero resistance state, as well as the correlation between both behaviors. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) analysis confirmed the granular microstructure and the results are explained in terms of the known models and in comparison with the Y123 system.

2. Sample preparation and characterization

Three samples of $Y_3Ba_5Cu_8O_{18}$ (Y358) were grown by solid-state reaction, starting from high purity powders (Sigma-Aldrich, 99.999%) of Y_2O_3, $BaCO_3$ and CuO. The powders were mixed in the appropriated stoichiometry ratios and reacted in air at 930 ºC for 12 h. Calcinations were repeated three times. Subsequently the powders were pressed into pellets of 10 mm in diameter and 2.5 mm of thickness under pressure. Finally the samples were sintered at 930 ºC during 24 h and annealed under oxygen flow. Previous magnetic and electric (four probe resistivity) measurements were used to verify the superconducting state of our samples. Due to the similarity between the results obtained we adopted one sample as representative of our study. The sample was cut into three pieces in order to perform the characterization and the electric and magnetic measurements.

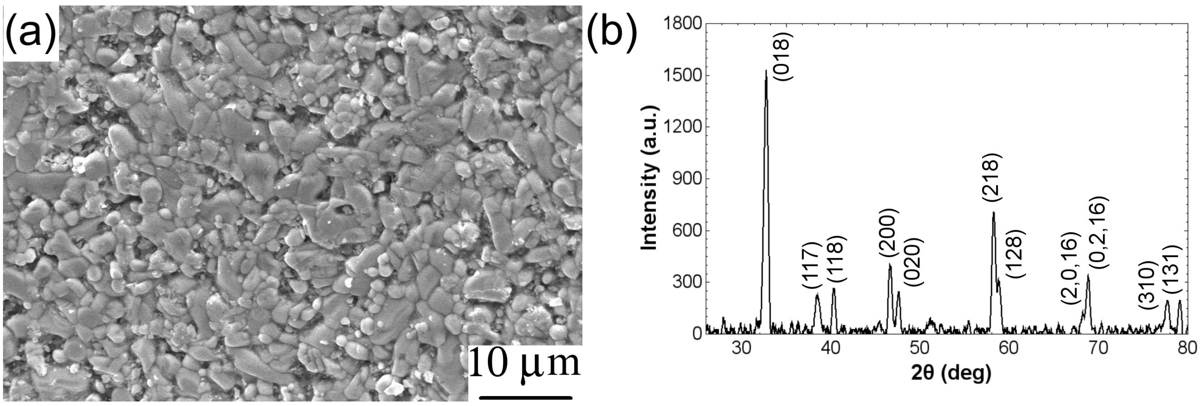

Figure 1. (a) SEM image showing the polycrystalline array with micrometric grains and (b) XRD pattern of the Y358 sample.

The characterization was made using scanning electron microscopy (JEOL JSM-6390LV microscope) and X-ray diffraction (PANalytical XPert Pro MPD diffractometer with CuKα radiation) techniques. Figure 1 shows scanning electron microscopy (SEM) image (figure a) and an XRD pattern (figure b) representative of the sample. The figure 1(a) clearly shows the polycrystalline characteristic, typical of sintered ceramic samples, with disordered grains and having an average size of few microns. The figure 1(b) shows an XRD pattern of our Y358 sample. The peaks in the diffractogram, as well as the lattice parameters obtained (*a* = *3.8878 Å*, *b* = *3.8185 Å* and *c* = *31.116 Å*), are in agreement with previous reports [1,4], and no significant impurity was found in our sample.

3. Results and discussion

Magnetization and magnetoresistance experiments as a function of temperature were performed in the Y358 sample employing magnetic fields up to 1 T. The magnetization experiments were performed in a SQUID magnetometer (SQUID MPMS-XL from Quantum Design) and consisted of the standard method for measuring the magnetic irreversibility, based on zero-field-cooled (ZFC) and field-cooled (FC) procedures [17]. The method consisted in initially cooling down our sample below the critical temperature (T_C) in zero magnetic field (ZFC). After the magnetic field was applied and the magnetization data were collected under constant field while the temperature was increasing up to values above T_C. Thereafter the FC magnetization was measured while cooling the sample back to temperature values well below T_C in the same magnetic field. The figure 2(a) shows ZFC and FC magnetization data for a magnetic field of 0.1 T. In the figure 2(a) the temperature of the bifurcation between both curves indicates the irreversibility limit T_{IRR} (H) in the given field.

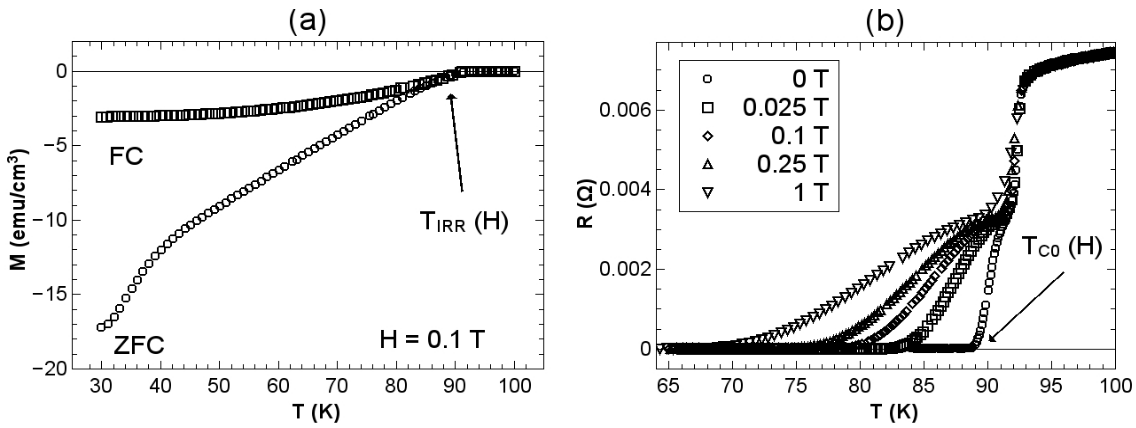

Figure 2. (a) ZFC and FC magnetization curves for H = 0.1 T showing the irreversibility limit T_{IRR} (H). (b) Magnetoresistance data measured in H = 0, 0.025, 0.1, 0.25 and 1 T. The arrow indicates the zero resistance temperature T_{C0} (H) for zero field.

The magnetoresistance experiments were made using the four-contact technique with a PPMS from Quantum Design, under magnetic fields up to 1 T and a constant measuring current of 1 mA. The figure 2(b) shows magnetoresistance results as a function of temperature for some of the magnetic fields employed. It may be observed that the magnetoresistance of our sample is strongly sensitive to the applied field. This behavior is typical of ceramic samples where superconducting granularity effects are dominant. The zero resistance temperature T_{C0} (H) was evaluated adopting a practical criterion, according to which the zero resistance temperature is obtained from the threshold of the plateau where the electric resistance falls to zero, as indicating by the arrow in the figure 2(b) for zero field.

We have determined the magnetic irreversibility limit, and the irreversibility line of our sample, for magnetic fields from 0.001 to 1 T, as shown in the figure 3(a). The continuous lines through the experimental data are fittings with Almeida-Thouless-like (AT) and Gabay-Toulouse-like (GT) [see expressions in Fig. 3a] power laws. The equation and the fitting parameters are displayed in the figure. These power laws have been largely employed to describe the irreversibility line for granular superconductors [17,18,19,20]. In the case of our sample, the results shown in figure 3(a) resemble the results obtained for pure and doped single-crystals and polycrystalline samples of $YBa_2Cu_3O_{7-\delta}$ (Y123) superconductor [17,19]. On the other hand the results shown in the figure 3(a) reveal a large regime from 0.1 T to 1 T governed by a Gabay-Toulouse power law. In the $YBa_2Cu_3O_{7-\delta}$ superconductor this power law is generally observed until magnetic fields about 0.4 T or less [17], however, similar results were found for the polycrystalline $DyBa_2Cu_3O_{7-\delta}$ system [20], where the GT power law could also be observed up to 1 T.

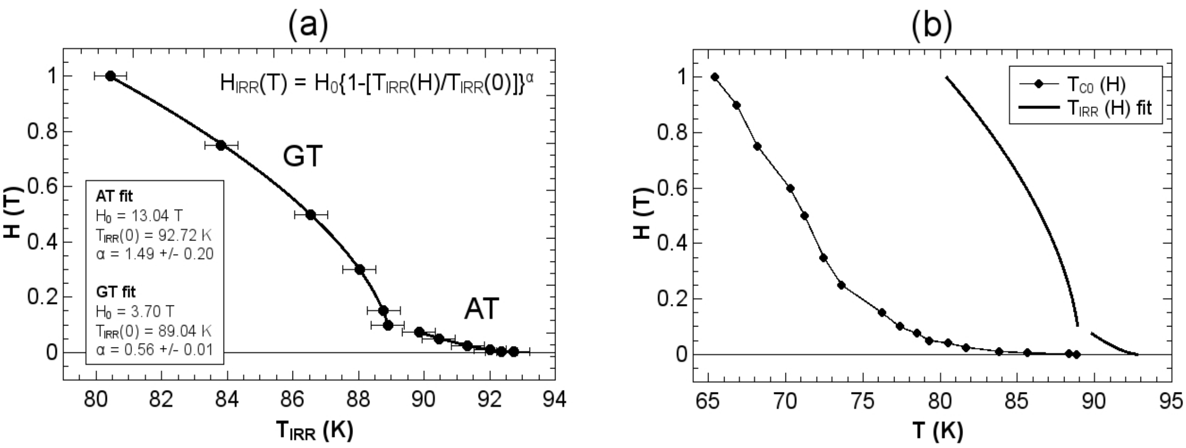

Figure 3. (a) Magnetic irreversibility data. The continuous lines are fittings with Almeida-Thouless-like (AT) and Gabay-Toulouse-like (GT) power laws. The equation and the fitting parameters are shown in the figure. (b) Zero resistance line (left) obtained from the T_{C0} (H) data together with the irreversibility line T_{IRR} (H) represented by the AT and GT fittings (right).

The figure 3(b) shows the correlation between the zero resistance line obtained from T_{C0} (H) data and the irreversibility line obtained from the T_{IRR} (H) data. In the figure the irreversibility line T_{IRR} (H) is represented by the AT and GT fittings.

The high-T_C cuprates, like the Y358 superconductor, normally are granular superconducting systems, and in this case the beginning of the magnetic irreversibility takes place when the first cluster of coupled grains is established in the sample. Consequently, the clusters of superconducting grains can retain the magnetic flux (Josephson-type), leading to magnetic irreversibility. However, the electric transport along these clusters will still be resistive because the clusters are disconnect from each other. The electric resistance falls to zero only when long-range coherence of the superconducting order parameter takes place. Therefore, in granular systems the electric resistance will be nonzero even in temperatures below the irreversibility line, vanishing only when percolation occurs and phase coherence establishes through the whole sample. The results shown in figure 3(b) clearly corroborate the aspects described above. Similar results have been found for granular Y123 samples [17], revealing the similarities between Y123 and Y358 superconducting systems.

In summary, our data show that the profiles of the magnetic irreversibility and zero resistance lines as a function of applied field of the granular Y358 superconductor, the new member of the YBaCuO-family, are similar to those of the Y123 system. However, the fact that the Gabay-Toulouse like power-law of the magnetic irreversibility limit is observed up to much higher fields than in the Y123 system apparently constitutes a significant difference between both superconducting materials. The electric resistivity shows a strong sensitivity to applied magnetic fields and is related with the considerably weaker connections between the superconducting grains in the Y358 system.

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