Transport and Magnetic J_c for MgB_2 Superconductor

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Magnetic measurements of J_c show strong dependence of J_{c0} and $J_c(H)$ on the sample size. This is due to agglomeration of crystals and bottlenecks to the current flow in MgB_2, resulting in superconducting screening on 3 different length-scales. This gives an artificial magnetic $J_c(H)$ that is still of the same order as the transport J_c. However, magnetic J_c can still be used for qualitative comparison of the samples with the same pattern of agglomeration.

1. Introduction

High-temperature superconductors exhibit a strong field dependence of critical current density (J_c) in low fields[1]. This occurs because of formation of Josephson junctions on most of the grain boundaries, which are easily decoupled by magnetic field.

Soon after discovery of superconductivity in MgB_2 [2], it was realized that there is no weak link-type behaviour in properly prepared MgB_2 bulk or wires [3]. MgB_2 has large J_c, prompting vast majority of workers to employ contact-less, magnetic measurements of J_c. The magnetic method relies on the critical state model [4], assuming that the superconducting screening currents flow only around the whole of the sample, with the characteristic screening length of the size of the sample [5].

However, magnetic J_c of MgB_2 shows a step at elevated fields [6], at about 4T at 20K. MgB_2 samples consist of agglomerates of grains of between 10 and 200μm in size. Assuming that decoupling of this agglomerates occurs at 4T and re-calculating J_c above 4T by taking the typical screening length of 200μm instead of the size of the whole sample, the sections of $J_c(H)$ for fields above and below the step seamlessly merged together. This implied there is a decoupling of grains in MgB_2 too, but unlike the case of the weak links, this decoupling occurs at elevated fields.

Further, the magnetic J_{c0} showed a strong dependence on the sample size [7]. J_c was larger for smaller samples below a characteristic field H_t, yet it was the opposite above H_t. More detailed analysis [8] revealed two inflections in the plots of $\ln(J_c)$ vs. H, one at H_t and one at a higher field, H_s. The value of H_s corresponds to the step in $J_c(H)$ reported earlier [7].

Both H_t and H_s increase logarithmically with the sample size. The values of H_t extrapolate to zero for a characteristic sample size, typically ~10μm, which is independent on the temperature [8]. On the other hand, H_s extrapolates to zero at a characteristic size of typically ~0.1μm. Therefore, the inflection at H_t does not occur for samples smaller than ~10μm. Likewise, the step in $J_c(H)$ at H_s does not occur for samples smaller than ~0.1μm. SEM and TEM examination showed that these characteristic lengths correspond to the average size of two tiers of agglomerations of crystals in the samples [8, 9]. Because the connections between agglomerates are bottleneck to the current flow around the whole of the sample, the overall superconducting current density J is the largest in the connections and is equal to J_c. However, $J < J_c$ within the agglomerates, enabling another tier of superconducting screening within the agglomerates, so that the total local J equals J_c everywhere. Each tier of the superconducting currents has a different screening length. This allows separation of the contribution of each tier of superconducting screening in the measured magnetic moment [8].

In the light of this, the question arises if magnetically obtained J_c gives a true value of J_c and can it be used at all for characterization and comparisons of different MgB_2 samples. This paper addresses this problem in direct comparisons of transport and magnetic J_c, performed on the same piece of sample for each of the comparisons.

2. Experimental Techniques

Measurements were performed on various copper- and iron-sheathed MgB_2 wires. The wires were prepared by powder-in-tube method, the details of which are given elsewhere [10]. Transport measurements were performed by a pulsed current method [11], with the peak current of 700A within the time of ~1ms. Further transport measurements were performed with a standard dc current method, for fields where J_c was small enough to avoid heating effects. Magnetic J_c was obtained by using an extraction magnetometer (Quantum Design, PPMS) and critical state model, assuming the screening around whole of the sample. Magnetic measurements were preformed on MgB_2 cores of the same wires as the transport measurements, taking care not to damage the core when the sheath was removed.

3. Results

Fig.1 shows the comparison between the transport and magnetic J_c of iron-sheathed, carbon nanotube doped MgB_2 wires at 20 K. While both measurements gave J_c of the same order of magnitude, the values of J_{c0} and the form of the field dependence of J_c are quite different. The transport J_c gives a unique curve in $\ln(J_c)$ vs. H plot, which can be described by a stretched exponential function[8]. However, magnetic J_c is quite complex, being contributed by superconducting currents with different screening lengths.

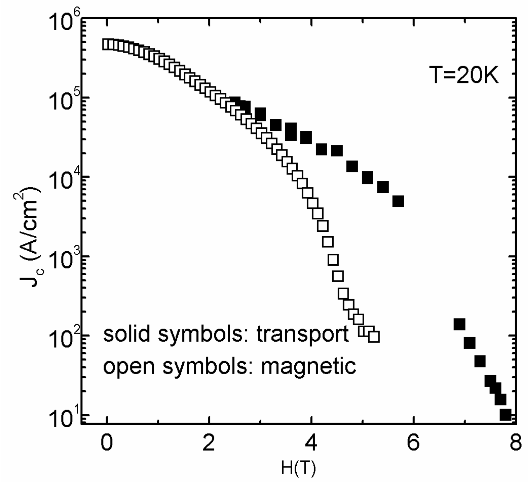

Fig.1: Transport and magnetic J_c for Fe-sheathed MgB_2 wire.

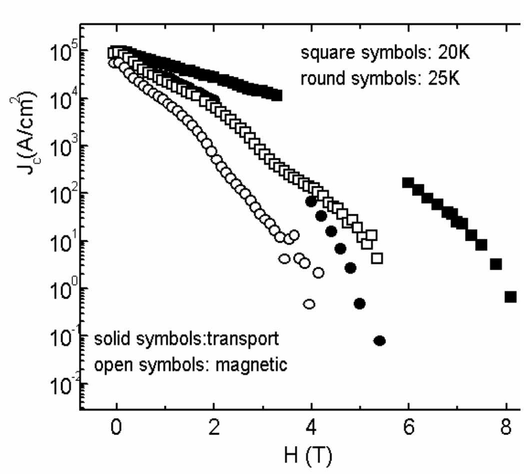

Fig.2: Transport and magnetic J_c for Cu-sheathed MgB_2 wire .

Fig. 2 shows the comparison of magnetic and transport J_c for a copper sheathed carbon nanotube doped MgB_2 wire. Transport measurements again give a unique stretched exponential function. With non-magnetic copper sheath, the peak at 2T is absent. The magnetic measurements are qualitatively the same as for iron-sheathed sample (Fig.1).

The obtained results fit well in the picture of several screening lengths in MgB_2 samples [8] . The analysis showed that the screening around the whole of the sample has a dominant contribution in magnetic moment for fields $H_t < H < H_s$. The J_c obtained from this magnetic moment should correspond to the transport Jc, which inevitably flows through whole of the sample. Indeed, transport and magnetic J_c are in the best agreement in this field range (Figs. 1 and 2). However, the form of $J_c(H)$ for the two types of measurements is still different. The transport J_c has weaker field dependence than magnetic one, even though both of them can be fitted by stretched exponential functions. The reason for this disagreement lies in the addition of the currents flowing on different length-scales to make up the measured magnetic moment. Even though the contribution of each of these screening currents in the measured magnetic moment dominates in a particular field range, the contribution of the other screening currents still cannot be neglected. Further, the distribution of each of the screening currents within the volume of agglomerates changes with the field as the currents add up within the agglomerates. This further complicates the analysis of magnetic data. In transport measurements, there are no such complications and measurements give a true value of J_c.

The above measurements strongly compromise the usefulness of magnetic J_c for MgB_2 if a detailed analysis of $J_c(H)$ is required. However, question still arises if the magnetic J_c can be used for comparative assessment of a series of MgB_2 samples. If not, a bulk of reports on the development of MgB_2 wires, based only on magnetic measurements, would be under a question mark.

Figures 3a and 3b show transport and magnetic J_c for a series of samples prepared under different conditions. Both transport and magnetic measurements give the same trend, even though the value and field dependence of J_c are different.

Therefore, magnetic J_c can still be used for comparison of a series of samples prepared under different conditions. However, these sample must have a similar structure of agglomeration, otherwise contributions of different screening lengths will be different, resulting in artificial changes in $J_c(H)$. For samples with significantly different agglomeration, magnetic measurements would be highly ambiguous.

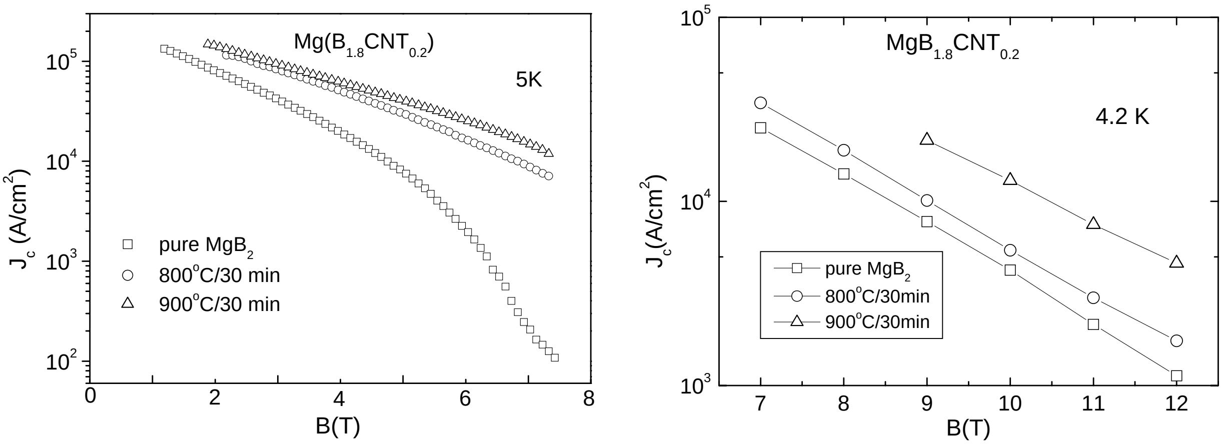

Fig.3: Magnetic (a) and transport (b) J_c for carbon-nanotube doped MgB_2 sintered at different temperatures.

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