Critical current measurements on extruded YBa$_2$Cu$_3$O$_y$ wires

M K MALIK*, V D NAIR†, R V RAGHAVAN*, P CHADDHA, P K MISHRA, G RAVI KUMAR and B A DASANNACHARYA

† Atomic Fuels Division, Nuclear Physics Division, Bhabha Atomic Research Centre, Bombay 400 085, India

MS received 9 July 1987

Abstract. The successful extrusion of short lengths of brittle wires of YBa$_2$Cu$_3$O$_y$ that are superconducting above 77 K is reported. Detailed critical current measurements are presented on wires having undergone different physical treatments. The highest critical current obtained from V–I data is \( \approx 90 \, \text{A/cm}^2 \), but this particular wire shows clear evidence of flux-pinning forces corresponding to \( \approx 150 \, \text{A/cm}^2 \).

Keywords. Superconductivity; critical current.

PACS No. 74-60

Superconductivity in YBa$_2$Cu$_3$O$_7$ is observed at temperatures around 90 K (Cava et al 1987) leading to the possibility of applications at liquid nitrogen temperatures. We have succeeded in extruding short lengths of brittle wires of YBa$_2$Cu$_3$O$_y$ that are superconducting above 77 K. The procedure is described briefly below and the details will be published later (M K Malik 1987, to be published).

The samples were prepared in bulk by heating together appropriate amounts of Y$_2$O$_3$, BaCO$_3$ and CuO powders at 900°C for a few days. The reacted mixtures were mixed with a binder, pelletised and hot-extruded using a copper sleeve. The extruded material was first swaged and then drawn into wires and the total area reduction achieved for various samples is listed in table 1. The copper-clad wires were then bared and fired in flowing O$_2$ gas at 950°C. Heat treatment (A) in table 1 corresponds to overnight annealing, while heat treatment (B) was for a longer period of time to enable better homogenisation of the wire. Resistivity measurements showed a \( T_c \) of \( \approx 86 \, \text{K} \) with a width \( \approx 1 \, \text{K} \). Powder diffraction patterns were obtained using Cu-K$_\alpha$ X-rays and confirmed that the wires were in the orthorhombic phase (Cava et al 1987).

As with our bulk samples (Malik et al 1987), critical current measurements were made using fresh silver-paint contacts. The voltage was measured using a Keithley 140 nanovoltmeter. The room temperature resistivities of various wires are given in table 1. The critical current measurements were made at 77 K in zero field and the V–I curves are shown in figure 1. We note that the data for samples I and II was quite noisy (noise \( \approx 1 \, \mu\text{V} \) ) and we attribute this to inhomogeneities causing noisy electrical contacts. The flux-flow transition is assumed to occur at the current where a measurable voltage appears, and the corresponding value of critical current density is denoted by \( J_c(V) \) and...
Figure 1. The V-I curves are shown for samples I to V. The error in voltage measurement is 1 \( \mu V \) for samples I and II and 50 nV for samples III to V. The voltage is not zero at zero current due to residual thermo-emf.

Table 1. Specifications of various samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Wire diameter (mm)</th>
<th>Heat treatment</th>
<th>Area reduction</th>
<th>( \rho_{300} ) (m( \Omega )cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>2.4</td>
<td>A</td>
<td>17:1</td>
<td>130</td>
</tr>
<tr>
<td>II</td>
<td>0.8</td>
<td>A</td>
<td>156:1</td>
<td>1.55</td>
</tr>
<tr>
<td>III</td>
<td>2.4</td>
<td>B</td>
<td>17:1</td>
<td>8.2</td>
</tr>
<tr>
<td>IV</td>
<td>0.8</td>
<td>B</td>
<td>156:1</td>
<td>4.4</td>
</tr>
<tr>
<td>V</td>
<td>0.3</td>
<td>B</td>
<td>1100:1</td>
<td>1.8</td>
</tr>
</tbody>
</table>

listed in table 2. It is clear that the prolonged heat treatment (B) has resulted in a rise in \( J_c \), and further analysis is limited to samples III, IV and V.

The critical current density for superconducting wires has previously been defined (see Sampson 1986) as the current at which the wire has an effective resistivity of \( 10^{-12} \Omega \)cm. Since the critical currents are very low for the present wire, the voltage and so the resistance corresponding to this resistivity is below our limits of detection. The
measured voltage at $J_c(V)$ corresponds to effective resistivities noted in table 2 as $\rho(J_c(V))$. We note that $\rho(J_c(V)) \approx 10^{-3} \times \rho_{300}$ (while $\rho_{\text{mean}} \approx 0.5 \times \rho_{300}$) and so the wires have not gone normal but are in the flux-flow state. We note that $\rho(J_c(V))$ thus obtained for sample IV is exceptionally low.

To investigate this further we have analysed V–I data to obtain $dV/dI$ vs $I$ using an 11-point smoothening. The resistivity obtained from $dV/dI$ is shown in figure 2 as a function of current density. The resistivity is rising sharply at $J_c(V)$ for samples III and IV, while for sample IV it is at a plateau of very low magnitude. It starts rising sharply only at $J \approx 125$ A/cm², indicating that sample IV has pinning centres corresponding to a higher critical current density than $J_c(V)$.

It is known (Sampson 1986; Ravi Kumar et al. 1986) that the quality-index $n$ of a superconducting cable or wire is obtained by fitting the V–I curve in the region of $I_c$ and above to a power law

$$V = V_0(U/I_c)^n. \quad (1)$$

In figure 3 we have plotted $\log V$ vs $\log I$ and the linear behaviour corresponding to (1) is clearly seen. The values of $n$ obtained as well as the values of $J_c(n)$ obtained (using $V_0 = 50$ nV) are listed in table 2. Sample IV clearly shows a $J_c(n) = 133$ A/cm² by this analysis.
Figure 3. log $V$ vs log $I$ is shown for samples III to V. Note the linear increase at $I \gtrsim I_c$ indicating a power-law behaviour of the voltage.
Critical current measurements on extruded $YBa_2Cu_3O_y$ wires

High accuracy $V-I$ data can also be used to directly obtain the distribution of critical currents (or of flux pinning forces). The method of Warnes and Larbalastier (1986a, b) is described briefly below. If the wire has a distribution $f(I)$ of critical currents, then the voltage at any current $I$ can, if one ignores interactions between flux-pinning centres, be written as

$$V(I) = A \int_0^I (I-I')f(I')dI'.$$  \hspace{1cm} (2)

Here $A$ depends on the details of the dissipative flux-flow in the material. From (2) we get

$$Af(I) = d^2V/dI^2$$  \hspace{1cm} (3)

and thus $f(I)$ can be obtained. It is easy to argue that $f(I)$ will always peak at a current $I^0_c$ which is above the critical current, and that the distribution will narrow as the wire becomes more homogeneous. $I^0_c$ thus provides a measure of the upper limit $J^0_c$ of the critical current density achievable by homogenisation.

In figure 4 we have plotted $d^2V/dI^2$ for samples III to V, and $J^0_c$ obtained for all samples is listed in table 2. Sample IV shows a very small peak at $I \approx 450$ mA with a major peak building up and not yet reached at $\approx 700$ mA. $d^2V/dI^2$ at $700$ mA is already more than 100 times that in the small peak. Since $d^2V/dI^2$ directly yields the
distribution of flux-pinning forces, it is clear that less than 1% of the sample has pinning forces corresponding to \( J_c \approx 90 \text{ A/cm}^2 \). The bulk of the pinning centres corresponds to \( J_c \approx 130 \text{ A/cm}^2 \) and such a current density appears achievable with the fabrication route followed for sample IV.

In conclusion, we have achieved a critical current density (at 77K and in zero field) of 90 A/cm\(^2\) in extruded \( \text{YBa}_2\text{Cu}_3\text{O}_y \) wires. The wires are brittle and short. They have to be made flexible and lengths can then be increased and efforts are underway to modify the fabrication route for this purpose, as well as for further increasing \( J_c \).

References


Sampson W B 1986 Proc. of Workshop on Superconducting Magnets and Cryogenics, Brookhaven National Laboratory, p. 153

Warnes W H and Larbalastier D C 1986a Appl. Phys. Lett. 48 1403

Warnes W H and Larbalastier D C 1986b Cryogenics 26 643