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Critical current measurements on extruded $YBa_2Cu_3O_y$ wires

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Abstract. The successful extrusion of short lengths of brittle wires of $YBa_2Cu_3O_y$ 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 $\simeq 90$ A/cm^2, but this particular wire shows clear evidence of flux-pinning forces corresponding to $\simeq 130$ A/cm^2.

Keywords. Superconductivity; critical current.

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Superconductivity in $YBa_2Cu_3O_7$ 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 $YBa_2Cu_3O_y$ 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_2O_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 $\simeq 86$ K with a width $\simeq 1$ K. Powder diffraction patterns were obtained using Cu-K_α 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 $\simeq 1$ μV) 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

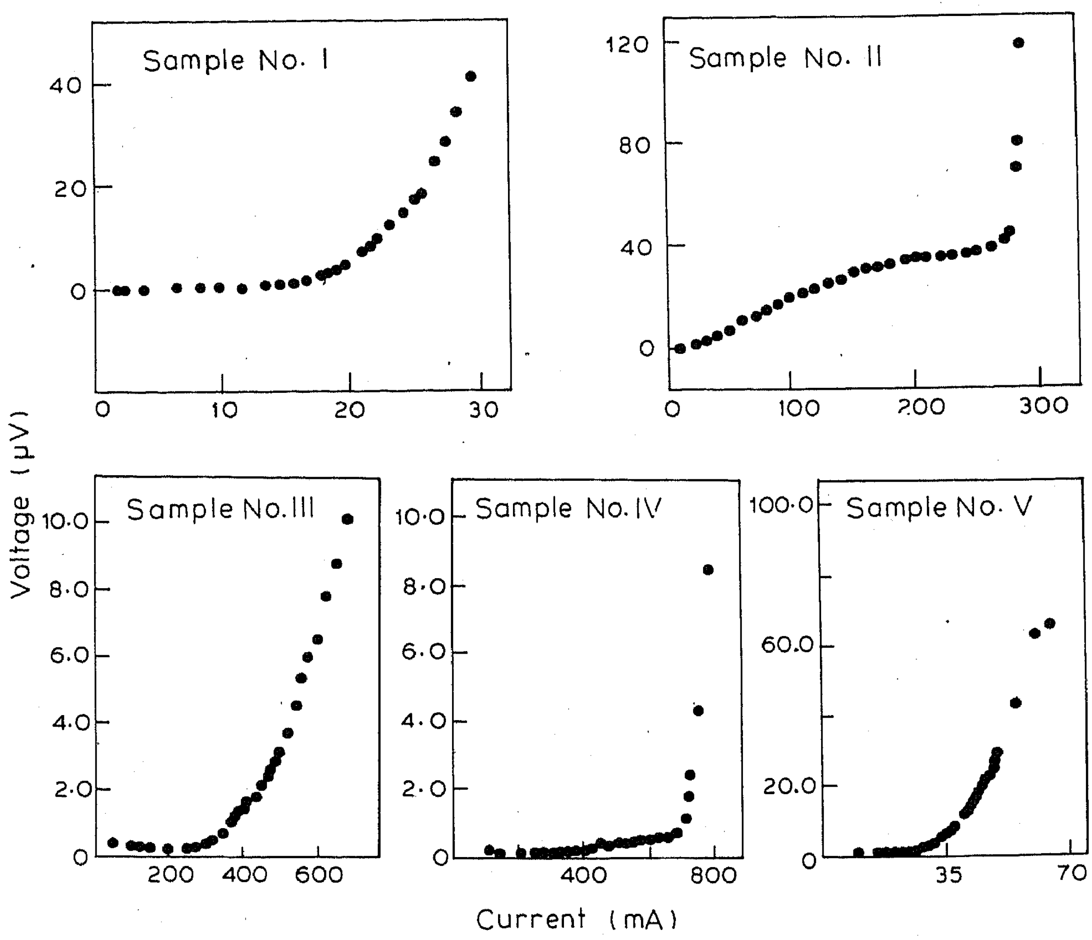

Figure 1. The V–I curves are shown for samples I to V. The error in voltage measurement is 1 μV for samples I and II and 50 nV for samples III to V. The voltage is not zero at zero current due to residual thermo-emf.

Table 1. Specifications of various samples.

Sample	Wire diameter (mm)	Heat treatment	Area reduction	ρ_{300} (mΩcm)
I	2·4	A	17:1	130
II	0·8	A	156:1	1·55
III	2·4	B	17:1	8·2
IV	0·8	B	156:1	4·4
V	0·3	B	1100:1	1·8

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} Ω 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

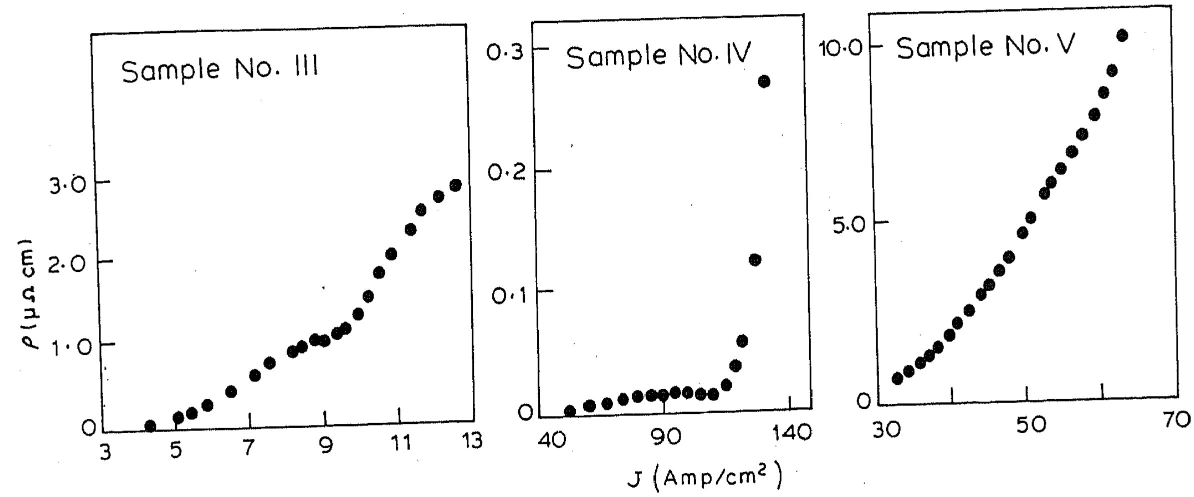

Figure 2. dV/dI is used to obtain the resistivity as a function of current density for samples III to V.

Table 2. Results obtained from the V–I measurements at 77 K and zero field.

Sample	ρ_{300} ($\mu\Omega$cm)	$J_c(V)$ (A/cm^2)	$\rho_{77}(J_c(V))$ ($\mu\Omega$cm)	$J_c(n)$ (A/cm^2)	J_c^0 (A/cm^2)	n
I	1.3×10^5	0·3	—	—	—	—
II	1550	4·0	—	—	—	—
III	8200	6·2	0·03	7.2	11	2·7
IV	4400	90·0	0·004	133·5	>135	19·4
V	1800	32·0	0·02	31	45	4·5

measured voltage at $J_c(V)$ corresponds to effective resistivities noted in table 2 as $\rho(J_c(V))$. We note that $\rho(J_c(V))$ is $\approx 10^{-5}\times\rho_{300}$ (while $\rho_{onset}\approx 0{\cdot}5\times\rho_{300}$) 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 V, while for sample IV it is at a plateau of very low magnitude. It starts rising sharply only at $J\simeq 125$ A/cm^2, 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

$$V=V_0(I/I_c)^n. \tag{1}$$

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/cm^2 by this analysis.

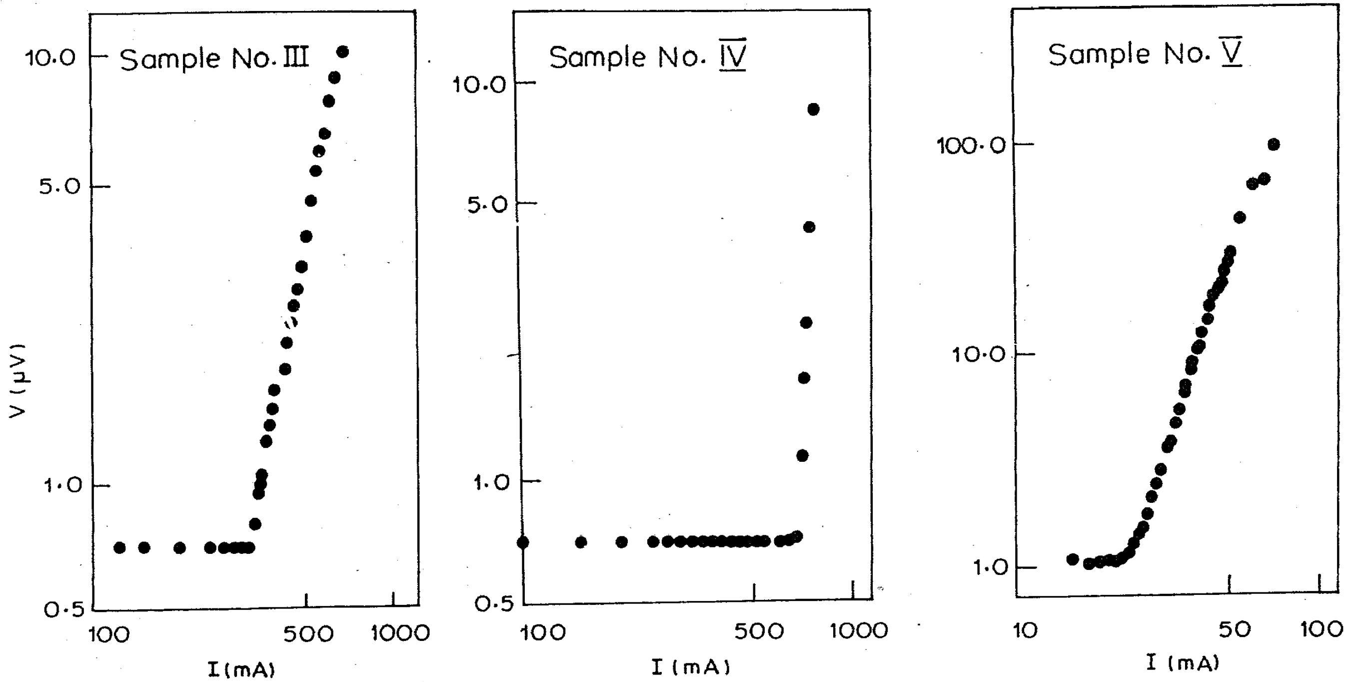

Figure 3. log V vs log I is shown for samples III to V. Note the linear increase at $I \gtrsim I_c$ indicating a power-law behaviour of the voltage.

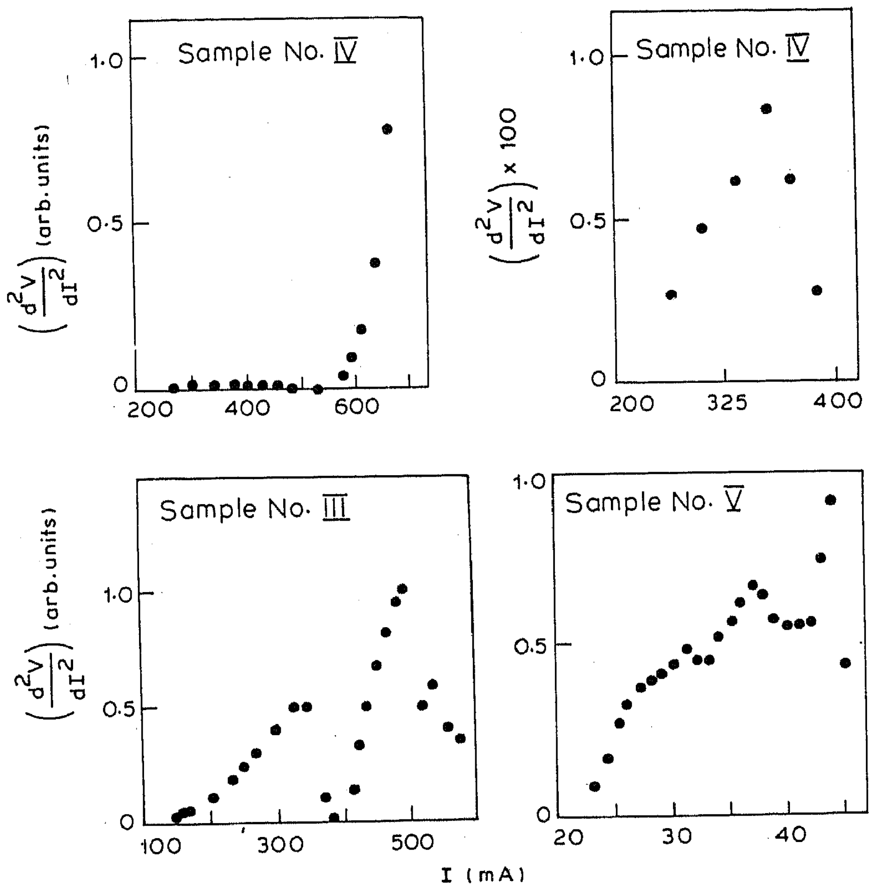

Figure 4. d^2V/dI^2 is shown for samples III and IV. There is a small peak in sample IV near 400 mA which is shown on the magnified scale.

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

$$V(I) = A\int_0^I (I-I')f(I')\,dI'. \tag{2}$$

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

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

and thus $f(I)$ can be obtained. It is easy to argue that $f(I)$ will always peak at a current I_c^0 which is above the critical current, and that the distribution will narrow as the wire becomes more homogeneous. I_c^0 thus provides a measure of the upper limit J_c^0 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_c^0 obtained for all samples is listed in table 2. Sample IV shows a very small peak at $I \simeq 450$ mA with a major peak building up and not yet reached at ≈ 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 $J_c \simeq 90$ A/cm^2. The bulk of the pinning centres corresponds to $J_c \simeq 130$ 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 $YBa_2Cu_3O_y$ 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.

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