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Critical current density of $\text{Bi}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_8$ monocore and multifilamentary wires from 4.2 K up to T_c in high magnetic fields

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Abstract

The transport critical current density (J_c) of a mono, 19 and 37 filament $\text{Bi}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_8$ wire has been measured in high fields at temperatures of 4.2 K up to 80 K. Measurements were made with the field applied parallel and perpendicular to the wire axis. The low-temperature high-field J_c values for the 19 and 37 filament wires are similar and markedly higher than the monocore wire.

The data have been analyzed in terms of pinning-force functions and an exponential field function. In low fields, below 40 K, the volume pinning force is given by a power law of the form $F_p \propto B^{3/4}$. In high fields, the functional form is given by $J_c(B, T) = \alpha(T) \exp[-B/\beta(T)]$. The parameters $\alpha(T)$ and $\beta(T)$ are measured for the three wires and compared with those of a monocore $\text{Bi}_{2-x}\text{Pb}_x\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_8$ silver-sheathed tape.

1. Introduction

For high-current and high-field applications the Bi based cuprates are still the most promising family of high-temperature superconductors. The $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_8$ (Bi-2223) phase has the highest critical current density (J_c) with the best field dependence at high temperatures. Fabrication of this phase in silver-sheathed wires, however, is difficult. The precursor powder must be off-stoichiometric and a series of accurately controlled thermomechanical treat-

ments (including rolling or pressing into tape form) are required to obtain good results. When upgraded to batch production on an industrial scale this approach is expensive and time consuming. The $\text{Bi}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_8$ (Bi-2212) phase is cheaper and simpler to make in wire form. The precursor powder is pure 2212-phase and only a single heat treatment is required. In addition, since rolling is not required, the wire can be fabricated with a circular cross-section which is preferred for applications which require coil-winding such as high-field magnets. For these reasons, further work on optimising the properties of multifilamentary Bi-2212 wires is warranted. This paper presents a study of the transport J_c as a function of field and temperature in monocore and multifilamentary Bi-2212 wires.

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The next section describes the three wires which were measured. Section 3 gives brief experimental details and Section 4 presents the J_c data. Then the data are analyzed and discussed in terms of a pinning-force model and an exponential description. The variation of J_c with the number of filaments and field orientation is investigated and comparisons are made with other Bi based conductors.

2. Fabrication

The $\text{Bi}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_8$ wires were made by the standard powder-in-tube method. Pure silver tubes packed with the precursor powder were drawn down to about 1 mm diameter for monocoil wires. For multifilamentary wires they were drawn down to 2–4 mm, bundled into a larger tube and drawn again down to 1 mm. For details of the heat treatments see Tenbrink and Krauth [1].

3. Experimental procedure

The wires were measured at temperatures of 4.2 K, 20 K, 40 K, 60 K and 80 K in applied fields up to 15 T with the Durham $J_c(B, T)$ probe [2]. Each sample was a 10–12 mm straight section cut from a wire of 10 cm length and the voltage taps

Table 1

Sample dimensions and critical currents of the Bi-2212 wires. I_c at 4.2 K was measured with a $1.5 \mu\text{V cm}^{-1}$ criterion in a magnetic field of 10 T parallel and perpendicular to the wire axis

Type of wire	Wire diameter (mm)	Fraction of superconducting area	$I_c(4.2 \text{ K}, 10 \text{ T})$ $B \parallel I / B \perp I$ (A)
Monocoil	1.04	59%	25.3/18.7
19 Filament	1.04	34%	46.0/21.8
37 Filament	1.04	34%	47.0/33.2

were soldered from 1.5–2.5 mm apart using indium solder. Measurements of each wire were taken for two orientations of the magnetic field: parallel to the wire axis and hence also to the macroscopic transport current, and perpendicular to the axis of the wire. After each change of orientation the critical current of the wire was measured in liquid nitrogen but no variation was found for any of the samples demonstrating that no damage occurred in the course of these measurements. A $1.5 \mu\text{V cm}^{-1}$ criterion was used to calculate J_c from the E - J characteristics.

4. Experimental results

Three different wires were measured: one monocoil; one with 19 filaments and one with 37 filaments. Table 1 lists the wire diameter, fraction of the

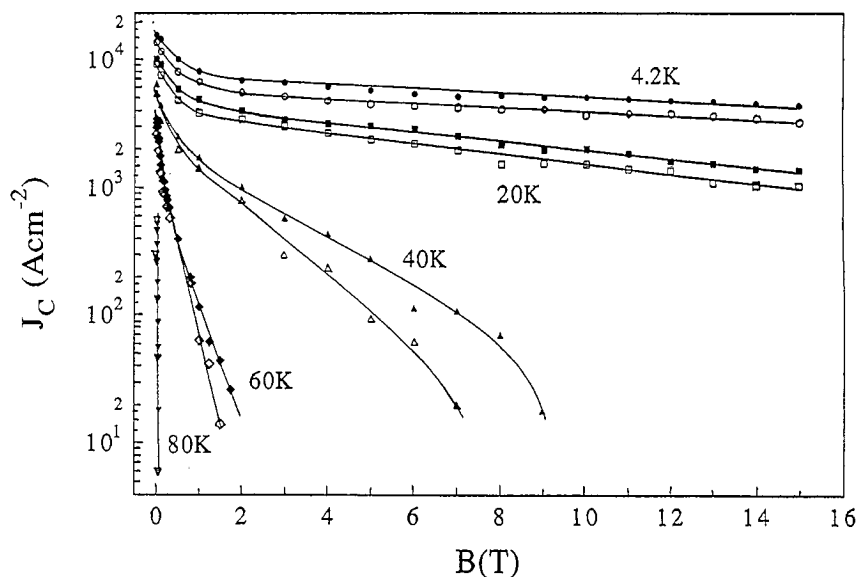


Fig. 1. $J_c(B, T)$ of the monocoil Bi-2212 wire with the field parallel (closed symbols) and perpendicular (open symbols) to the wire axis.

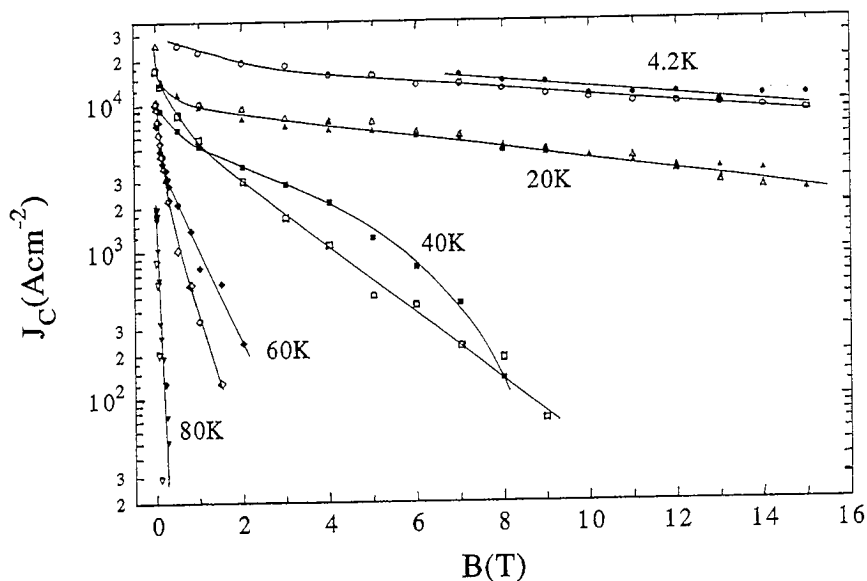


Fig. 2. $J_c(B, T)$ for the 19 filament wire (open symbols) and 37 filament wire (closed symbols) for the perpendicular field orientation.

cross-sectional area that is superconducting material and the critical current at 4.2 K in a field of 10 T for the two orientations for each wire.

Fig. 1 presents J_c for the monowire in the perpendicular and parallel orientation. The values of J_c shown are calculated using the cross-sectional

area of the superconductor. Figs. 2 and 3 show the equivalent data for the 19 filament and 37 filament wires. In Fig. 2, J_c is plotted for the two multifilamentary wires in the perpendicular orientation. Fig. 3 shows the data for the corresponding parallel orientation. In Fig. 4, J_c for the 19 filament wire at 4.2 K is

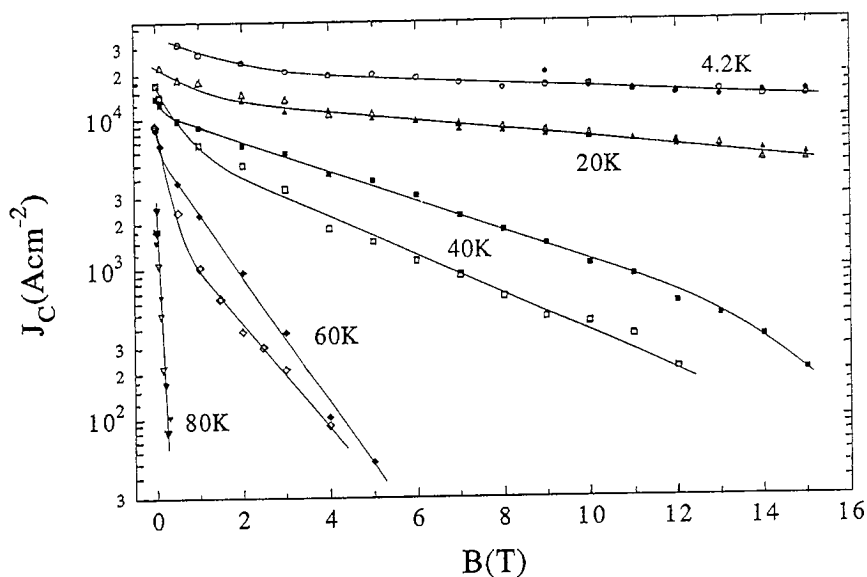


Fig. 3. $J_c(B, T)$ for the 19 filament wire (open symbols) and 37 filament wire (closed symbols) for the parallel field orientation.

plotted for an increasing and decreasing applied field. J_c is hysteretic only below 4 T at 4.2 K.

5. Analysis of the data

5.1. J_c in terms of the pinning force

5.1.1. Low field ($1 \text{ mT} < B < 1 \text{ T}$)

The bulk volume pinning force (F_p) of the 19 filament wire, is plotted for both orientations of the magnetic field in Fig. 5. F_p is higher for the parallel orientation at all temperatures than the perpendicular orientation. The peak in F_p shifts to lower fields very quickly with increasing temperature above 20 K though it is at a higher field for the parallel orientation. The pinning-force characteristics are similar for the other two wires, which are not shown. To within the accuracy of the measurements, for all the wires at temperatures at and below 40 K in magnetic fields from 1 mT to 1 T, we have

$$F_p \propto B^{3/4}. \quad (1)$$

5.1.2. High field ($B > 1 \text{ T}$)

The J_c data have also been fitted to the Kramer model [3] for the 19 filament wire in Fig. 6. The

Kramer plots for the other wires show broadly the same features. Kramer's model predicts that $J_c^{1/2} B^{1/4}$ should vary linearly with B with a negative slope. Although the Kramer plots in Fig. 6 are straight lines, at low temperatures the lines have positive, unphysical slopes.

5.2. An exponential field description of J_c for $B > 1 \text{ T}$

As an alternative to the pinning-force description, J_c can be described by an exponential function. In Figs. 1–3 it can be seen that the field dependence of J_c is similar for each wire at all temperatures and orientations: at low fields ($< 1 \text{ T}$), J_c decreases quickly. At higher fields the rate of decrease slows and the field dependence becomes exponential (although an exception to this behaviour is at 40 K for the 37 filament wire where J_c decreases more rapidly than the exponential function above 4 T/10 T for the perpendicular/parallel orientations). The J_c data above 1 T have been fitted to an exponential function of the form

$$J_c(B, T) = \alpha(T) \exp[-B/\beta(T)]. \quad (2)$$

The parameters $\alpha(T)$ and $\beta(T)$ are plotted in Figs. 7 and 8 for each wire and field orientation. Also

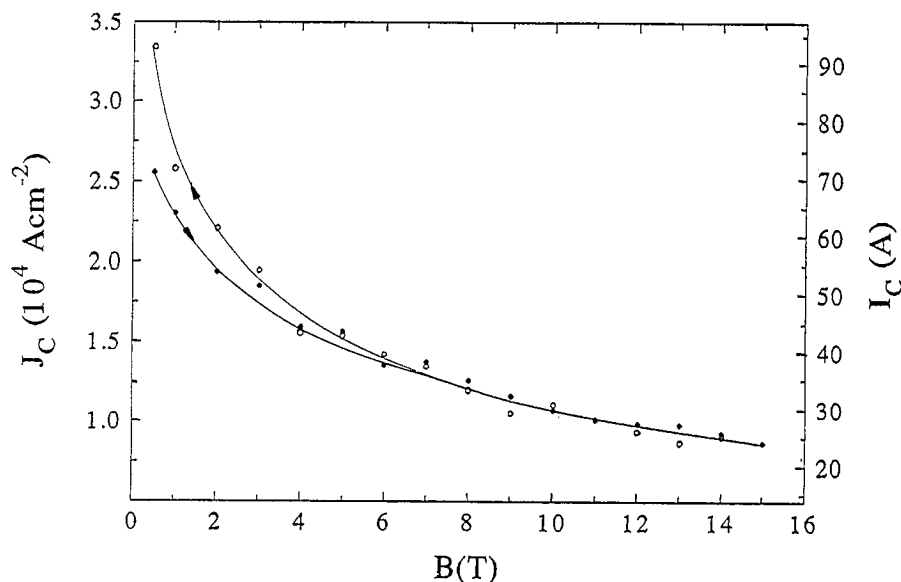


Fig. 4. $J_c(B, T)$ for the 19 filament Bi-2212 wire at 4.2 K in increasing (closed circles) and decreasing fields (open circles).

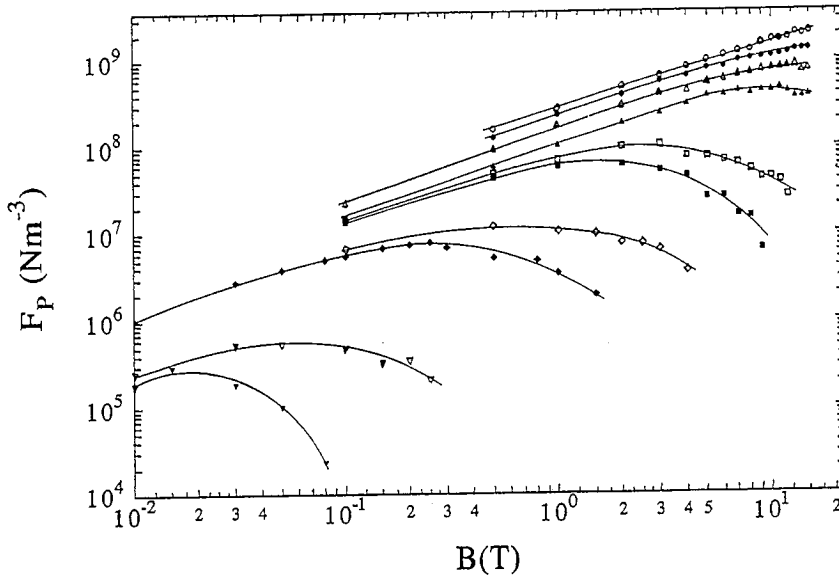


Fig. 5. The bulk pinning force for the 19 filament wire. The open symbols refer to the parallel orientation and the corresponding closed symbols to the perpendicular orientation; (○), 4.2 K, (△) 20 K, (□) 40 K, (◇) 60 K, (▽) 80 K.

plotted in these two figures are the parameters $\alpha(T)$ and $\beta(T)$ for two orientations of a monocoire $\text{Bi}_{2-x}\text{Pb}_x\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_8$ silver-sheathed tape measured at Durham [4]. Because of the small number of

data points for the Bi-2212 wires it is not possible to draw smooth curves for each wire, but the following trends can be observed:

- (1) $\alpha(T)$ for the multifilamentary wires is about a

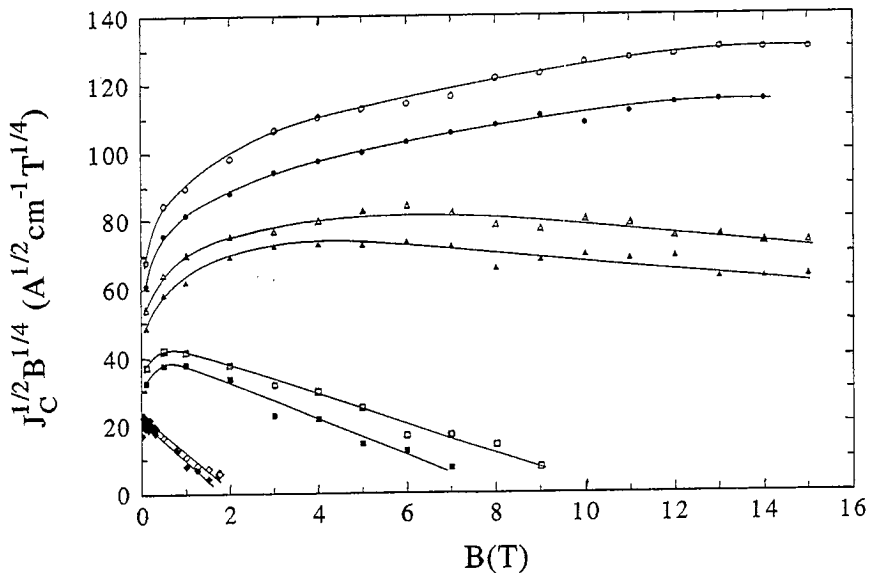


Fig. 6. A Kramer plot for the 19 filament wire. The open symbols refer to the parallel orientation and the corresponding closed symbols to the perpendicular orientation; (○), 4.2 K, (△) 20 K, (□) 40 K, (◇) 60 K, (▽) 80 K.

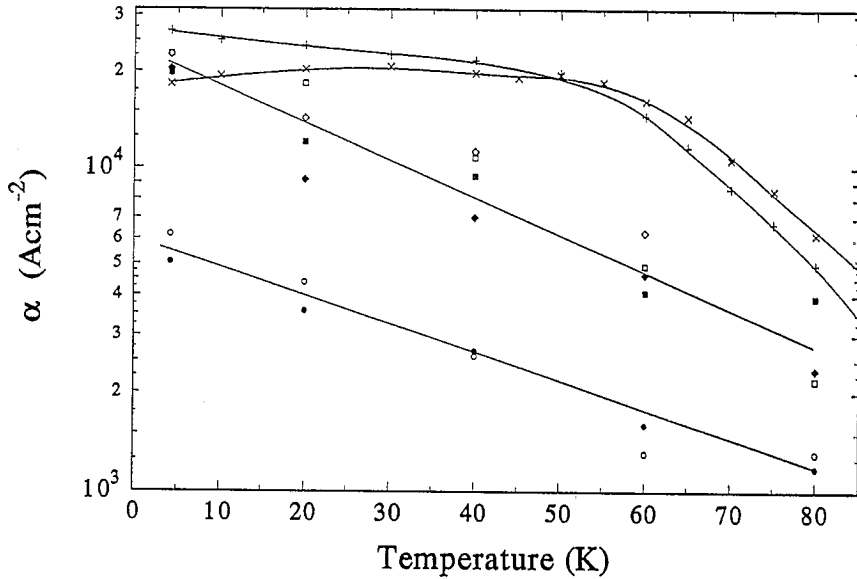


Fig. 7. The parameter $\alpha(T)$ for the (●, ○) monocore, (■, □) 19 filament, (◆, ◇) 37 filament wire. Closed symbols signify a perpendicular field, open symbols signify a parallel field. Also included is $\alpha(T)$ for a Bi-2223 tape in a field parallel (+) and perpendicular (×) to the tape surface.

factor of 3 greater than that of the monocore wire. $\alpha(T)$ is typically 20% higher for the parallel orientation at each temperature than for the perpendicular orientation.

(2) $\alpha(T)$ for the wires has a different temperature dependence to the Bi-2223 tape for both orientations. It is similar at the lowest and highest temperatures but is considerably lower in the range 30–60 K.

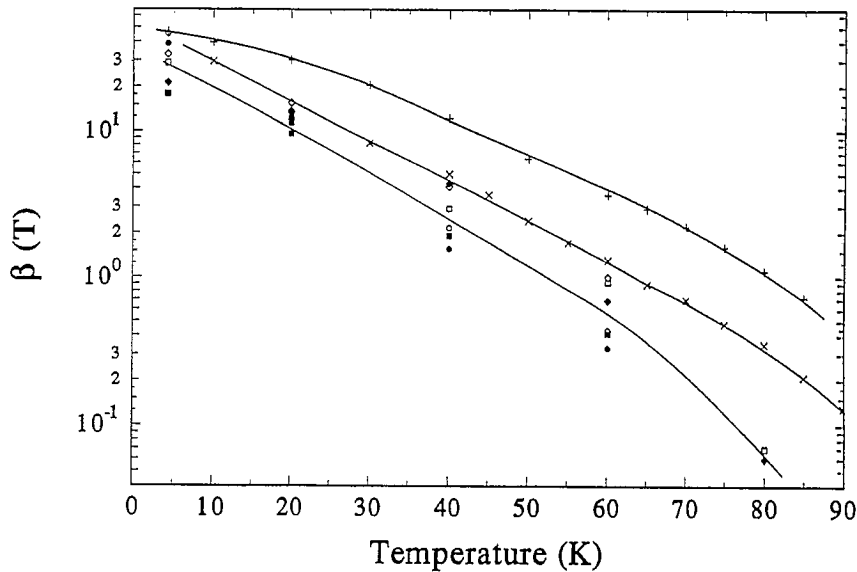


Fig. 8. $\text{Log}_{10} \beta(T)$ as a function of temperature for the (●, ○) monocore, (■, □) 19 filament, (◆, ◇) 37 filament wire. Closed symbols signify a perpendicular field, open symbols signify a parallel field. Also included is $\text{Log}_{10} \beta(T)$ for a Bi-2223 tape in a parallel (+) and perpendicular (×) field.

Table 2

Some values of the transport critical current density of the Bi-2212 wires and the Bi-2223 tape. BPAB refers to the tape orientation where the field is parallel to the tape surface and BPC refers to the field being perpendicular to the tape. In both cases the field is perpendicular to the macroscopic transport current

Sample	$J_c(4.2 \text{ K}, 10 \text{ T})$ 10^3 A cm^{-2}	$J_c(60 \text{ K}, \text{ self field})$ 10^3 A cm^{-2}	$J_c(60 \text{ K}, 1 \text{ T})$ 10^3 A cm^{-2}
2212- monocore	3.7	2.6	0.063
2212-19 filament	11	10	0.34
2212-37 filament	11	7.3	0.79
2223-tape, BPAB	21	21	11
2223-tape, BPC	17d	24	7.5

(3) $\beta(T)$ for the wires is generally largest for the parallel orientation. $\beta(T)$ for the wire is close to that of the 2223 tape for the orientation when the field is perpendicular to the tape. At all temperatures with the field parallel to the surface, the Bi-2223 tape clearly has the highest $\beta(T)$.

6. Discussion

6.1. The magnitude of J_c

Table 2 lists some values of J_c for the wires and for comparison includes equivalent data for the monocore Bi-2223 tape. Heine et al. [5] and Tenbrink et al. [6] have also measured the J_c of similar monocore and multifilamentary wires. They found maximum values of J_c of $5.5 \times 10^4 \text{ A cm}^{-2}$ at 4.2 K in self-field [6] and $1.6 \times 10^4 \text{ A cm}^{-2}$ at 4.2 K and 9 T [7] with a scatter in J_c for nominally identical wires that is consistent with the data in this work. At 4.2 K in self field, Sumption et al. [7] measure values from 10^4 up to 10^5 A cm^{-2} for 259 filamentary wires with decreasing filament size and Wesche et al. [8] find $9 \times 10^4 \text{ A cm}^{-2}$ in a monocore wire of diameter 1.0 mm. Löhle et al. [9] quote a zero-field value of $1.4 \times 10^4 \text{ A cm}^{-2}$ at 4.2 K for a 2 m length of 19 filament 2212 wire. Hence the values of J_c for our wires are typical of optimised conductors although this is two orders of magnitude lower than

the best values found in epitaxial Bi-2212 films [10]. Comparing J_c for the wires with the Bi-2223 tape at 4.2 K and 10 T, J_c is about a factor of two lower. For both wires and tape, J_c at 60 K in the self-field has similar values to that at 4.2 K and 10 T. However, increasing the field to just 1 T at 60 K reduces J_c for the wires by a factor of 20 compared to less than 2 for both orientations of the tape.

Multifilamentary 2212 wires then, are only suitable for applications at 4.2 K or possibly 20 K but exhibit excellent field dependences at these temperatures. By extrapolating the $J_c(B)$ curve for the 19 filament wire at 4.2 K and in the perpendicular orientation, a value of 10^4 A cm^{-2} is expected up to at least 25 T.

6.2. The pinning-force description of J_c

Löhle et al. [11] have calculated the volume pinning force for their multifilamentary 2212 wires and found a $B^{3/4}$ dependence at 4.2 K, similar to the wires here. As in Fig. 5, when the temperature was increased above 20 K, Löhle et al. found that the peak in the pinning force quickly moved to lower fields. The magnitudes of their pinning force were a factor of two less for the monocore and at least six less for the multifilamentary wires than for the wires measured here. However, there is no adequate theoretical explanation for the data – although F_p is of the form of a universal scaling law, the index of $3/4$ in Eq. (1) is not predicted by any standard pinning model.

Rose et al. [12] have measured J_c of bulk polycrystalline Bi-2212 and found that their data fitted the Kramer dependence at 6 K and above. By comparison, the data of figure 6 is only consistent with Kramer's model at 20 K and above. Since at low temperatures the Kramer model provides non-physical results, this suggests that the Kramer dependence may only provide a useful high-field high-temperature parameterisation rather than a physical insight into the mechanism limiting J_c . Indeed it is questionable if the functional form derived by Kramer is valid for the mechanism he postulated [13]. The combination of Eq. (1) and Kramer's model does not provide a comprehensive description of J_c for the 2212 wires. The crossover from the power law of

Eq. (1) to the Kramer model is not distinct. At high temperatures the low-field data are not accurately described by either pinning model.

6.3. The exponential field description of J_c

The high-field J_c characteristics for the Bi-2212 wires have the familiar exponential field dependence, as exhibited by most bulk and thin-film HTSC materials [14–16]. Much published work can provide the exponential field dependence, including a modified Josephson junction model [17], collective pinning [18], a railway-switch model [19] and S–N–S pair breaking [20]. However, there are sufficient number of free parameters in these models that at present there is no consensus on which mechanism determines J_c .

The dependence of J_c on the orientation of the magnetic field is similar for all three wires we have investigated. Except at the highest temperatures and fields where J_c is less than $5 \times 10^2 \text{ A cm}^{-2}$, the ratio of J_c in the two orientations is typically 1–2.

6.4. Increase of $J_c(B)$ with number of filaments

There is strong evidence that in Bi-2223 tapes, J_c is highest at the silver interface where highly textured Bi-2223 occurs [21]. Wesche et al. [9] find texturing can also occur in Bi-2212 since SEM micrographs of monocoil wires show interfacial regions with a high granular alignment extending 10–20 μm radially into the core centre. There is also indirect evidence supporting this result: J_c increases in some Bi-2212 conductors as the number of filaments increases. Sumption et al. [8] and Wesche et al. [9] both observe an increase in the transport J_c as the filament diameter is reduced, in multifilamentary and monocoil wires, respectively. Tenbrink et al. [4] found the magnetically determined J_c of a 49 filament 2212 wire was up to seven times larger than for a monocoil wire which was attributed to the increase in textured material because of the larger area of 2212–Ag interface in the multifilamentary wires.

From Table 1 and complementary micrographs (not shown), the ratio of material at the Ag–2212 interface for the monocoil, 19 and 37 multifilamentary wires is approximately 1:3.2:4.7 respectively. The values of $\alpha(T)$ for the multifilamentary wires

are larger than the monocoil wire in Fig. 7 and demonstrate an initial improvement in J_c . However, at low temperatures, the 37 filament wire is not markedly better than the 19 filament wire although the Ag–superconductor interfacial area is approximately 30% higher. Similarly at temperatures above 40 K, there is no clear difference between the wires; indeed a low-field–high-field crossover is observed. In fields below 1 T, J_c for the 19 filament wire is higher than for the 37 filament wire for both orientations. Above 1 T, however, this behaviour is reversed and the 37 filament wire has the higher J_c at a fixed field. These results suggest that in both multifilamentary wires either J_c is a bulk property determined by macroscopically isotropic material or the fraction of highly textured material at the Ag interface is the same.

Figs. 7 and 8 show that the values of $\alpha(T)$ and $\beta(T)$ at low temperatures for the multifilamentary Bi-2212 wires are only a factor of two different from the Bi-2223 tape, although at higher temperatures the Bi-2223 tapes have markedly higher J_c values in high fields. The very high values of J_c that have been reported at the Bi-2212 and Bi-2223 Ag–superconductor interface suggest that significantly higher J_c values can be achieved if better texturing is achieved. Hence the technological choice of material for low-temperature high-field applications will be determined by both the electromagnetic properties and the thermomechanical properties.

7. Conclusion

The transport critical current density of three Bi-2212 multifilamentary wires (monocoil, 19 filaments and 37 filaments) has been measured in high magnetic fields and at temperatures from 4.2 K to 80 K with the field applied parallel and perpendicular to the wire axes. From the data the following observations and conclusions have been drawn:

- (1) In low fields, below 40 K, F_p is described by a power law of the form $F_p \propto B^{3/4}$.
- (2) In high fields, the functional form is given by $J_c(B, T) = \alpha(T) \exp[-B/\beta(T)]$.
- (3) The multifilamentary wires have a significantly higher J_c than a similarly fabricated monocoil wire. However, increasing the number of filaments from

19 to 37 produced no significant improvement in the low-temperature high-field properties of these wires.

At temperatures of 4.2 K and 20 K both Bi-2212 and Bi-2223 have great potential for use in high-field applications. There is growing evidence that the magnitude of J_c for these wires is primarily determined by a textured region near the superconductor/silver interface of each filament. It is expected that increasing J_c further will be achieved by improving the texturing of the superconductor in these conductors.

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