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Effect of magnetic field, thermal cycling and bending strain on critical current density of multifilamentary Bi-2223/Ag tape and fabrication of a pancake coil

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Abstract. Multifilamentary HTSC tapes are important for their applications in various electrical devices. Powder-in-tube technique with improved optimized synthesis parameters is regarded as one of the most promising ways to prepare long-length multifilamentary Bi-2223/Ag tapes. Nevertheless, usefulness of such tapes depends on their electrical and mechanical properties. Critical current density of a Bi-2223/Ag tape with 37 filaments has been studied at 77 K with field, field orientation, thermal cycling and bending strain as parameters. Results have been discussed in light of various mechanisms and models. A small pancake coil has been fabricated out of the same tape and the test results presented.

Keywords. Multifilamentary Bi-2223/Ag tape; powder-in-tube technique; critical current density; thermal cycling; bending strain; pancake coil.

1. Introduction

Critical current density of superconductors is one of the most important properties which decides its potential for numerous electrical engineering applications. Salama *et al* (1992) reviewed different processes which are useful for synthesizing HTSC tapes with highly-textured microstructure and the ability to carry high current density. Efforts are now being made to prepare long-length mono and multifilamentary tapes of Bi-2223 superconductors, using various techniques. Of these dip coat technique (Tomita *et al* 1996a), multilayer tape by continuous heat treatment (Hasegawa *et al* 1995), sequential processing (Ashworth *et al* 1995) and powder-in-tube process (Rosner *et al* 1992; Shukla *et al* 1992; Hautanen *et al* 1993; Gubser *et al* 1995; Minot *et al* 1995) appear to be promising. Superconducting and mechanical properties of high T_c superconductors are now known to be greatly improved when silver is used as the material to make the oxide–metal composite (Dou *et al* 1995). Apart from being a relatively simple technique, the powder-in-tube process is regarded as an attractive route for producing Bi-2212 and Bi-2223 multifilamentary tapes with the c-axis oriented microstructure leading to high J_c values. However, factors such as densification, grain alignment, heat treatment, grain growth, microstructural defects and phase assemblage play a significant role for the improvement in J_c of Ag-cladded Bi-based superconducting tapes (Dou and Liu 1993).

In the present paper, we report our results on the influence of magnetic field and field orientation on the critical current density (J_c) of multifilamentary (37 filaments) Bi-2223/Ag tape, which has been produced by powder-in-tube technique. The tape was also evaluated for critical current degradation due to thermal cycling and bending

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strain. The characteristics of a small pancake coil fabricated from the same tape are also presented.

2. Experimental

The silver-sheathed Bi-2223 tape with 37 filaments was prepared by powder-in-tube process and was supplied by M/s Intermagnetics General Corporation, USA. Pre-reacted powders were initially optimized for high T_c 2223 phase, using high-purity (99·9%) oxides and carbonates of Bi, Pb, Sr, Ca and Cu with the cation ratio 1·8:0·4:2·0:2·2:3·0. The powder was packed in silver tubes (99·9% pure) and was drawn through a series of dies. Multiple lengths were cut from the drawn rod and were restacked into a second tube. The restacked rod was then rerolled to the final size (0·2 mm thick and 100 m long) with intermediate annealing to avoid work hardening. The final heat treatment was performed at 870°C for 150 h under low oxygen partial pressure (5–10%).

XRD pattern of the tape was taken after removing the silver sheath from one side, using Cu Kα radiation as shown in figure 1. XRD analysis was performed using a least square fit method, assuming a tetragonal unit cell. The XRD pattern shows strong $(0\,0\,L)$ texturing of Bi-2223 grains with c-axis normal to the tape surface. Our XRD analysis could detect the existence of only one small peak for 2212 phase. This confirms that 2223 phase is the major superconducting phase present in the tape. The lattice parameters obtained, corresponding to 2223 phase, are $a = b = 5{\cdot}411$ Å and $c = 37{\cdot}03$ Å.

Superconducting transition temperature (T_c) and the critical current density (J_c) of the tape were measured using standard four-probe technique. Critical current density (J_c) was measured as a function of magnetic field and also as a function of temperature between 77 and 64 K. All the measurements were taken with the sample completely immersed in a liquid nitrogen bath. Temperature below 77 K was achieved and maintained by controlled pumping over LN_2 bath. A cryostat was designed for J_c measurement, which incorporates provision for high current (100 amp) leads, as well as smooth rotation of the sample under magnetic field (angular resolution 1°). Sample length chosen was 50 mm and criterion adopted for J_c measurement was 1 μV/cm.

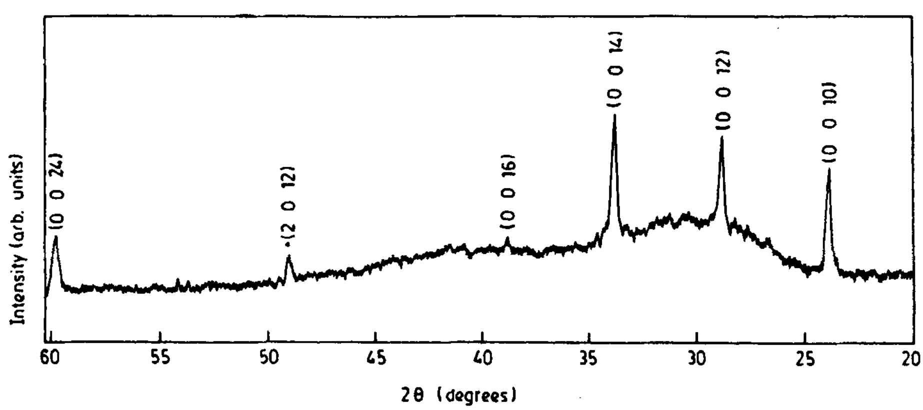


Figure 1. XRD pattern of Bi-2223/Ag multifilamentary tape. (●) corresponds to 2212 phase.

Current and voltage leads were attached to the tape with indium. Voltage across the sample was measured with a resolution of 0·1 μV using a Keithley 181 Nanovoltmeter. A HP (model 6260B) Power Supply (10 V, 100 Amp) and a Ramp Programmer (AMI model 400) were used to generate the desired current ramp for J_c measurement. The I–V characteristics of the tape were plotted on an X–Y recorder (Iakagawa model 302513). Temperature of the bath was monitored by a calibrated Si diode sensor coupled to Lakeshore model 330 Temperature Indicator-Controller. The external magnetic field was provided by an electromagnet. The overall uncertainty in the J_c measurement was within 1%.

3. Results and discussion

Temperature dependence of the resistance of the Ag-sheathed Bi-2223 tape, having 37 filaments is shown in figure 2. Sharp transition to superconducting state with $T_{c0} = 107{\cdot}4$ K has been observed. Transition width (ΔT_c) of the tape was close to 2 K.

3.1 *Temperature and magnetic field dependence*

Critical current density (J_c) of the tape as a function of temperature is shown in figure 3. Over the measured temperature range of 77–64 K in zero field, the critical current density increases approximately linearly with lowering of temperature. Variation of J_c of the tape at 77 K with magnetic field both parallel and perpendicular to c-axis is shown in figure 4a. The tape shows strong anisotropy in J_c, which increases with the increase of magnetic field (viz. $J_{c\perp}/J_{c\parallel} \cong 2$ at 0·1 T and ~ 9 at 0·3 T). It is seen that J_c for magnetic field perpendicular to the broad face of the tape ($B \parallel$ c-axis) is nearly an order of magnitude lower than that observed for B $\perp$ c-axis. Further, decrease of J_c in magnetic field for $B \parallel$ c-axis is much more rapid (J_c attains a very low value ~ 275 A/cm^2) compared to the case when B is perpendicular to the c-axis. Under zero field condition at 77 and 64 K, the maximum J_c observed for the tape was $1{\cdot}25 \times 10^4$ amp/cm^2 and

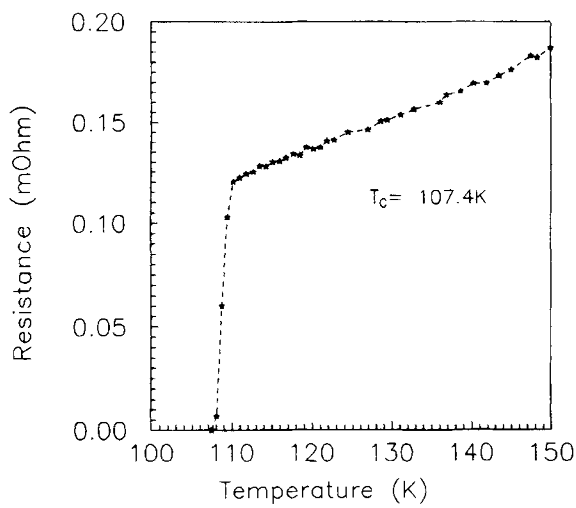


Figure 2. Resistance of Bi-2223/Ag multifilamentary tape as a function of temperature.

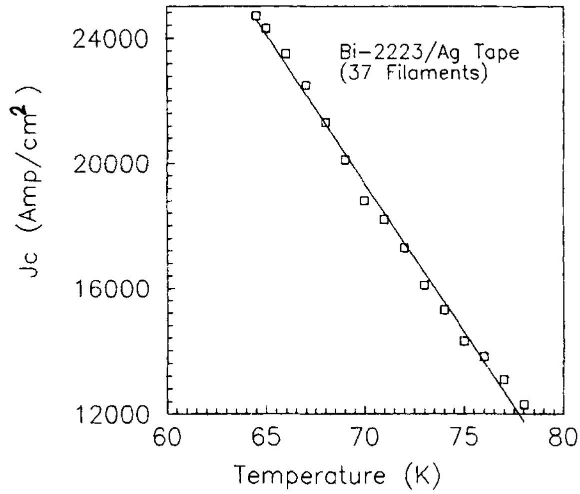
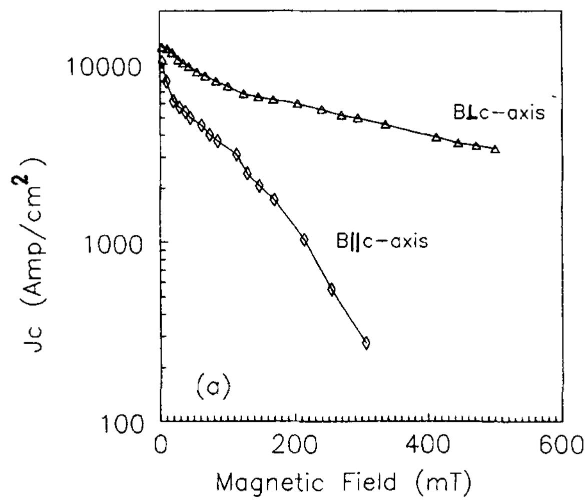


Figure 3. Critical current density of Bi-2223/Ag multifilamentary tape as a function of temperature at zero field.



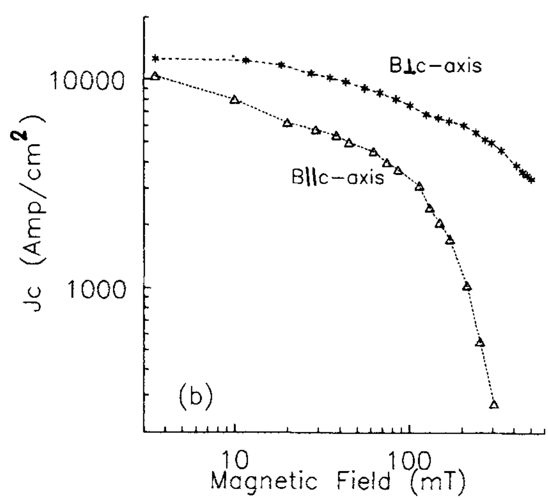


Figure 4. Magnetic field dependence of critical current density at 77 K. (**a**) ln J_c vs B and (**b**) ln J_c vs ln B.

$2{\cdot}54 \times 10^4$ amp/cm^2 respectively. Hysteretic behaviour of J_c of Ag-sheathed Bi 2223 tapes have been reported by Sato *et al* (1991), Grasso *et al* (1995) and others. Ries *et al* (1994), based on a model proposed by D'yachenko (1994), attributes this to the reversible shielding current and irreversible current due to pairing of Abrikosov vortices near the grain surface. It is important to note that we have not observed any hysteretic behaviour for our Bi-2223/Ag tape at 77 K in the field range between 0 and 0·6 T.

Figure 4b is the ln–ln plot of the magnetic field dependence of J_c. The critical current density (J_c) for our tape can be described by a power law of the type: $J_c \propto B^{-\alpha}$ up to about 100 mT, where the field independent component α has a value of $\sim 0{\cdot}35$. This agrees with the other reports (Mawatari *et al* 1995b). For field higher than 100 mT, J_c for $B \parallel$ c-axis shows an exponential dependence

$$[\exp(-B/B_0)],$$

where, B_0 is a field independent constant. It may be noted that in the low current region (viz. $< 10^2$ amp/cm^2), the effect of sharing current in the silver sheath can not be neglected and a correction for J_c may become necessary. Considering the Ag-sheathed superconducting tape as a parallel combination of the superconductor and the Ag-sheath, the field dependence of J_c can be obtained by subtracting the sharing current through the Ag sheath from the experimental value of I_c. The (J_c–B) dependence observed in our tape, namely, power law dependence at low fields ($<$ 100 mT) and exponential dependence for magnetic field $>$ 100 mT is consistent with the prediction of the brick wall model (Bulaevskii *et al* 1993), as well as collective pinning theory (Feigel'man and Vinokur 1990). From the measured data, the flux pinning force densities ($F_p = J \times B$) for the two orientations of magnetic field at 77 K have been computed and are shown in figure 5 as a function of magnetic field. As expected, flux pinning is substantially higher for $B \perp$ c-axis. In the measured magnetic field range, a clear maximum in F_p evolves when $B \parallel$ c-axis, while for $B \perp$ c-axis F_p barely shows the sign of a maximum, but at a much higher field. However, in absence of (J_c–B) data at different temperatures, it is rather difficult to come to any definite conclusion regarding the nature of scaling behaviour in the present case.

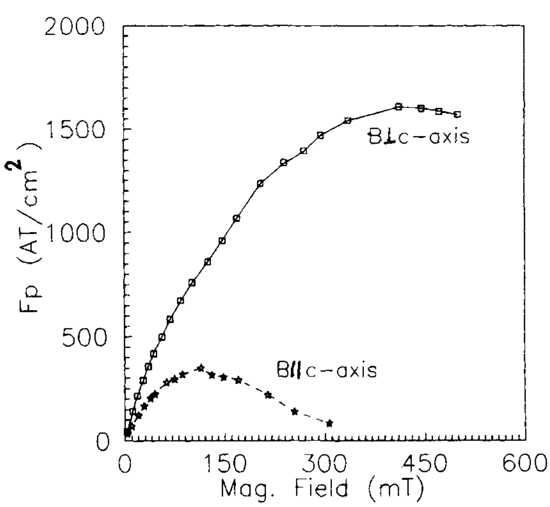
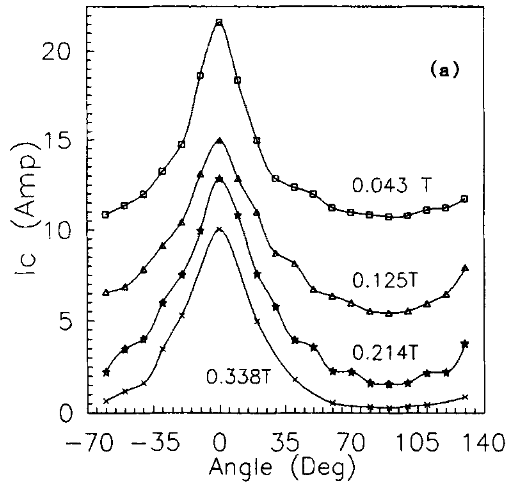


Figure 5. Magnetic field dependence of F_P at 77 K.



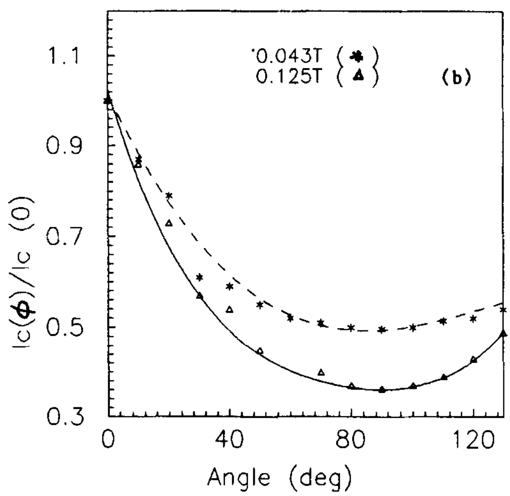


Figure 6. a. Angular dependence of I_c of Bi-2223/Ag multifilamentary tape at different applied fields and (b) $I_c(\phi)/I_c(0^0)$ vs ϕ for $B = 0{\cdot}043\,T$ (*) and $0{\cdot}125\,T$ (Δ). The dashed and solid lines are the calculated values using the $T - T$ model for $B = 0{\cdot}043\,T$ and $0{\cdot}125\,T$ respectively.

3.2 *Angular dependence*

Figure 6a shows the angular dependence of J_c of our Bi-2223/Ag tape for four different magnetic fields measured at 77 K and plotted as a function of the field tilt angle (ϕ). The angle ϕ has been defined as that between the applied field direction and the tape surface. It is seen from figure 6a that when the magnetic field is applied perpendicular to the broad face of the tape ($\phi = 90°$), J_c attains its lowest value. The highest value is observed for $B \perp$ c-axis ($\phi = 0$). Similar behaviour has been reported by Liebenberg *et al* (1992), Hu *et al* (1992) on Bi-2223 tapes as well as on thin films by Fukami *et al* (1993).

In the layered oxide superconductors the CuO_2 layers and their vicinities are strongly superconducting and other layers are weakly superconducting. Accordingly, these materials may be considered to be made up of alternate stackings of strongly and weakly superconducting layers. The weakly superconducting layers act as natural pinning centres with considerably high pinning force (Tachiki and Takahashi 1989a). Assuming the presence of extrinsic planar pinning centres (effective for flux lines parallel to c-axis) in addition to the above mentioned intrinsic pinning centres, Tachiki and Takahashi (1989b) calculated the critical current density (J_c) as a function of the direction of the applied external magnetic field. According to which, $J_c(\phi)$ vs ϕ under the condition of J perpendicular to B is given by:

$$\frac{J_c(\phi)}{J_c(0^\circ)} = \left[\frac{J_c(90^\circ)}{J_c(0^\circ)}\right] \Big/ |\sin(\phi)|^{1/2},$$

where, $J_c(0^\circ)$ and $J_c(90^\circ)$ are the critical current densities in magnetic fields applied along the basal plane and parallel to the c-axis respectively. The dotted lines in figure 6b show $J_c(\phi)/J_c(0^\circ)$ calculated using the above expression for different ϕ and for two different field strengths. It is seen that the $T-T$ model describes fairly well the angular dependence of J_c of silver-sheathed multifilamentary Bi-2223 tapes for low external fields. At higher fields, the deviations of the calculated values from the measured ones occur particularly in the low-angle regions. The cause for such deviations are not clearly understood.

3.3 *Thermal cycling*

A major problem reported for the powder in tube composite conductors has been the degradation of critical current density due to thermal cycling (van Sciver *et al* 1992; Jenkins *et al* 1993; Hilton and Hascieek 1995). Jenkins *et al* (1993) reported the occurrence of bloating (viz. opening up of Ag sheath) on thermal cycling which resulted in severe degradation of J_c. When bloating occurs J_c degradation is expected due to considerable strain induced on the superconducting core. Other mechanisms, which may also cause J_c degradation on thermal cycling are, differential thermal expansion within the HTSC tape (Ochiai *et al* 1991; Jenkins *et al* 1993) and pinholes penetrating the Ag sheath (Jenkins *et al* 1993). Therefore, to test the reliability of our Bi-2223/Ag tapes, J_c of several pieces of the tape was measured at 77 K after repeated thermal cycling between room temperature and 77 K. A total of 100 such thermal cycling were given to the tapes. Results obtained are shown in figure 7. J_c showed an initial nominal decrease of $\sim 4\%$ after 10 cycles, beyond which it remained practically constant up to 100 cycles. It is important to note that no sign of bloating was noticed in our tapes, even after 100 thermal cycling between room temperature and 77 K. However, when the end sections of the tape were not covered with indium, bloating of the silver sheath was observed in some samples after a few thermal cycling. In such cases, J_c showed a dramatic decrease, as is expected because of excessive strain on the superconducting filaments.

3.4 *Bending strain*

Depending upon the fracture strength, bending of tape results in micro cracks in the brittle ceramic filaments. Such cracks may be initiated by stress concentration around voids/pores, as well as by the inclusions from the secondary phase particles and

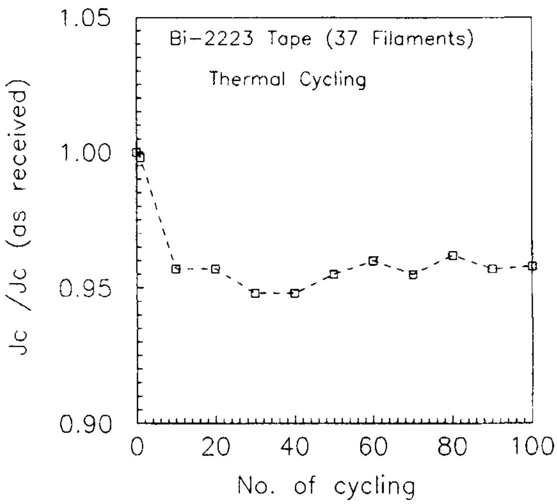


Figure 7. Normalized critical current density (J_c) plotted as a function of number of thermal cycling between 300 and 77 K for Bi-2223/Ag sheathed tape.

agglomerates (Lawn 1993). This leads to an irreversible strain limit (ε^*) above which permanent deterioration of J_c occurs. Critical current density (J_c) is generally reversible to its prestrain level below ε^*. Several reports on HTSC tapes (Sato *et al* 1991; Ekin *et al* 1992; Ochiai *et al* 1993; Sato 1993) indicate that strain degradation can be arrested either by decreasing the fill factor or by subdividing the core into multifilamentary geometries. Improved strain tolerance observed in multifilamentary tapes is thought to be due to limited crack propagation by increased Bi-2223/Ag interfaces (Osamura *et al* 1992).

Critical current degradation due to bending strain in our multifilamentary Bi-2223/Ag tape was studied using a series of eleven non-metallic mandrills with bending diameters ranging from 90 mm to 12·9 mm. Test sample was fixed on the surface of the mandrill with current and voltage leads attached by indium solder. Separation of the voltage leads was 10 mm. Bending strain (ε%) on the superconducting core has been calculated from:

$$\varepsilon = [t/2r] \times (100\%),$$

where, r is the radius of bending and t the thickness of the tape. Two sets of experiments were performed at 77 and 64 K under zero magnetic field. In the first set of experiments, J_c was measured with the tape in bent state on different mandrills (single bend), while for the second set the bent tapes were again straightened out prior to J_c measurements.

Figure 8a shows the normalized J_c $[= J_c(\varepsilon)/J_c(0\%)]$ as a function of the bending strain (ε%) for the tape at 77 and 64 K. It is seen from figure 8a that J_c does not change significantly for bending strain up to about 0·27%, beyond which J_c has been found to decrease irreversibly with increasing strain. At larger strain value ($\varepsilon > 1·1\%$), the critical current density shows a tendency of saturation. In our tape, J_c retains half its zero strain value even at strain level of 0·8%. Results on the present tape have been found to be consistent with the reported data on multifilamentary Bi-2223/Ag tapes having nearly same number of filaments (Osamura *et al* 1992; Carter *et al* 1995). In comparison to the data available on mono core Bi-2223/Ag tape (Osamura *et al* 1992), our tape displays

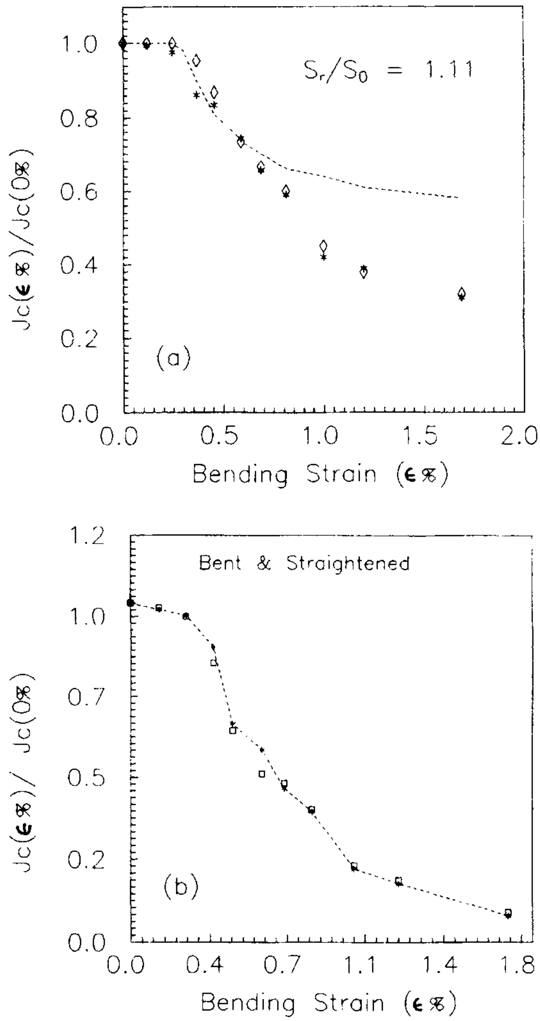


Figure 8. **a**. Bending strain (ε%) characteristics of the Bi-2223/Ag multifilamentary tape at 64 K (*) and 77 K (◇). Dashed line is the calculated values using the expression by Otto *et al* (1993) and **b**. $J_c(\varepsilon\%)/J_c(0\%)$ vs bending strain (ε%) for tape bent to different diameters and then straightened prior to measurement.

a significant improvement in strain tolerance. Figure 8b shows the results on the tapes which have been straightened after bending it once to different diameters on the mandrills. J_c for such bent and straightened tapes not only displays beginning of degradation at low strain value ($\varepsilon = 0{\cdot}14\%$), but also deteriorate faster with strain. Only 10% of the pre-strain J_c value is retained when the tape is subjected to an initial bending strain of 1·8% and straightened before measurements.

A model describing the deterioration of critical current density due to fracture of superconducting filaments on the tensile side of the tape was proposed by Otto *et al* (1993), which in case of single bend is given by:

$$I/I_0 = \frac{S_r \varepsilon^*}{2S_0 \varepsilon} + \frac{1}{2},$$

where, ε^* is the critical strain on the filaments under uniaxial tension, $2S_r$ the tape thickness, and $(S_r - S_0)$ is the distance from the outside of the tape to the outermost filaments. The model assumes a uniform distribution of filaments in the region out to S_0 and that I_c of the filament drops to zero when the strain on the filament exceeds ε^*. The retained critical current density for an average critical strain of 0·27% for our tape has been calculated from the above equation and is shown in figure 8a. A fairly good agreement is obtained for strain up to $\varepsilon = 0{\cdot}7\%$, beyond which deviations between the experimental and the predicted values are clearly seen. Otto *et al* (1993) also observed such deviations and argued that it originates due to the gradual current taper beyond the critical strain rather than the sudden decrease to zero critical current at the critical strain assumed in the model. Other reasons viz. silver work hardening and the loss of inter-plane symmetry in the properties might also contribute to the observed deviations at higher strain values.

3.5 *Fabrication of pancake coil*

Making of pancake coils have evolved due to the fact that it is easier to produce shorter lengths of tape than the longer ones, especially in the laboratory scale. Besides if one of the coils of the stacked pancake magnet breaks, it is much easier to replace the faulty coil than to replace the entire windings of the magnet (as in solenoidal coils). Preliminary studies reported by Okada *et al* (1995a, b), Tomita *et al* (1995b), Schwenterly *et al* (1995) and others on the performance of single and stacked pancake coils fabricated from Bi-2223 tapes show promise for their use in high-field applications. We present here the fabrication details and the results obtained for a single pancake coil prepared using the present Bi-2223 tape 1·2 m long.

The coil was wound on a brass former (o.d. = 27 mm and i.d. = 23 mm) with current leads extending perpendicular to the plane of the coil. Voltage taps separated by 1 m were soldered at the conductor ends. Number of turns in the coil was 10. Teflon tape was cowound to provide interlayer insulation. After the winding of the tape, the coil was placed in a suitable casing and was impregnated with paraffin wax to improve its mechanical strength. In our design, the tape was exposed to a minimum bending radius of 14 mm, which corresponds to 0·81% surface strain.

Voltage–current characteristics of the fabricated coil were measured by standard four-terminal method and critical currents were extracted using the electric field criterion of 10 and 100 μV/m over the temperature range from 64 to 77 K (figure 9). Index number (n) was calculated from the measured I_c at two levels of electric field using the expression:

$$n = \frac{\ln(E_2/E_1)}{\ln(I_2/I_1)},$$

where, $E_1 = 10\,\mu\text{V/m}$ and $E_2 = 100\,\mu\text{V/m}$. The n values of the fabricated coil ranged from 6·4 at 77 K to 6·7 at 64 K. The generated magnetic field of the Bi-2223/Ag pancake coil was detected with a Hall sensor (M/s Lakeshore, USA) set at the centre of the coil. In zero background field, the coil generated a peak field of 2·5 mT and 4·7 mT at 77 K and 64 K respectively. This compares well with the results of similar coils (18·4 turns) reported by van Vo *et al* (1996) which generated a peak field of 5 mT.

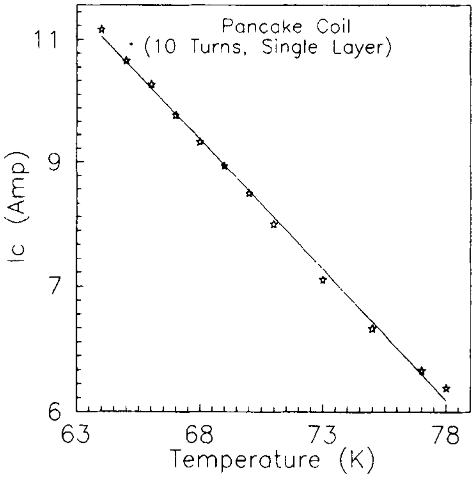


Figure 9. Critical current (I_c) of the single pancake coil as a function of temperature.

4. Conclusion

Silver sheathed Bi-2223 tape with 37 filaments was prepared by a powder-in-tube method (supplied by M/s Intermagnetics, USA). The tape shows a zero field J_c of $1{\cdot}25 \times 10^4$ A/cm^2 at 77 K. J_c of the tape displays strong anisotropy with the direction of applied magnetic field. Dependence of J_c on field orientation could be described fairly well by a model proposed by Tachiki and Takahashi (1995b). The tape shows good stability against repeated thermal cycling, as well as good strain tolerance to bending strain. J_c remains unaffected by the bending strain of $\sim 0{\cdot}27\%$ and maintains $\sim 50\%$ of the prestrain J_c at strain level of 0·8%. A small 10 turns pancake coil has been fabricated and tested using $\sim$ 1 m long piece of the tape. The coil generates at 64 K a maximum field of 4·7 mT carrying a current of 11·05 A.

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References

Ashworth S P, Glowacki B A, James M P, Garre R and Conti S 1995 *IEEE Trans. Appl. Supercond.* **5** 1271

Bulaevskii L N, Daemen L L, Maley M P and Coulter J Y 1993 *Phys. Rev.* **B48** 13798

Carter W L, Ridey G N, Otto A, Parker D R, Christopherson C J, Masur L J and Buczek D 1995 *IEEE Trans. Appl. Supercond.* **5** 1145

Dou S X and Liu H K 1993 *Supercond. Sci. & Technol.* 6297

Dou S X, Guo Y C, Wang R K, Ionescu M, Liu H K, Babic E and Kusevic I 1995 *IEEE Trans. Appl. Supercond.* **5** 1831

D'yachenko A I 1994 *Physica* **C213** 167

Ekin J W, Finnemore D K, Li Q, Tenbrink J and Carter W 1992 *Appl. Phys. Letts* **61** 858

Fukami T, Lee D H, Panogopoulos C, Nishizaki T, Ichikawa F, Horie Y and Aomine T 1993 *Physica* **C215** 375
Feigel'man M V and Vinokur V M 1990 *Phys. Rev.* **B41** 8986
Grasso G, Hensel B, Jeremie A and Flükiger R 1995 *IEEE Trans. Appl. Supercond.* **5** 1255
Gubser D U, Soulen R J, Datta T and Kirven D 1995 *IEEE Trans. Appl. Supercond.* **5** 1302
Hasegawa T, Hikichi Y, Kumakura H, Kitaguchi H and Togano K 1995 *Jap. J. Appl. Phys.* **34** L1638
Hautanen K E, Oussena M and Cave J R 1993 *Cryogenics* **33** 326
Hilton D K and Hascieek Y S 1995 *IEEE Trans. Appl. Supercond.* **5** 3478
Hu O Y, Liu H K and Dou S X 1992 *Cryogenics* **32** 1048
Jenkins R G, Jones H, Belenli I, Yang M, Goringe M J and Grovenor C R M 1993 *Cryogenics* **33** 81
Lawn B 1993 in *Fracture of brittle solids*, Cambridge Solid State Series (UK: Cambridge University Press) 2nd Ed p. 307
Liebenberg D H, McIntyre P C, Cima M J and Francavilla T L 1992 *Cryogenics* **32** 1066
Mawatari Y, Yamasaki H and Kosaka S 1995a *IEEE Trans. Appl. Supercond.* **5** 1305
Mawatari Y, Yamasaki H, Kosaka S and Umeda M 1995b *Cryogenics* **35** 161
Minot M J, Buczek D, Gannon J J, Miles P K and Parker D R 1995 *IEEE Trans. Appl. Supercond.* **5** 1246
Ochiai S, Hayashi K and Osamura K 1991 *Cryogenics* **31** 954
Ochiai S, Hayashi K and Osamura K 1993 *Cryogenics* **33** 976
Okada M, Tanaka K, Sato J, Awaji S and Watanabe K 1995a *Jap. J. Appl. Phys.* **34** 4770
Okada M *et al* 1995b *Jap. J. Appl. Phys.* **34** L981
Osamura K, Ochiai S and Hayashi K 1992 *Adv. Cryo. Engg. Mater.* **38** 875
Otto A, Masur L J, Gannon J, Podtburg E, Daly D, Yurek G Y and Malozemoff A P 1993 *IEEE Trans. Appl. Supercond.* **3** 915
Ries G, Neumüller H W, Schmidt W and Struller C 1994 *7th Int. workshop on critical currents in supercond. Alphach, Austria*
Rosner C H, Walker M S, Halder P and Motowidlo L R 1992 *Cryogenics* **32** 940
Salama K, Selvamanickam V and Lee D F 1992 in *Processing and properties of high T_c superconductors* (ed.) S Jin (Singapore: World Scientific) **1** Chap. 5 p. 155
Sato K 1993 in *Processing and properties of high T_c superconductors* (ed.) S Jin (Singapore: World Scientific) **1** 121
Sato K, Hikita T, Mukai H, Ueyama M, Kato T, Masuda T, Nagata M, Iwata K and Mitsui T 1991 *IEEE Trans. Magn.* **27** 1231
Schwenterly S W *et al* 1995 *IEEE Trans. Appl. Supercond.* **5** 507
Shukla S R, Reddy Y S and Sharma R G 1992 *Pramana – J. Phys.* **38** 179
Tachiki M and Takahashi S 1989a *Solid State Commun.* **70** 291
Tachiki M and Takahashi S 1989b *Solid State Commun.* **72** 1083
Tomita N, Arai M, Yanagisawa E, Morimoto T, Kitaguchi H, Kumakura H, Togano K and Nomura K 1996a *Cryogenics* **36** 485
Tomita N *et al* 1995b *IEEE Trans. Appl. Supercond.* **5** 520
Van Sciver S W, Hascieek Y S, Markiewicz W D, Motowidlo L R, Hazelton D R and Halder P 1992 *Proc. 5th international superconductors symposium* (Tokyo: Springer) p. 819
Van Vo N, Dou S X and Liu H K 1996 *IEEE Trans. Appl. Supercond.* **6** 102