Development of High Temperature Superconducting Coils Using Bi-2223/Ag Tapes

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Abstract **- Four double wound pancakes with inner diameters of 98 mm have been successfully fabricated with multifilamentary Bi-2223/Ag tape using the react and wind technique. Two pancakes were impregnated with wax and the other two with resin. The pancakes have been tested at 77 K producing critical current (I_C) values up to 14.5 A and index of transition values (n) of up to 11.4. The field profiles produced by the pancakes have been modelled. The I_C field dependence of short samples of the component Bi-2223/Ag tape has been studied. I_C is most sensitive to field when the field is parallel to the c-axis of the tape, reducing I_C from 28 A to 13.2 A between 0 T and 30 mT. Although the bending strain of the tape in the coil is ~0.3%, the fabrication procedure for the pancakes has produced very little handling damage to the tapes. It is demonstrated that the I_C of the coils is almost entirely self field limited.**

I. Introduction

Since the discovery of high temperature superconductors (HTS) in 1986, significant work has gone into improving the properties of the materials. We have now reached a period when conductors can be produced over long lengths [1,2] making large scale magnet applications realistic. Multifilamentary HTS cuprates remain the most likely candidates, in particular the Bi-2223 phase due to the high J_C properties that can be produced in long lengths using powder route processing [2-4]. There are three main areas of applications development for these conductors; 1) High temperature, low field applications (B < 1 T) allowing relatively cheap liquid nitrogen to be used a coolant; 2) Medium field magnets (2 T < B < 10 T) operating at temperatures of 20-30 K, enabling the easy use of cryocoolers and 3) Very high field inserts (> 20 T) for use at 1.8-4.2 K temperatures, taking advantage of the high J_C and B_{C2} values. For example a 1000 m Bi-2223/Ag tape was used to produce a magnet [2] which produced a self-field of 4 T at 4.2 K, 1 T in 20 T background field and 0.37 T in a 23 T background field [5].

In this paper, we report on the design and fabrication of four double wound pancake coils from Bi-2223 multifilamentary tape using the react and wind route. Two of the pancakes have been impregnated with wax and two with resin. The self field generated for the coils has been calculated. The bore for these coils is 98 mm which produces a bending strain on the tape of about 0.3%. Since strain measurements on short samples show that J_C markedly decreases at strain values of typically 0.3% [6,7], the handling of the tapes during the fabrication procedure must be kept to a minimum. The voltage-current characteristics have been measured for all sections of the pancakes in liquid nitrogen in self-field. In addition, J_C measurements have also been made on short samples of the tape used to fabricate the coils at 77 K in fields up to 300 mT. These data allow us to assess the performance of the coils.

Section II describes the fabrication procedure of the pancakes. Section III outlines the self field produced by the coil and the bending strain of the tape. The experimental results for the short sample and the coil are presented in Section IV. Finally we discuss the results and conclusions from this work.

II. Coil Fabrication Procedure

Three different 37 filament Bi-2223/Ag tapes fabricated using the powder-in-tube route were used to fabricate the pancakes. Table 1 presents the cross-section, fill factor and I_C of the three tapes. The I_C values quoted were measured over a 100 m length of tape. The important differences between the tapes are discussed in Section IV.

The basic construction of all four double pancakes was similar and is shown by Fig. 1. The Tufnol former was held in the chuck of a lathe. The superconducting tape and the insulating Mylar are co-wound onto the former from two

Manuscript received September 14, 1998
This work was supported by BICC Limited and EPSRC.

1051-8223/99$10.00

TABLE 1
THE MAIN PARAMETERS AND DIMENSIONS OF THE BI-2223 TAPES

	Tape 1	Tape 2	Tape 3
No. Filaments	37	37	37
Total Cross-Section	$0.854mm^2$	$0.961mm^2$	$0.973mm^2$
Fill Factor	36.2%	29.5%	32.0%
I_C in 100m long sample	20A	25A	27A

TABLE 2
THE MAIN PARAMETERS OF THE DOUBLE PANCAKES

	Coil 1	Coil 2	Coil 3	Coil 4
Bi-2223 tape used	1	1	2	3
Total length of tape	14m	9m	21.2m	17.8m
No of turns	20 + 19	15 + 12	30 +30	25 + 23
Impregnation	Wax	Wax	Resin	Resin

separate spools by slowly rotating the chuck. There is little tension in the tape to minimise strain damage. However the insulator is tensioned to ensure the packing factor of the coil remains high. The former has six slots to enhance cooling for the inner turns. Each double wound pancake consists of 2 oppositely wound pancakes insulated from each other by a ring of Kapton. In Table 2, the total length of tape, the number of turns on each pancake and the impregnation material for each coil is shown.

The individual pancakes were joined together using three silver strips soldered to the bottom turn of each coil. Two current leads were connected to the double pancake by soldering a silver strip to the top layer of each coil. Two copper voltage taps were also connected to each coil, one on the top layer and one on the bottom layer. This configuration ensured each pancake and the joints between the pancakes could be tested individually as well as the whole coil. In making these connections, care was taken to limit mechanical damage to the tape by the soldering iron.

The coils were held in PTFE moulds and vacuum impregnated at 0.1 mbar. Each wax coil was heat-treated at 70°C for 10 hours during which time the wax first melted and then impregnated the coil. Then the coil was slowly cooled to room temperature. The Ciba-Geigy resin used to impregnate coils was CY1300, HY906 and DY073. First the coil and the mixed resin were out-gased for 24 hours at 50°C. Then the resin was poured into the mould containing the coil. The temperature was ramped at 10°C per hour up to 80°C and the pressure increased to ambient pressure. The resin was then gelled for 18 hours at 80°C. Then the temperature was again ramped at 10°C per hour and finally the coil was cured for 11 hours at 120°C.

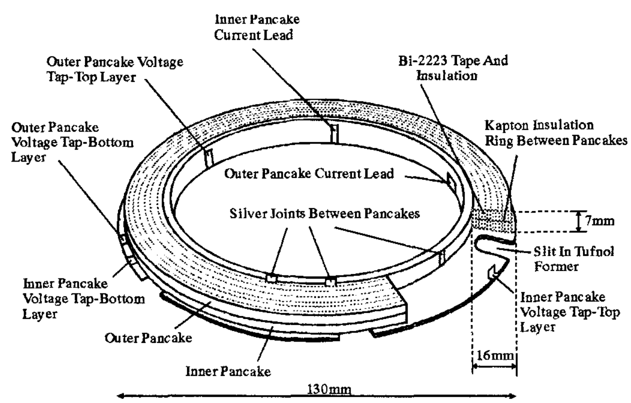

Fig. 1. A schematic diagram of a Bi-2223/Ag double wound pancake showing a cross-section through the turns.

III. FACTORS DETERMINING COIL PERFORMANCE

Two of the critical factors that affect the performance of HTS react and wind coils are the magnetic field produced by the coil and the bending strain of the tape. These are considered in turn.

In Fig. 2, the calculations of contours for the magnitude of the self field within the double wound pancake (Coil 3) are presented. Similar contours occur for all the coils. The field is zero on contour 1 increasing in equal steps for subsequent contours out to a maximum at point B_{MAX} on contour 10. The distances on the radial axis are given from the centre of the pancake. Point B_{RMAX} shows the point in the coil with the highest field in the radial direction (i.e. the field parallel to the c-axis of the tape). The coil constant is 2.74 $mT.A^{-1}$ and

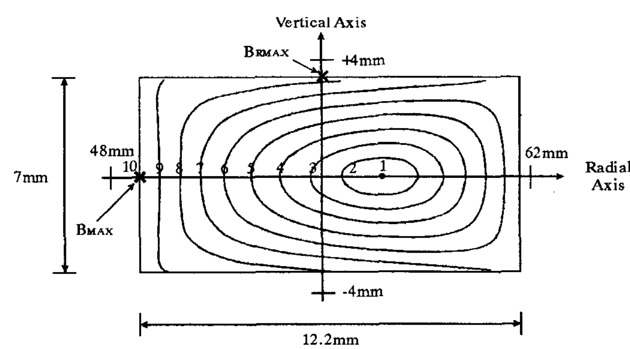

Fig. 2. The field profile through the pancake showing field line contours from zero field (contour 1) up to a maximum field (contour 10).

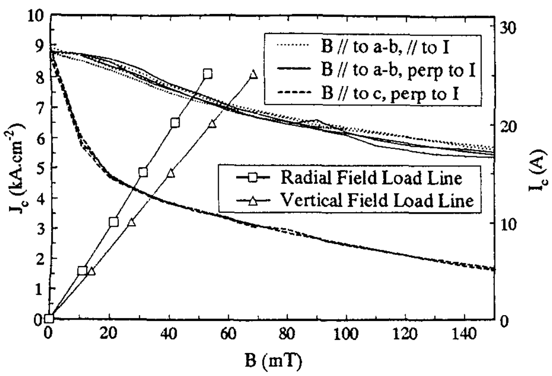

Fig. 3. The critical current density (J_C) as a function of field up to 150 mT for three orientations of the tape with respect to field. Measurements taken on a short sample of Tape 1. Also shown are the radial and vertical field load lines for the double wound pancakes.

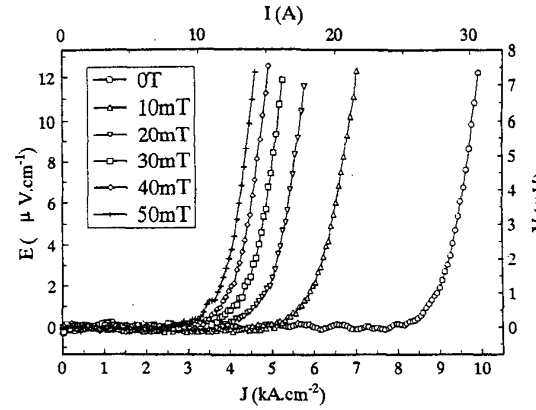

Fig. 4. The electric field-current density characteristics of a short sample of Tape 1 every 10 mT up to 50 mT at 77 K. The field is applied parallel to the c axis and perpendicular to current.

$B_{RMAX} = 0.72\ B_{MAX}$.

The bending strain exerted on the tape has been calculated using $\epsilon = t/D$, where t is the thickness of the tape and D is the bending diameter of the pancake. With the tape thickness of 0.33 mm and bending diameter of 98 mm the bending strain on the tape is ~0.3%.

IV. Experimental Techniques

A. Short Sample Measurements

Critical current density transport measurements were taken on short samples of Tape 1 as a function of field at 77 K from 0 T up to 300 mT to investigate the low field dependence of I_C. Using these data we can determine the self field limitations for the coils. Samples were cut to 20 mm in length and mounted on tufnol. A four terminal measurement was used with voltage taps connected using silver paint and separated by 6 mm and the current leads soldered to the tape. A criterion of 1.5 μVcm^{-1} was used to calculate I_C. The field was applied using a resistive copper magnet and results were taken during 1.5 field cycles - in increasing, decreasing and increasing field - to study any hysteretic effects of field on J_C. Data were take every 10 mT up to 100 mT and thereafter every 20 mT.

As shown in Fig. 3, measurements were taken for 3 orientations of the tape with respect to field. We expect the short-sample data for all three tapes to be similar. The orientation with field parallel to the c-axis shows the strongest I_C field dependence dropping from 28 A in zero applied field to 13.2 A at 30 mT. Eventually I_C dropped to 1.9 A at 280 mT. The two orientations parallel to the a-b planes are similar to each other. They have a much weaker dependence dropping to 14.5 A at 250 mT. Very little hysteresis in I_C is found in any of the data although the decreasing field values are slightly higher due to trapped flux within the superconductor.

Figure 4 shows some detailed electric field - current density characteristics over the first 50 mT in the orientation field parallel to the c-axis. The baselines are flat to within the limits of the experiment indicating there is very little damage to the sample. The n-index has been calculated using the standard equation $V=\alpha I^n$ where n is the index of transition. From the data in Fig. 4 it was found that in zero field at 77 K the short sample value for n is 18.7 and at 30 mT, n is 9.4.

B. Double wound pancake test results

The voltage-current characteristics of each coil were

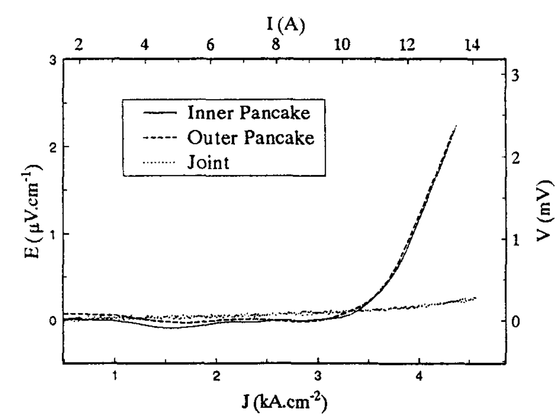

Fig. 5. The electric field-current density characteristics at 77 K of the double wound pancake (Coil 3).

TABLE 3
TEST RESULTS OF THE DOUBLE PANCAKES AT 77K IN ZERO APPLIED FIELD

	Coil 1	Coil 2	Coil 3	Coil 4
Joint Resistance	10 μΩ	22 μΩ	10 μΩ	10 μΩ
Inner Pancake I_C	13.3 A	14.5 A	12.3 A	14.5A
Outer Pancake I_C	13.9 A	14.5 A	12.3 A	14.4 A
n Index Inner pancake	3.70	6.19	11.3	10.00
n Index Outer pancake	2.50	6.91	11.4	9.2

measured at 77 K using a four terminal technique. A criterion of 1 μVcm^{-1} was used to define I_C. In Fig. 5 the voltage-current characteristics are shown for the three components of Coil 3 - the two individual pancakes and the joint. It can immediately be seen that the n-index of transition for the pancakes is similar to that of the short sample (cf. Figs 4 and 5). In Table 3, the resistances of the joints are shown as well as I_C values and n-indexes for all the individual pancakes.

IV. Discussion

From the calculations of the field contours within the coils (Fig. 2), the load lines which define the field produced per Amp by the coil have been calculated for point B_{MAX} - vertical field load line and point B_{RMAX} - radial field load line. The intercept between these load lines, shown in Fig. 3 and the J_C characteristics show the ideal performance were the short sample values of current density achieved throughout the turns. The intercept between the critical current data for B parallel to c-axis and the radial field load line occurs at a lower current than the intercept for B parallel to a-b and the vertical field load line. Therefore the performance of the coil is determined by the conditions at point B_{RMAX} in Fig. 2 where the local field lines are parallel to the c-axis of the tape. The ideal critical current is predicted to be about 13.5 A giving a B_{RMAX} of 28 mT and B_{MAX} of 39 mT. Table 3 and the data in Fig. 5 clearly show that these critical current values have been achieved in practice.

The index values for the coils characterise the performance of the coils at low electric field values. It can be seen from Table 3 that Coils 1 and 2 have markedly lower n-values than Coils 3 and 4 (n~ 10 ~ 11.4) or the short sample (n ~ 9.4 at 30 mT). We suggest that this result is consistent with the relatively low I_C value for Tape 1 over long lengths (~20 A) compared to short sample currents (~28 A) and suggests damage to the tape prior to coil fabrication. The values of the n-index for the resin impregnated coils which use Tapes 2 and 3, are actually slightly higher than that of the short sample. This confirms that independent of the E-field criterion used to define I_C, the coil performance is very close to that expected for undamaged turns limited by self-field.

V. Conclusions

Four large bore double wound pancakes have been fabricated from 37 filament Bi-2223/Ag tapes, produced by the powder in tube route, using the react and wind technique. The field produced throughout the windings of the coil has been calculated. Measurements have also been completed on short samples to determine the dependence of I_C on the orientation and magnitude of the field at 77 K.

Although the bending strain in the pancakes is similar to the maximum that can be sustained by these brittle materials, the performance of the coils is almost entirely self field limited.

Acknowledgment

The authors wish to thank G. Teasdale and P. Armstrong for their technical support and all the audio visual staff in the Durham University Physics Department.

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