YBa₂Cu₃O_x Low Loss Current Leads

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Abstract—The low thermal conductivity of High Temperature Superconducting ceramic YBCO ($<1\text{Wm}^{-1}\text{K}^{-1}$ at 77K) in comparison with normal metal such as copper ($\sim 480\text{Wm}^{-1}\text{K}^{-1}$ at 77K) suggests their use as current leads. We demonstrate a modular lead design which has very low resistance contacts and where the power dissipated at an arbitrarily chosen current level of 100A is several orders of magnitude lower than that dissipated by the normal metal leads presently used in such applications. This suggests that significant cost savings may be made resulting from the reduced liquid helium boil-off rate. The leads are fabricated by novel ceramic processing techniques which give a high degree of uniformity and reproducibility, and strengths in flexure approaching 200MPa for the individual elements, the highest values reported.

I. INTRODUCTION

Current leads for superconducting magnets supply power from a room temperature source to the magnet which operates at 4.2K. Conventional current leads are made from normal metals such as brass or copper which have high thermal conductivities of approximately 480 and $65\text{Wm}^{-1}\text{K}^{-1}$ respectively at 77K. If the magnet is run in the persistent mode, then the current leads are withdrawn after the magnets have been energised and thus do not represent a significant heat load. However, in magnet applications where the field is frequently altered the leads usually remain in place. In this case a significant proportion of the running costs of the magnet result from loss of liquid helium due to heat leaks. The heat flow down the current lead and the heat produced due to joule heating in the lead are two major factors. The high temperature superconducting (HTS) materials YBa₂Cu₃O_x (YBCO) and Bi-Pb-Sr-Ca-Cu-O (BSCCO) are ceramics which have thermal conductivities at 77K at least two orders of magnitude lower than copper. There is thus a great incentive to consider the use of these materials for current leads.

Since the first demonstration of a HTS current lead by Gubser et al [1], there has been significant progress notably by the group at Hoechst [2,3] using melt cast BSCCO 2212. The superconducting properties of sintered YBCO and melt cast BSCCO are similar and, at 77K, both materials can tolerate only moderate magnetic fields before their current carrying capability is drastically reduced. For applications in higher magnetic fields, melt

textured or zone refined YBCO would be the preferred choice but the processing difficulties associated with such materials are considerable and only short lengths can be produced over reasonable timescales at the present time. Fortunately, for the applications targetted here, the stray fields are quite small ($\leq 0.1\text{T}$) and do not present significant problems. It is interesting to note that a major manufacturer of Magnetic Resonance Imaging equipment has recently tested DyBa₂Cu₃O₇ current leads in a new system [4].

The present programme of work examines the use of YBCO in a modular design and aims to address the technology required for a complete cryogenic current lead assembly. This includes manufacture, the surface area of the lead - which is particularly important in the case of gas cooled leads, contact technology between the HTS, normal metal and the low temperature superconductor, contact resistance, reliability and mechanical integrity. This paper describes progress towards these aims.

II. EXPERIMENTAL

A. Manufacture of the YBCO Elements

The manufacture of the powder and the extrusion process used to produce the individual pre-fired YBCO elements has been described in detail elsewhere [1,5]. Briefly, the powder was made by calcining barium carbonate, yttrium oxide and copper oxide at 900-950°C for several hours. The sintered mass was then ground in a vibro-energy mill consisting of a polyethylene vessel containing zirconia grinding media and ethanol. The material was ground until a surface area of between $3\text{-}6\text{m}^2\text{g}^{-1}$ was achieved. The powder was then mixed with polymers and non-aqueous solvents using very high shear mixing. This causes the breakdown of powder agglomerates which are a significant cause of defects in sintered ceramics [6-8]. The resultant plastic mixture was extruded through a 2mm diameter die in a ram extruder and sintered in flowing oxygen at approximately 900°C for 12 hours and slowly cooled to room temperature.

B. Construction and Testing the Current Leads

Four different lead assemblies were made. Firstly, three modular leads were constructed using the sintered YBCO rods (now approximately 1.6 - 1.8mm in diameter) cut into 150mm lengths. Silver paste (ICI) was applied to 10mm

TABLE I
PROPERTIES OF SINTERED YBCO

Flexural Strength (MPa)	216.3 ± 16.4
Young's Modulus (GPa) at 87% Theoretical Density	141.8 ~ 180
K _{1c} (MPam ^{0.5})	1.07 ± 0.18
Critical Flaw Size (μm)	15
Thermal Expansion 50-450°C (x10 ⁻⁶ K ⁻¹)	11.5
Specific Heat at 82% Theoretical Density (Jkg ⁻¹ K ⁻¹)	431
Thermal Conductivity at 85% Theoretical Density (Wm ⁻¹ K ⁻¹)	
300K	2.67
77K	1
Resistivity (μΩcm)	
300K	670
100K	220
T _c (K)	92 (width 1K)
J _c 77K, zero field (Acm ⁻²)	500-1000

sections at each end of the rods and annealed at 900°C in flowing oxygen, followed by an oxygen anneal at 400°C. Two modular leads were constructed, each consisting of 20 YBCO rods, 1.8mm in diameter, soldered with indium into copper end caps. This arrangement formed 10mm long contacts on each end of the rod giving a total contact area between superconductor and metal of 11.8cm² per end. To give increased mechanical strength and added protection, one of these leads was fitted with an outer cupronickel sheath soldered between the end caps around the outside of the YBCO rods. A third, unsheathed modular lead was constructed as above but comprising 28 YBCO rods, each 1.6mm in diameter.

For comparison, a larger diameter YBCO rod (10mm diameter, 150mm long) was manufactured using isostatic pressing techniques. This was constructed into a fourth "monolithic" current lead using the techniques described above.

The I-V characteristics of the leads were measured in liquid nitrogen using the equipment set-up shown in Fig. 1. It should be noted that for this application it is the resistance of the whole lead including the contacts which is important, and not just the response of the superconductor. The voltage connections were therefore made to the copper end caps and not directly to the superconductor.

III. PROPERTIES OF SINTERED YBCO

The properties of sintered YBCO elements fabricated using the techniques described above are given in Table I. The sintered ceramic has a preferred density of around 85% of theoretical to allow oxygenation and to maintain a fine grain size. Fine grain size is important because it suppresses the tendency towards spontaneous microcracking caused by differential thermal expansion of the YBCO crystallographic axes. The thermal expansion coefficients for the individual axes α_a , α_b , and α_c have been estimated using data from [9] to be 14, 19.2 and 19.4 x10⁻⁶K⁻¹, respectively. The grain facet length, L_c above which cracking will spontaneously occur is given by [10]

$$L_c = 3.1 \left(\frac{K_b}{E \Delta \alpha T} \right)^2$$

where K_b is the grain boundary fracture resistance which we take to be 1MPam^{0.5}, E is the stiffness = 180GPa, $\Delta \alpha = \Delta \alpha_c - \Delta \alpha_a = 5.4 \times 10^{-6}$ K⁻¹ and $\Delta T = 900$ K, the difference between the sintering temperature and room temperature. We then find that L_c is 4.05μm and, for grain sizes above this length, we can expect spontaneous microcracking to occur. It is of paramount importance that the grain size of the sintered YBCO is kept below this critical length.

IV. CURRENT LEAD PERFORMANCE AND TESTING

The variation in resistance with current for the monolithic and modular leads is shown in Figs. 2 and 3, respectively. All the leads show an approximately constant resistance for currents between 0 - 100A indicating critical

Fig. 1. Experimental set-up for characterisation of the current leads.

TABLE II
PROPERTIES OF YBCO LEADS

	$R_L(\mu\Omega)$	$A_c(\text{cm}^2)$	$\rho_c(\mu\Omega\text{cm}^2)$
Modular YBCO Leads			
20 Rods with Cu/Ni	0.9	11.8	5.3
20 Rods	0.8	11.8	4.7
28 Rods	0.8	14.6	5.8
Monolithic YBCO Lead	40.7	3.9	80.0

currents $>100\text{A}$ at 77K . Note however, that the resistance of the monolithic lead is approximately $40\mu\Omega$ compared to $<1\mu\Omega$ for the modular leads, probably due to the increased contact area and parallel resistance paths in the latter case. In addition, all the YBCO leads have much lower resistances than a conventional brass lead, which was found to have a resistance of $140\mu\Omega$ at 77K over the same length. The addition of the protective cupro-nickel sheath does not significantly alter the electrical properties of the modular leads.

Whilst the rods are in the superconducting state the measured resistance is due to the contacts, thus the resistance per contact is half the lead resistance (R_L). The

total contact area per contact (A_c) can be calculated from the dimensions of the rods and contacts, and it is then possible to calculate a contact resistivity (ρ_c) for the indium YBCO interface. A summary of the results at 77K is given in Table II.

The contact resistance cannot be accounted for by the layer of indium between the YBCO and copper as the resistance measured for the modular leads would imply a layer of indium approximately 100nm thick. However, no attempt was made to investigate the nature of the contact further.

The improved performance of the modular HTS leads can be clearly seen in Fig. 4 where the power dissipated at 77K is plotted against current for a conventional brass lead, the monolithic bulk YBCO lead (10mm diameter) made by isostatic pressing, and the modular lead comprising 20 YBCO elements. At a nominal operating current of 100A the brass lead dissipates 1.4W , the bulk YBCO lead 0.45W and the modular lead dissipates only 10mW .

Trials of these new leads are now in progress with a magnet manufacturer. In order to incorporate the leads into the magnet system connections at the "warm" (77K) end of the lead were made with copper braid. At the "cold" (4.2K) end a NbTi wire was attached with indium solder. This modular design was favoured because the multi-bundle concept allows channels for gas cooling, it avoids catastrophic failure which is a danger in monolithic leads, and it enables the manufacturer to easily vary the current carrying specifications. For this application, as the temperature of the majority of the lead is $<77\text{K}$, the properties should be considerably enhanced compared to those measured when all of the lead is at 77K .

Fig. 2. Resistance vs current for bulk monolithic lead (77K).

Fig. 3. Resistance vs current for modular leads (77K).

Fig. 4. Comparison of the power dissipated in brass (-), monolithic YBCO (+) and modular YBCO (■) current leads.

V. CONCLUSIONS

A modular YBCO current lead design has been demonstrated. It has been shown that the overall resistance of these leads is very low resulting in the power dissipation at an arbitrarily chosen current level of 100A being several orders of magnitude lower than the normal metal leads presently used. This, together with the low thermal conductivity of the HTS ceramic, suggests that in many applications significant cost savings may be made resulting from a reduced liquid helium boil-off rate. The leads

were fabricated by novel ceramic processing techniques giving a high degree of uniformity and reproducibility, and strengths in flexure >200MPa for the individual elements. Trials of these new leads are now in progress with a magnet manufacturer and will be reported later.

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REFERENCES

- [1] D. U. Gubser, M. M. Miller, N. McN. Alford and T.W. Button, *J. Supercond.*, vol. 3, pp. 221-226, 1990.
- [2] S. Elschner, J. Bock, M. Brand and S. Gauss, *Applied Superconductivity*, vol. 1, H.C. Freyhardt, Ed., 1993, pp. 285-292.
- [3] P.F. Herrmann et al, *IEEE Trans. Appl. Supercond.*, vol. 3, pp. 876, 1993.
- [4] *Superconductivity News*, vol. 6, no. 22, 1994.
- [5] N. McN. Alford, J.D. Birchall, W.J. Clegg, M.A. Harmer, K. Kendall and D.H. Jones, *J. Mater. Sci.*, vol. 23, pp. 761-768, 1988.
- [6] N. McN. Alford, J.D. Birchall and K. Kendall, *Nature*, vol. 330, pp. 51-53, 1987.
- [7] N. McN. Alford, K. Kendall, W.J. Clegg and J.D. Birchall, *Adv. Ceram. Matls.*, vol. 3, pp. 113-117, 1988.
- [8] K. Kendall, N. McN. Alford, W.J. Clegg and J.D. Birchall, *Nature*, vol. 339, pp. 130-132, 1989.
- [9] P.K. Gallagher, H.M. O'Bryan, S.A. Sunshine and D.W. Murphey, *Mat. Res. Bull.*, vol. 22, pp. 995, 1987.
- [10] A.G. Evans and Y. Fu, *Advances in Ceramics*, vol. 10, W.D. Kingery, Ed. Columbus Ohio: American Ceram. Soc., 1984, pp. 697.