Thermal Conductivity of Mica/glass Insulation for Impregnated Nb_3Sn Windings in Accelerator Magnets*

Andries den Ouden and Herman H.J. ten Kate

Applied Superconductivity Centre, University of Twente, POB 217, 7500 AE Enschede, The Netherlands

The thermal conductivity of a combination of glass fibre tape and mica/glass sheet as insulation for superconducting Nb_3Sn cables for a fully impregnated accelerator dipole magnet has been investigated. At 4.3 K a value for the thermal conductivity coefficient of 45 mW/m/K has been found, which is a considerable improvement compared to values of 5-15 mW/m/K if only mica/glass sheet is applied. An improved resin penetration to both sides of the mica/glass sheet not only increases the thermal conduction and therefore the stability margin of the superconductor, but it also enhances the shear strength of the insulation layer.

INTRODUCTION

As a contribution to the magnet development program for the CERN Large Hadron Collider an 11.5 Tesla single aperture Nb_3Sn dipole magnet has been designed and is currently under construction [1]. Application of the wind-and-react method demands a reaction process for the formation of the proper Nb_3Sn phase at 675 ^{0}C of the wound coils, whereafter the coils are resin impregnated to obtain mechanical stability of the conductors. The electrical insulation of the Rutherford cables, with an effective thickness of 0.07 mm, has to show a high dielectric strength (~ 10 kV/mm), flexibility and mechanical strength during magnet production and heat resistivity during the reaction process. At the same time the impregnated insulation layer has to withstand a shear stress of maximal 15 MPa which occur in the windings at maximal field. The only candidate so far that meets most of these demands is mica/glass, which is commercially available as SURITEX [2] and consists of a 0.1 mm sheet of pressed mica flakes and a thin glass fibre sheet, bonded with silicone resin

During operation in an accelerator, the magnet is subjected to several heat loads of which the most important one is absorption of radiation from beam losses, which amounts to maximal 10 mW/cm^3 in the azimuthal plane of the magnet [3].Assuming that the Nb_3Sn superconductor operates at 85 % of its critical current density at maximal field, the temperature margin is approximately 1 K. The effectivity of heat transport to the helium bath is completely determined by the conduction properties of the turn-to-turn and the winding insulation. Investigations of the thermal conduction of 0.1 mm thick mica/glass sheet, which is wrapped around the cables with 50 % overlap (figure 1^a) and pressed to a thickness of 0.07 mm resulted in an extremely low effective heat conductivity coefficient of 5-15 mW/m/K, mainly due to insufficient resin penetration between the pressed sheets [4]. A finite element computer simulation of the temperature distribution in the windings based on these data showed a maximum temperature rise of 1.5 K, well above the stability margin. At the same time the bad resin penetration into the insulation layers and the interior of the cables leads to a low shear strength between the cables. An alternative insulating method therefore has been developed in order to profit from the good electrical properties of the mica/glass and to improve the resin penetration into the windings as well by an insulation scheme as illustrated in figure 1^b. In this case a sheet of mica/glass is folded around the sides along the conductor and wrapped without overlap with a 0.1 mm thick tape of traditionally woven S2-glass fibres. Although an a priori improvement of the heat conduction is expected, experimental verification is of major importance.

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EXPERIMENTAL SET-UP AND SAMPLE PREPARATION

The heat conductivity measurements between 4.2 and 20 K, perpendicularly to the sheets, have been performed with the steady state gradient method using a set-up as illustrated in figure 2. Inside a vacuum can, that is placed in a helium bath, samples and copper blocks are glued to the temperature regulated heat sink with STYCAST 1266 wetted cigarette paper, which thermal resistance appeared to be negligible compared to the sample conduction. Miniature germanium resistors serve as 4 point thermometers [5], whereas the heaters are wound from manganine wire. The temperature gradient never exceeded 2 % of the heat sink-temperature. The reproducibility between different samples of the same kind and measurements on old samples [4] amounts 1 %, whereas the absolute accuracy appeared to be 12 % at 4.2 K and 7 % at 20 K.

The investigated samples consisted of different combinations of mica/glass and glass sheet. Both type of sheet have an initial thickness of 0.1 mm which is reduced to 0.07 mm by pressing before vacuum impregnation. The glass sheet is cleaned by a heat treatment in air and contains no binder material. In table 1 the sample compositions. are summarised. At least 2 samples of each kind have been prepared and investigated. All samples are impregnated with epoxy resin CIBA MY 740, HY 905 and DY 62, whereafter they are glued between copper blocks. The heat treatment is performed at 675 ^{0}C in a vacuum oven during 45 hours. Cable samples CGM and CGMG are insulated according to figure 1a and 1b respectively.

Table 1 Composition of the investigated samples

Samplename	Composition	Heat treated at 675 ^{0}C
GM	12 layers mica/glass	no
GMG	6 layers mica/glass-6 layers glass	no
GMHT	32 layers mica/glass	yes
CGMG	8 cables mica/glass-glass	yes
CGM	8 cables mica/glass	yes

RESULTS AND DISCUSSION

The results of the thermal conductivity measurements in a restricted temperature range from 4.2 to 18 K on the samples listed in table 1 are shown in figure 3, together with typical values for commonly used epoxy impregnated glass fibres, as G10 [6]. The large differences between the GM and GMG cannot be explained by the thermal conduction of epoxy impregnated glass fibres. However, pressing stacked mica/glass sheets to 70 % of their initial thickness before impregnation leads locally to areas with a weak silicone resin bonding between two successive layers, which results in insufficient epoxy penetration between the mica/glass sheets. A larger reduction of the conduction of mica/glass sheet occurs after the heat treatment in vacuum, as shown by the GMHT data. The evaporation of the silicone resin binder generates micro cracks between the mica flakes and the bonded glass fibres, which reduces the contact area between the mica flakes inside the sheet. These micro cracks apparently cannot be filled with epoxy during vacuum impregnation, as is confirmed by X-ray scanning [4]. The low shear strength of the mica/glass sheets is a logical consequence from these defects.

A comparison between the cable samples CGM and CGMG, which are exactly treated as the magnet windings, shows qualitatively the same behaviour. The exchange of a mica/glass sheet by a glass sheet increases the effective thermal conductivity of the insulation layer from 10 to 45 mW/m/K at 4.3 K, which can be attributed to the good porosity for epoxy resin of the glass fibre sheets. The heat treated CGMG samples again show a lower conductivity than the GMG samples. The increase of the thermal conductivity by replacing a layer of mica/glass with glass fibre sheet leads to an acceptable temperature rise of about 0.5 K in the magnet windings if they are subjected to the expected radiation load. The resulting temperature margin of 0.5 K enables safe and reliable operation of Nb_3Sn accelerator dipole magnets.

The shear strength of the insulation layers in the CGMG samples is determined completely by the impregnated glass fibres, which normally prevents crack formation in the windings during magnet operation as long as the shear stress does not exceed 20 MPa. A mechanical analysis of this magnet shows, that the maximum shear stress at full field amounts to 15 Mpa [7].

A dummy half coil has been wound, pressed to its final dimensions, cured at 675 ^{0}C and impregnated with the mica/glass-glass insulation around the conductors. During winding of the cos(θ)-dipole coil with heavy cables it is hard to prevent damage of any insulation material between cables and winding mandrel in the coil heads. These locations however are reasonable accessible for repair after curing. No insulation problems have been met between the conductors. Although the insulation layers are vulnerable after the heat treatment, careful coil handling prevents additional damage, which has been confirmed by a representative voltage discharge measurement of about 100 V per turn on the impregnated dummy coil.

CONCLUSIONS

Mica/glass sheet is until now the only serious candidate that has acceptable properties as electrical insulator for Nb_3Sn cable in fully impregnated accelerator dipole magnets. Its effective thermal conductivity of 10-20 mW/m/K at 4.3 K however results in an unacceptable temperature rise inside the windings of 1.5 K due to the expected radiation load in an accelerator. Insufficient resin penetration between the mica/glass sheets and micro cracks between the mica flakes inside the sheets are responsible for this low conductivity value and leads to a low shear strength of the insulation layers. A combination of mica/glass and glass-fibre sheet as cable insulation increases the thermal conductivity to 45 mW/m/K at 4.3 K. The maximum temperature rise in this case is reduced to 0.5 K which leaves an acceptable stability margin for the superconductor of 0.5 K. The acquired shear strength of this insulation system meets the mechanical demands for reliable magnet operation.

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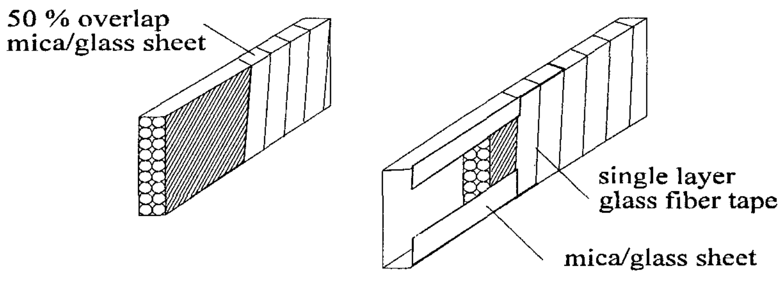

Figure 1 Cable insulation with mica/glass sheet only (1a) or combined with glass fibre sheet (1b)

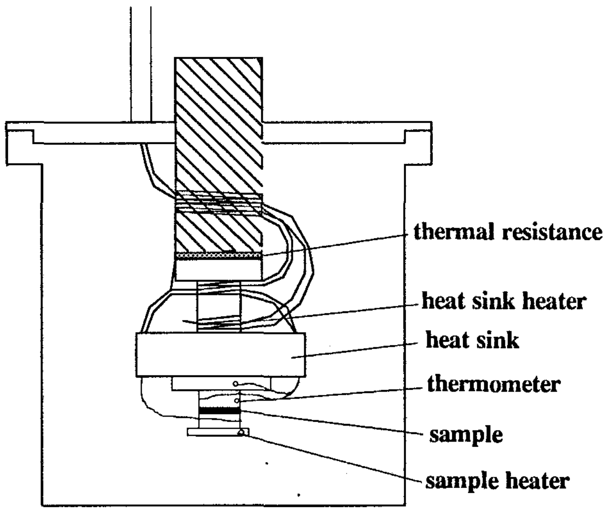

Figure 2 Experimental setup for heat conductivity measurements

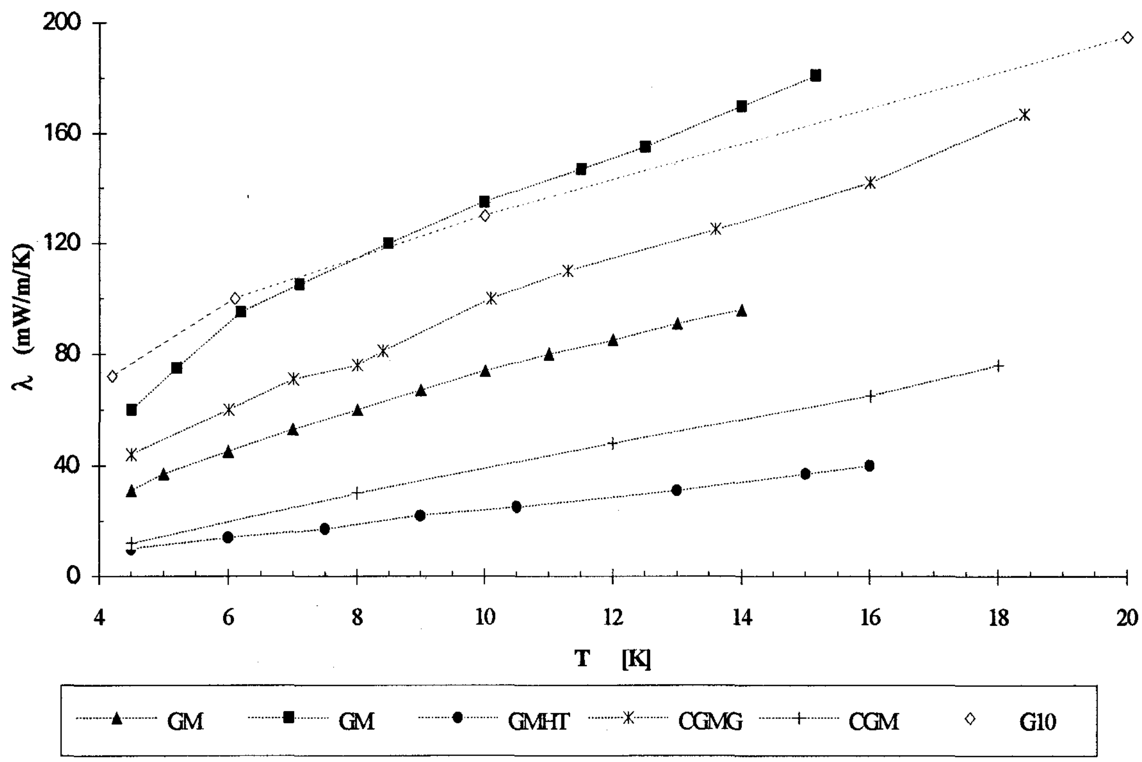

Figure 3 Thermal conductivity coefficients of investigated samples (G10 data taken from ref. [6])