Magnetic shielding of MgB\(_2\) tubes in applied DC and AC field

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Abstract. The magnetic shielding produced by superconducting tubes was of applicative interest in high energy physics apparatus. Except several attempts with LTS materials, up to now no HTS material has been used for this application, partly due to the low current capability and partly to the poor mechanical properties of the conventional bulk cuprates. An alternative, among the Medium Temperature Superconductor (MTS) material is represented by MgB\(_2\) in bulk form. This material can be quite easily produced at high density by the reactive liquid Mg infiltration route, generating tubular bodies of various shape and good mechanical strength. The shielding efficiency in several tubular MgB\(_2\) objects has been tested at 4.2 K, applying DC and AC fields and the criticality of the thermal instability due to flux jumps of the superconducting manufac\(ts\) has been evidentiated. The possibility to shield field larger than 1 T has been demonstrated.

1. Introduction

The magnetic shielding is one of the most appealing applicative area of the superconducting materials, due to their intrinsic properties to respond to a magnetic perturbation with the generation of supercurrents which can shield completely the field. In the past, attempts to use low T\(_c\) superconducting tubes was done in high energy physics experiments\([1,2]\) and today the most advanced magnetic shielding systems are used in the space projects, to protect the analytical instrumentation applying superconducting Pb foils, at the cryogenic temperatures of the liquid He\([3]\). The possibility to use High Temperature Superconductors (HTS) as magnetic shields represents a substantial technological advancement in term of energy saving and of volume reduction of the overall system, including the cryogenics. Among the HTS, the recently discovered superconductivity of the MgB\(_2\) up to 39K\([4]\) can open interesting applicative windows for the beneficial characteristics of this material, summarized in an easier manufacturing process, better mechanical strength and lower density with respect to the oxide superconductors. The densification of the bulk MgB\(_2\), in various shape, as for example tubes or rings, can profit from a new manufacturing technology based on the Reactive Liquid Mg Infiltration (RLI), discovered by EDISON \([5]\). According to this technology large bulk superconducting materials can be produced without the use of hot high pressure apparatus, obtaining manufac\(ts\) of about 90\% of the theoretical density and with excellent superconducting properties \([6]\). In the present work we present the first data of the magnetic shielding ability of several bulk MgB\(_2\) samples, in form of rings or tubes, obtained by RLI. The magnetic fields have been applied at 4.2K, coaxial to the ring main axis, and have a DC component added to an AC component of various frequencies, up to about 60 Hz. Several kind of material preparations have been analysed in order to test different bulk MgB\(_2\) morphologies.
2. Samples preparation
In this study bulk magnesium diboride rings and tubes, obtained by Reactive Liquid Mg Infiltration, have been taken into account.
The samples tested in this work belong to four different preparation procedures, of which (A,B) refer to rings and (C,D) to tubes:
A. Pure amorphous boron powders, of micrometre grains size, was packed in a cylindrical stainless steel container and infiltrated by liquid Mg at 900°C for 1 hour, in order to achieve a highly dense MgB\textsubscript{2} bulk material (density of bulk sample= 2.4 g/cm\textsuperscript{3}). By electro erosion a hollow cylinder of dimensions: diameter(\text{ext/int})= 16/7 mm; height =7 mm) has been obtained
B. Pure amorphous boron powders, of micrometre grains size, were mixed with Mg chips of size less than 1 mm. After reaction at 900°C for 1 hour, in a closed stainless steel container, a macro-porous sample of bulk MgB\textsubscript{2} was extracted (bulk density of the sample= 2.10 g/cm\textsuperscript{3} and mean size of the pores about 0.7 mm). By electro erosion a hollow cylinder of dimensions: diameter(\text{ext/int})= 25/15 mm; height =15 mm) has been cut
C. Pure crystalline boron powders with grain size < 100 \(\mu\)m were packed between the internal wall of a stainless steel tube and an internal coaxial cylindrical rod of Mg (density of the B preform=1.5 g/cm\textsuperscript{3} and Mg/B about 20% more of the stoichiometric value). The boron preform was infiltrated by liquid Mg at 900°C for 2 hours, in order to achieve a highly dense MgB\textsubscript{2} bulk tube, 26 cm long, and of diameters (\text{ext/int})= 9/7 mm (density of bulk sample= 2.35 g/cm\textsuperscript{3}). From the long tube, a 60 mm long tube, used for the magnetic shielding experiments was cut, by diamond sawing.
D. A well dispersed mixture of 70 wt% crystalline boron powders and of 30 wt% of amorphous boron powders was inserted in the space comprised between coaxial stainless steel tubes and infiltrated from both sides by liquid Mg at 900°C for 1 hour. A dense bulk MgB\textsubscript{2} manufact was obtained (density of bulk sample = 2.35 g/cm\textsuperscript{3}) having hybride morphology, partly constituted by large crystalline grains, partly by micron size grain, corresponding to the proportion of the starting boron mixture. A tube of dimensions: diameters (\text{ext/int})=12.5/8.5 mm and height 43.5 mm was cut by electro erosion

3. Magnetic measurements

3.1 – Magnetic field shielding measurements

The magnetic field values were recorded by an Hall probe, inside the superconducting rings or tubes placed at He liquid temperature (4.2 K), when subjected to an applied external coaxial magnetic field produced by a superconducting magnet. In such a way we can determine the field value, corresponding at the maximum complete shielding. Furthermore the applied magnetic field can be a DC field or an AC field with a time dependence described by a \(B_{ac}\) sinusoidal field, superimposed by a constant field \(B_o\), like:

\[
B(t) = B_o + B_{ac} \cos (2\pi \nu t)
\]

The frequency interval taken in consideration was up to 61 Hz. Due to limitation in the superconducting magnet supplying the alternate fields, the chosen \(B_o\) values were decreasing with the field intensity. By switching off the applied field, in the case of the DC fields, it was possible to distinguish between the existence interval of a trapped field and the field that destroy the superconductivity.
3.2 Results

The general behaviour of the measured residual magnetic field, in the case of an applied DC field, is described in Figure 1, for the Sample A. Varying the applied magnetic field, there is a first interval up to 0.51 T in which the field is completed shielded, afterwards, in the field range between 0.51-0.73 T, a trapped field was monitored. After the removal of the applied field, and finally for larger values than 0.78 T there is a quench of superconducting state.

Assuming a simple model of an uniform current distribution in the sample A, the maximum trapped field corresponds to a superconducting current of about 250A; if a more realistic model of the current distribution in the peripheral skin of the ring is assumed and the typical $J_c$ for this material (4000A/mm² at 4.2K) is assumed, the thickness of the ring interested by the current is about 0.4 mm.

The results of the AC measurements for the rings show a very sharp transition to the normal state, as reported in Figure 2 for the sample A, at 5Hz and with $B_o=0.59$ T. In the histograms of Figure 3 are reported, for the A and B rings, the highest field values $B_o+B_{ac}$ corresponding to full shielding, for selected frequency of the AC field. In these AC experiments, we monitor the internal field with a good sampling time, nevertheless only in one case it was possible to detect the transition event to the normal state. The reported event, for sample A at 2Hz and $B_o=0$, $B_{ac}=0.67$T, is described in Figure 4 and it indicates a transition to the normal state after 3 seconds.

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**Figure 1.** Residual DC magnetic field in ring A

**Figure 2.** Hall measurements of the internal field of the MgB₂ ring B, for different coaxially external applied AC fields.

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**Figure 3.** Maxima shielded fields (DC+AC) for the MgB₂ rings A and B (see text)

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*a* Due to our actual sensitivity limitations in the voltage measurements of the Hall probe, at lower fields the apparently non zero residual fields, in the full shielded region, must be considered an experimental artefact.
Figure 4. Transition process from superconducting to normal state

The AC measurements for the tubes (samples C,D) show a broad transition to the normal state, as evidenced in Figure 5.

Figure 5. Hall measurements of the (DC+AC) field inside the MgB$_2$ tubes C and D, as function of the frequency of the applied AC field

4. Discussion and conclusions

The MgB$_2$ rings(A,B), made by amorphous B powders, show good performance as magnetic shields, in particular the sample B, characterized by macroporosity, reaches at 4.2K a max shielding field (DC+AC) of 1.1T. The transitions of the rings to the normal state, as a function of the applied fields, are very steep, on the contrary the tubes (C,D) have a more sharp behaviour. The actual tubes, made by full crystalline or partially crystalline B have less performance but, also in this case, the addition of amorphous Boron improves the shielding characteristics.

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