Physica C 505 (2014) 18–23

Contents lists available at ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

Trapped magnetic field in a (NdFeB)–(MgB_2) pair-type bulk magnet

Gheorghe Aldica [a], Mihail Burdusel [a,b], Petre Badica [a,*]

[a] National Institute of Materials Physics, Atomistilor 105bis, 077125 Magurele, Ilfov, Romania

[b] Faculty of Materials Science and Engineering, "Politehnica" University of Bucharest, Splaiul Independentei 316, 060042 Bucharest, Romania

ARTICLE INFO

Article history:
Received 3 March 2014
Received in revised form 17 June 2014
Accepted 1 July 2014
Available online 10 July 2014

Keywords:
MgB_2
NdFeB
Superconducting bulk magnet
Trapped magnetic field
Spark Plasma Sintering

ABSTRACT

Superconducting bulk discs, S, of 20 mm in diameter and 3.5 or 3.3 mm thickness of MgB_2 (pristine or added with cubic BN, respectively) with density above 97% were prepared by Spark Plasma Sintering. Discs were combined in a pair-type sandwich-like arrangement with a permanent NdFeB axially magnetised magnet, PM (~0.5 T). Measurement of the trapped field, B_{tr}, with temperature, time, and the reduction rate of the applied magnetic field was performed using a Hall sensor positioned at the centre between the superconductor and the permanent magnet. It is shown that the permanent magnet with certain polarity favors higher trapped field of the superconductor owing to suppression of flux jumps specific for high density MgB_2 samples. The B_{tr} of the PM–S pair was 2.45 T (20 K) and 3.3 T (12 K).

1. Introduction

MgB_2 is recognized as a potential candidate for superconducting applications. This is because it is a light-weight, commercially available and relatively cheap material, it can be produced into large and various geometries and it has a relatively high coherence length, ξ, so that the weak link problem at the grain boundaries is not critical as for high-temperature superconductors. The temperature domain of MgB_2 application is close to 20 K where, owing to high irreversibility magnetic field, B_{irr}, and critical current density, J_c, it can compete both with low and high temperature superconductors. Recent development of cryocooling systems and prospects of hydrogen cooling and technologies in the future makes MgB_2 valuable in terms of high potential for different applications.

Different groups reported trapped field of bulk MgB_2 [1–23]. Theoretical calculations indicate the possibility of trapped fields up to 7 T at 5 K [1]. The maximum attained trapped fields for MgB_2 superconducting bulk magnets are 4.6 T at 14 K [17] or 5.4 T at 12 K [18]. Trapped field, B_{tr}, in superconductors, is [18]:

$$B_{tr} = B_0^* k = 0.5\mu_0 J_c^{bulk} R k \quad (1)$$

with $k = g \ln((1 + (1 + g^2)^{1/2})/g)$, $g = h/R$, h and R are the height and the radius of the cylindrical sample, respectively, J_c^{bulk} is the field-independent (bulk) critical current density of the superconductor within the Bean model, and B_0^* is the measured trapped field B_{tr} at the position $(r, z) = (0, 0)$ for a 'half' infinite long cylinder of radius R which occupies $-\infty < z < 0$. Eq. (1) indicates that a larger sample size or a higher J_c^{bulk} can enhance B_{tr}. Enhancement of B_{tr} with the size is an advantage of the superconductors because in permanent magnets remanent field and energy density do not depend on sample size and are fixed materials properties. However, in practice, for superconductors situation is complex because there are limitative factors such as thermo-magnetic instabilities, i.e. macro flux jumps. Usually macro jumps are critical for the work of a superconducting magnet since J_c lowers abruptly and significantly, sometimes to zero values. Macro jumps are often observed in MgB_2 samples at temperatures below 10 K. We also note that when bulk density of the samples exceeds 95%, micro jumps occur in the 10–20 K temperature range [24] suggesting that in dense MgB_2 samples, J_c is almost constant, while the system tends to thermo-magnetic instabilities. Sample quality (microstructure, doping, and defects), geometrical arrangement and magnet charging procedure can influence thermomagnetic instabilities leading to, or preventing, the catastrophic situations when macro flux jumps are active.

Sandwich-like superconductor–superconductor (S–S) pairs [4,8,10,16,17] composed of MgB_2 discs with the same size show a higher B_{tr} with about 0.7–0.9 T i.e. with 20–40% at 20 K than for the single superconducting disc. It would be of interest to study pairs of MgB_2 superconductor (S) and a permanent magnet (PM). In the PM–S case, PM can be arranged with a different polarity vs. superconductor and of the charging field. This cannot be obtained for a superconductor–superconductor pair. Another advantage is that magnetic profile and behavior of a PM under given conditions or for varying external parameters is different than for a superconductor. This provides extended possibilities in

* Corresponding author. Tel.: +40 21 3690170; fax: +40 21 3690177.
E-mail address: badica2003@yahoo.com (P. Badica).

http://dx.doi.org/10.1016/j.physc.2014.07.001
0921-4534/

applications where e.g. distribution of magnetic field should be controlled. In this regard, usually different combinations between a superconductor and a ferromagnetic material were used and demonstrated [25–28]. In Ref. [18] stacking of MgB_2 cylinders was suggested using intercalated metallic spacers in the gap between the individual cylinders in order to improve the thermal stability avoiding limitative macro flux jumps, but, no example was presented. Considering also previous observations, it is of interest that metallic spacers are ferromagnetic or permanent magnets.

In this work we study behavior of B_{tr} in a NdFeB (PM)–MgB_2 (S) pair bulk magnet system of 20 mm in diameter and 3.3 or 3.5 mm thickness (part S) and we show expanded working window owing to suppression of macro flux jumps. The maximum B_{tr} of the PM–S pair attained 2.45 T (20 K) and 3.3 T (12 K).

2. Experimental

Two bulk discs of 20 mm in diameter were prepared by *ex-situ* Spark Plasma Sintering and are presented in Table 1. One sample is a pristine sample ‘a’ and the second one ‘b’ contains cubic BN ((MgB_2) + $(c\text{-}BN)_{0.01}$). Powder of MgB_2 was commercial (Alfa Aesar, 99.5%, catalog stock No. 88149). Sample ‘a’ was SPS ed by two-temperature route at 1150 °C for 2 min and at 1100 °C for 5 min [24]. For sample ‘b’ we applied one-temperature route with SPS at 1150 °C for 3 min. In both cases the maximum pressure during SPS was 95 MPa. The heating rate was 110 °C/min and furnace cooling was applied. Graphite moulds with punches were used. The curves of relative density during SPS processing (R^{SPS}) are presented in Fig. 1. Curves were determined according to Ref. [24] based on the Archimedes density of the as-SPS-ed bulk sample and on the vertical shrinkage of the distance between punches measured *in-situ* by SPS machine (FCT Systeme GmbH HP D5, Germany). Samples have shown some differences in the consolidation behavior. Namely, shapes of the curves are different and the initial relative green density is higher for added sample ‘b’, while the temperature where accelerated densification occurs, T_d, is lower for the same sample. This suggests that c-BN is favorable to MgB_2 consolidation. However, the final density of the samples is not much different, i.e. 99.2% and 97.7% for sample ‘a’ and ‘b’ (added sample), respectively. The two samples are not much different (Table 1) also from the viewpoint of residual phases (MgB_4 and MgO), or lattice parameters of MgB_2 as revealed using X-ray diffraction (Bruker-AXS D8 ADVANCE diffractometer, Cu Kα1 radiation) and Rietveld refinement (MAUD software, version 2.31). The c-BN is not reacting with MgB_2 and preserves its cubic structure during processing: sample ‘b’ can be considered a typical composite. Its T_c is 38.65 K, close to value of 38.8 K for MgB_2 pristine sample ‘a’. Both samples show sharp transitions into superconducting state, and J_c at low fields and at 5–30 K is similar. J_c at low fields is considered to determine B_{tr} [4]. More details on preparation and properties of MgB_2 samples added with c-BN will be presented elsewhere.

The PM–S pair arrangement of the bulk magnet was realized as shown in Fig. 2, and for magnetic testing of the device we used PPMS equipment (Quantum Design, 14T). A single S-disk or the pair PM–S bulk magnet was fixed on a standard puck (sample holder) for PPMS resistive measurements. The Hall sensor (LHP-MU by AREPOC s.r.o, Slovakia) was placed at the centre and on the surface of the S-disk or between the PM and S disks. In the second case, to protect the Hall probe we used a Plexiglas (part 6 in Fig. 2). In our arrangement some layers (3, 5, 8, and 10) were two-side sticking tapes. They fix the parts and ensure rigidity during magnetic experiments. In some cases they were selected to be relatively soft and thick (3, 10) to play the role of a cushion under the pressure of a long stick adjustable in length and fixing the entire arrangement from the top (not shown). Before measurements on single or pair bulk magnets we performed a calibration of the Hall sensor resistance vs. magnetic field.

PM is a NdFeB magnet from Webcraft GmbH (type S-20-08-N, 20 mm in diameter, 8 mm thickness, Ni-plated, and with axial magnetization).

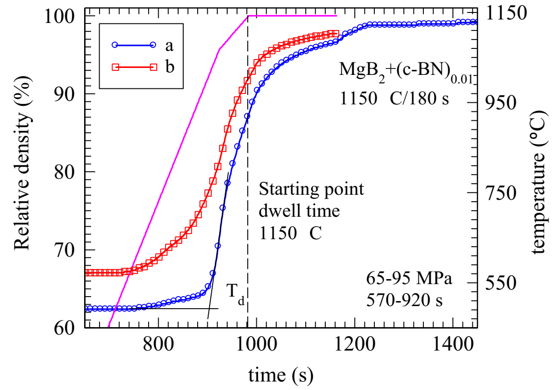

Fig. 1. Relative density, R^{SPS}, and heating temperature vs. SPS processing time for pristine MgB_2 (disc ‘a’), and MgB_2 + $(c\text{-}BN)_{0.01}$ (disc ‘b’) samples. Separate curve without markers represents the temperature–time dependence during SPS.

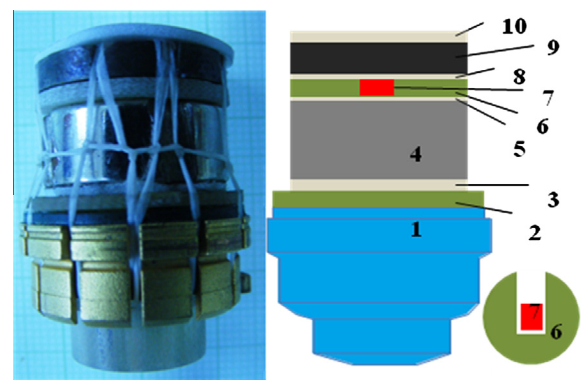

Fig. 2. Pair-type bulk magnet arrangement: permanent magnet (PM) (4) – Hall sensor (7) – superconducting samples (S) (9) arrangement on a PPMS puck holder (1). Double-side sticking tapes are denoted with 3, 5, 8, and 10 (see also text).

3. Results and discussion

We first investigated the trapped magnetic field in the single-S disk arrangement. Results for sample ‘a’ are shown in Fig. 3.

Table 1
MgB_2 samples, composition, apparent and relative densities, lattice constants, impurities phase content and sample size (D = diameter, t = thickness).

Sample	Composition	Apparent density, ρa^{SPS} (g/cm^3)	Relative density, R^{SPS} (%)	Lattice parameter		Content wt (%)		Size (mm)
				a (Å)	c (Å)	MgO	MgB_4	$D \times t$
‘a’	MgB_2	2.62	99.2	3.082(8)	3.524(8)	6.3	8.6	20 × 3.5
‘b’	$MgB_2(c\text{-}BN)_{0.01}$	2.61	97.7	3.083(4)	3.529(2)	7.7	10.9	20 × 3.3