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► To cite this version:

Kazuya Yokoyama, Tetsuo Oka, Kévin Berger, Rémi Dorget, Michael Rudolf Koblischka, et al.. Investigation of flux jumps during pulsed field magnetization in graphene-added MgB₂ bulks. *Journal of Physics: Conference Series*, 2020, 14th European Conference on Applied Superconductivity (EU-CAS2019) 1-5 September 2019, Glasgow, UK, 1559, pp.012080. 10.1088/1742-6596/1559/1/012080 . hal-02885701

HAL Id: hal-02885701

<https://hal.science/hal-02885701>

Submitted on 30 Jun 2020

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Investigation of flux jumps during pulsed field magnetization in graphene-added MgB₂ bulks

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Abstract. MgB₂ bulk superconductors are expected to be utilized as rare-earth-free and light-weight trapped field magnets. However, the flux jumps frequently happen during the magnetizing processes, and heavily degrade the field-trapping performances. We have investigated the effect of additives to the MgB₂ bulk samples prepared by spark plasma sintering process, and observed various flux jumps during the pulsed field magnetizing processes, which were carried out at 14 K which was obtained by the 2-stage GM cryocooler. The authors classified the flux motions as three categories as “no flux flow”, “fast flux flow”, and “flux jump” regions, and investigated the conditions where the flux jumps happen. We observed some drastic flux jumps in the pristine and clarified the effect of graphene addition to the flux jumps. The experimental results showed us a possible expansion of no flux jump region, and suggested us the improvement of field trapping capability.

1. Introduction

The large-grown high temperature superconducting (HTS) bulk materials are capable of acting as the quasi-permanent magnets in their superconducting state. In general, they are called “trapped field magnets” (TFM) or bulk magnets [1], [2]. Since the field-trapping performance linearly increases with descending temperature, it is important to cool the TFM at the temperature less than 77 K. High T_c values are not always necessary when we employ cryo-coolers instead of liquid nitrogen. Because we can easily attain certain low temperature conditions only by turning on the switches of cryo-coolers [3].

Besides RE-Ba-Cu-O (RE: rear earth) family, MgB₂ bulk compounds, whose T_c is 39 K [4], have been regarded as promising candidates with uniform microstructure which are superior to REBCO TFMs. Since the MgB₂ bulk superconductor is homogeneous metallic compound with less numbers of



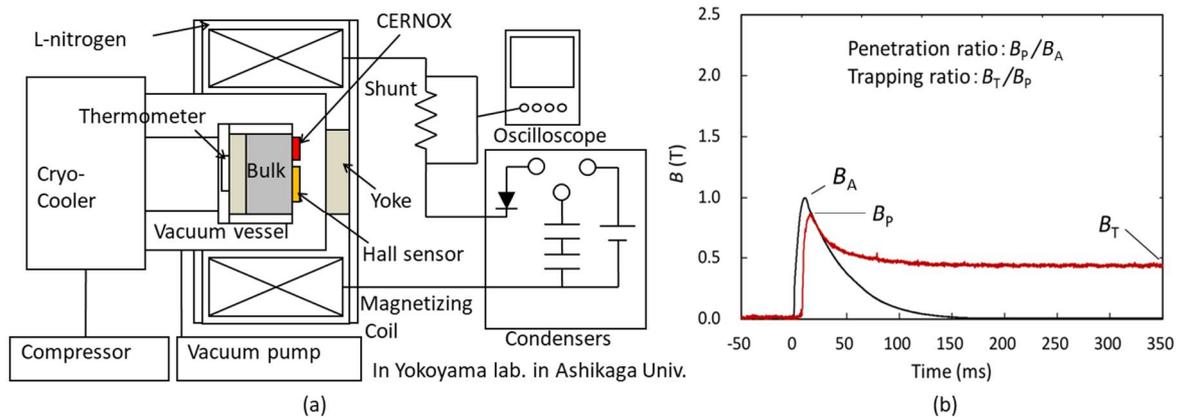


Figure 1. Experimental set up of PFM at 15 K (a), and the definition of parameters (b)

cracks or segregated inclusions than those of REBCO, we may obtain more uniform magnetic field distribution than REBCO when they would be utilized as NMR/MRI magnets [5], [6]. This useful advantage is attributed to longer coherence length than that of oxide superconductors, which may likely overcome the weak-link problems. Mg is one of the common metals, which suppresses the material cost low [7].

Low specific heat and high thermal conductivity of MgB_2 bulks cause the magneto-thermal instability, and result in the frequent flux jumps and the dissipation of trapped-flux during the pulsed field magnetization (PFM) processes [8], [9]. In this paper, typical experimental results on PFM are introduced, and the flux motions are categorized into three patterns which indicate the characteristic behaviors of flux dissipations from the samples in order to clarify the mechanism of flux stability.

2. Experimental procedure

2.1. Sample preparation and experimental setup for PFM

We employed a pair of MgB_2 bulk magnet samples which were synthesized by Spark Plasma Sintering (SPS) performed at 1150 °C for 3 min under 95 MPa. The size of the samples was unified to 20 mm in diameter and 3.5 mm in thickness. We prepared a pristine sample called as “pure”, and graphene-added sample “G”, aiming the improvement of J_c [10]. They were processed by *ex-situ* method which adopted MgB_2 compound as a raw material.

The structure of equipment is shown in Figure 1a [11], [12]. A Hall sensor and a thermometer were attached on the cold stage of the 2-stage GM cryocooler. A pair of iron yokes were attached close to the MgB_2 sample to lead magnetic flux to the bulk sample. The pulsed fields of 0.4 to 2.0 T were applied to the bulk magnet at 14 K by 112-turn pulse coil which was immersed in liquid nitrogen. The trapped fields B_T during and after PFM operations were measured at the centre of the sample surface. The sample was heated to the normal state after each measurement.

2.2 Definition of parameters and estimation

Figure 1b shows a typical time-evolutional profile of PFM. The authors defined the parameters, which estimate the flux-penetrating and -trapping properties as “Field penetration ratio B_p/B_A ” and “Field trapping ratio B_T/B_p ”, respectively [13]. The value of B_p/B_A reflects the shielding effects of bulk sample in its flux invasion stage, and B_T/B_p depends on the heat generation and its transfer. In the paper, we focus on the flux-trapping property B_T/B_p and the occurrence of flux jumps.

3. Results and Discussion

3.1 Trapped field performance

Figure 2a shows the trapped field B_T for the pristine sample. The flux began to invade into the centre point of the sample surface at $B_A = 0.6$ T, and gradually increased with increasing applied fields to the maximum value of 0.51 T at 1.3 T. The penetration field and the trapping ratio were 0.98 T and 52.0%, respectively. The flux jumps often occurred in the sample “pure” when the applied field exceeded 1.3 T, and the trapped field drastically decreased to 0.1 T, shown by arrows. As shown in Figure 3a, as for sample “G”, although the field invasion starts at 0.5 T as well as the pristine sample, one sees no substantial increase of B_T with increasing applied field, and field trapping was suppressed less than 0.2 T till 2.0 T application. This implies that the J_c value might have been lowered by graphene addition. However, one sees no flux jumps at all even at high field application of 2.0 T.

3.2 Flux motion during the PFM process

Figure 2b and 3b show the time-evolutional profiles of field invasion for samples “pure” and “G” at low field applications of 0.4 - 0.5 T. The characters “b” – “d” in (a) correspond to the profiles aside in the figure. The flux penetration in the samples kept the same intensities as B_p without any serious decrease until 350 ms. This stage is classified as “no flux flow” region. There, the flux motion does not generate the substantial heat which hindered the field trapping. Trapping ratios remained high values of 82.6% and 70.4% for the pristine and sample “G”, respectively. The time when the magnetic flux began to invade was a little delayed to the time of field application. This means the shielding effect works well at low field application region.

Figure 2c and 3d show the time-evolutional profiles for sample “pure” at 1.3-T application and for sample “G” at 1.8 T, respectively. The trapped flux B_T have drastically descended just after the peaks of B_p . It is noted that no flux jumps were observed in these cases. The fast flux flow (FFF) occurs at the

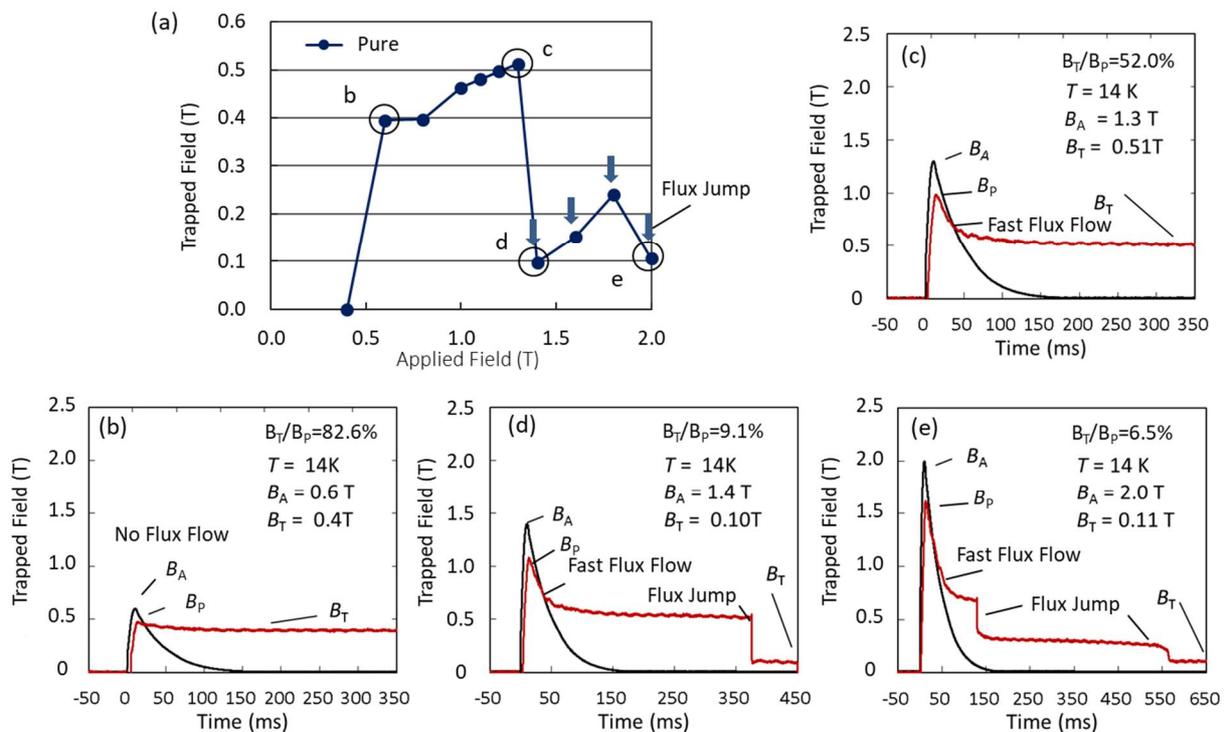


Figure 2. Trapped fields of the pristine sample after PFM operations, and their evolutionary profiles showing the flux motion at 0.6 – 2.0 T (b)-(e).

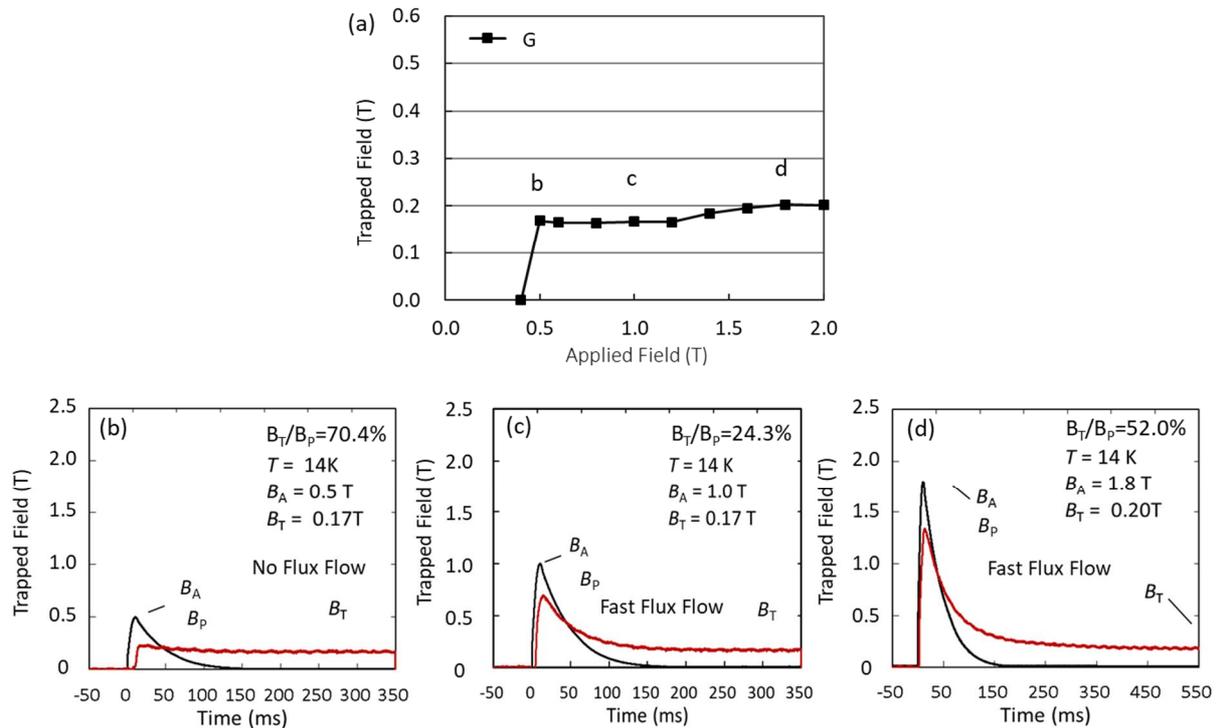


Figure 3. Trapped fields of the graphene-added sample “G” after PFM operations, and their evolutionary profiles at 0.5 (a), 1.0 (b), and 1.8 T (c).

lower applied field than the flux jump region (abbreviated as FJ). The appearance of FFF should be attributed to the heat generation due to the flux motion.

In Figure 2d, we observed a prominent flux jump which happened at 380 ms. In Figure 2e, we can find two different flux jumps at 120 and 570 ms. These flux jumps may be correlated to regions of FFF. In other words, FFF brings FJ, which results in the low flux-trapping less than 10% due to the heat generation by releasing the flux which were pinned in the bulk sample with high J_c values.

The two-stage flux dissipation shown in Figure 2e may be understood by the explanation that the locally-generated heat reached the position of the Hall sensor twice in different times. This means heat generation happened and transferred at different positions and times in the sample. The magnetic flux never uniformly invades even in the MgB_2 bulk sample. In Figure 2 and 3, we do not observe any delay of time at the very beginnings of field invasion in the high field applications. This means the flux-shielding is not effective at the very beginning of field applications. It is commonly observed in the past, as well in the case of sample “pure” in this study, that FJ region appears after FFF regions. Furthermore, the occurrence of flux jump makes the trapped flux distribution after PFM stable. We should note that no flux jumps happened in the sample with low J_c conditions because of low heat generation even when magnetic flux moves around in high field region of up to 2.0 T.

4. Conclusion

The authors estimated the magnetic flux trapping of MgB_2 samples made by SPS technique, investigating the occurrence of flux jumps. Different J_c performances between the pristine and graphene-added samples suggest us that the flux jumps appear in high flux-trapping area due to strong J_c values, while no flux jumps were observed in FFF region as for the sample having less J_c value. The flux jumps which happened for two times suggest us that the heat generation attacked the trapped flux again even in the condition classified as NFF region. We need further study on the difference between the FJ and NFF regions.

ACKNOWLEDGMENT

Romanian team acknowledges MCI-UEFISCDI, grant POC 37_697 no. 28/01.09.2016 REBMAT and Core Program 2018/2019.

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