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Shielding Effect on Flux Trapping in Pulsed-Field Magnetizing for Mg-B Bulk Magnet

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Abstract. MgB₂ superconducting bulk materials are characterized as simple and uniform metallic compounds, and capable of trapping field of non-distorted conical shapes. Although pulsed-field magnetization technique (PFM) is expected to be a cheap and an easy way to activate them, the heat generation due to the magnetic flux motion causes serious degradation of captured fields. The authors precisely estimated the flux trapping property of the bulk samples, found that the flux-shielding effect closely attributed to the sample dimensions. The magnetic field capturing of Ti-5.0wt% sample reached the highest value of 0.76 T. The applied field which reached the centre of the sample surface shifted from 1.0 T to 1.2 T with increasing sample thickness from 3.67 mm to 5.80 mm. This means that the shielding effect was enhanced with increasing the sample thickness. Moreover, Ti-addition affected the frequency of flux jump happenings. The occurrence of flux jumps was suppressed in 5.0wt%Ti-added sample. This means that the heat capacity of the compounds was promoted by Ti addition.

1. Introduction

The field-trapping principle of high temperature superconducting bulk materials (hereafter abbreviated as HTS bulk magnets or bulk magnets) is different from that of conventional permanent magnets such as Nd-Fe-B or ferrite magnets [1], [2], [3]. Since the trapped field of bulk magnets are roughly simulated as what we call pancake coils, one can obtain extremely intense magnetic field by flowing the intense current to the coils composed of superconductors because the electrical resistivity is negligible. Melt-grown bulk materials are regarded as a sort of non-insulated coils. Both systems may be characterized by the rearrangement of superconducting current. Extraordinary intense magnets are realized when they capture the applied fields by field cooling method (FC) from superconducting solenoid magnets [4], [5] or the pulsed-field magnetizing (PFM) technique [6], [7].

Beside the rare earth-based compounds (REBa₂Cu₃O_{7-y} system, RE means rare earth elements), MgB₂ bulk materials are characterized as its uniform crystal structure and resultant uniform field trapping [8]. Although the T_c is low as 39 K, the field distribution with no distortion brings its advantageous applications which demand homogeneous field spaces [9], [10], [11].



Table 1. Specification of bulk samples

Sample	Ti addition (wt%)	Thickness (mm)	Aspect ratio
MH104b	2.5	3.30	6.06
MH104d	2.5	5.55	3.60
MH113a	5.0	3.23	6.19

20 mm in diameter, Hot-pressed, Single-layer
Dr. Häßler *et al.* in IFW Dresden

Although the world-highest record of 1.61 T has been reported [12], the thermal instability originated from the low specific heat and high thermal propagation coefficient due to “metallic” character has caused serious flux jump phenomena in PFM processes, as compared with FC-activated 5.4 T [13].

The authors have been attempting to overcome the crucial drawbacks to obtain high field trapping in MgB₂ bulk magnets. The experimental approaches were proposed as a couple of ways of material processing and application procedure of magnetic pulses. On the other, it was reported that the flux jumps assist the flux invasion at the very beginnings of field application against the critical state model [14], [15]. Thus, the flux jump is the essential property to be controlled. The authors analysed various flux jump matters which dissipated the trapped fields from the bulk magnets. Since the Ti-addition results in the enhancement of J_c [16], in this paper, the authors preliminarily notice the flux shielding with sample thickness and effect of metallic Ti-addition to estimate the flux jump phenomena.

2. Experimental procedure

2.1 MgB₂ sample preparation

The samples were processed by in-situ mode with using hot-press in IFW Dresden. Since the Ti-addition was effective for enhancing J_c and surface shielding of bulk magnet, the authors chose the 2.5 wt% and 5.0 wt%Ti-added samples. Table 1 shows the specifications of the samples with varying the thickness and Ti-content. The detailed were shown elsewhere [17], [18].

2.2 Pulsed field magnetization and magnetic flux motions

As shown by the illustration and photos in Figure 1, the authors conducted the PFM activation with use of a two-stage GM-cryocooler. The pulse-fields of 0.6 - 2.0 T with a rise time of 10 ms were fed from 60 mF condenser to the cryocooled bulk MgB₂ samples with use of 112-turn copper coil, which was cooled in liquid nitrogen vessel to reduce its resistance. The coil constant is 1.26 mT/A. The magnetic field data were measured at the centre of the bulk surface by a Hall sensor (F. W. Bell). The

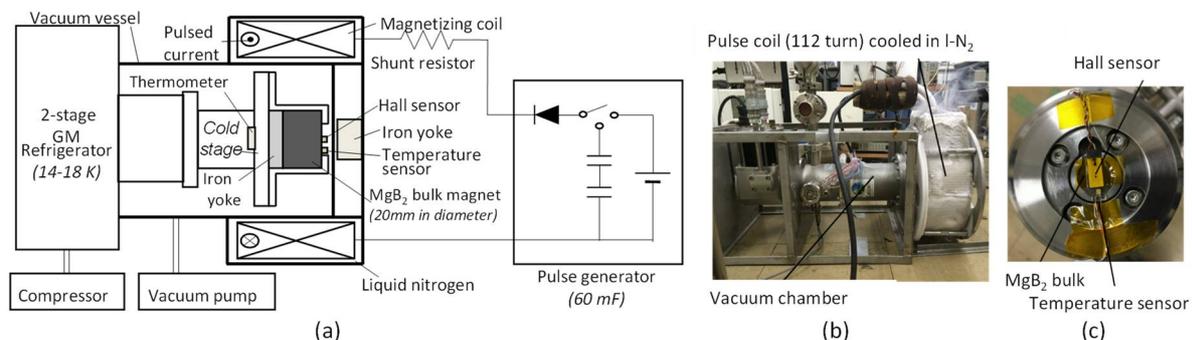


Figure 1. Illustration of equipment structure (a), views of experiment (b) and the bulk sample surface (c).

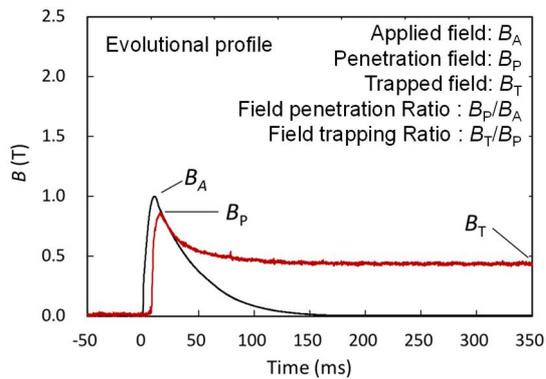


Figure 2. Definition of parameters.

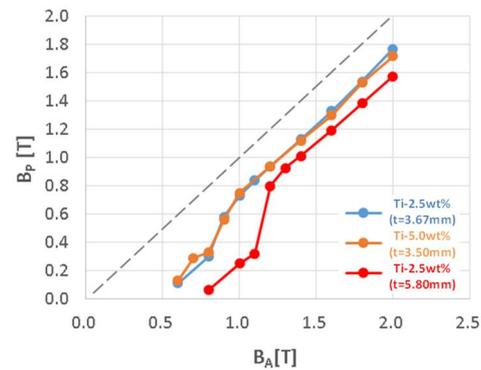


Figure 3. Penetration field B_P .

temperatures before starting PFM were settled at 14 K which was controlled at the cold stage behind the bulk sample.

As shown in Figure 2, the parameters were defined as the field penetration ratio B_P/B_A and field trapping ratio B_T/B_P to estimate the flux motion during the PFM processes, where B_A and B_P were the highest applied field calculated from the voltage of shunt resistor and the highest flux penetration measured by the Hall sensor, respectively [18], [19]. B_T means the final trapped field at the end of time-changing profiles. The ratio of B_P/B_A indicates the shielding effect against the flux invasion into the sample and introduction of fluxoid in the mixed state. The ratio of B_T/B_P indicates the flux-trapping which reflects the heat generation and propagation in the sample.

3. Results and Discussion

3.1 Penetration fields

Figure 3 shows the applied field dependence of the penetration fields B_P with varying thickness and Ti-content. The lines deviated beneath the line of $B_P/B_A=1$, suggesting the shielding effects which were affected by the thickness and not by Ti-addition. In the low field region, the B_P of thick sample clearly shifted to be small. And plotted lines aligned parallel to each other, which means that the shielding effect remains as it was to its high field region.

3.2 Trapped field and field trapping ratio

Figure 4 and 5 show the applied field dependence of the trapped fields B_T as functions of sample thickness (a) and Ti-content (b), respectively. The trapped flux reached the highest peak of 0.76 T at 1.3 T application to thick sample. In Figure 4, one sees apparent shift of data plots to high field region as

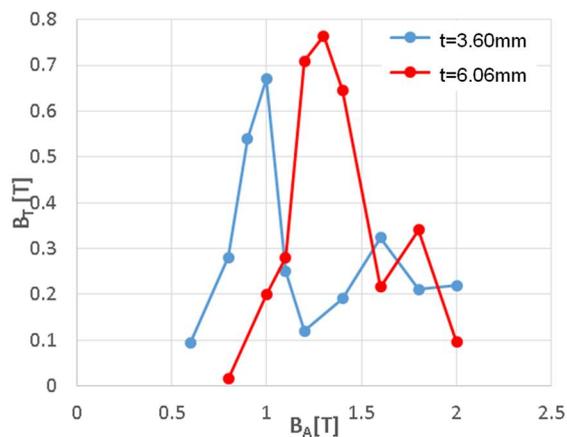


Figure 4. Effect of Sample Thickness on B_T .

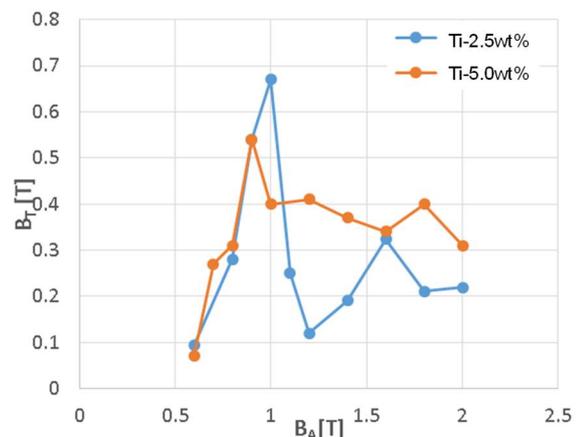


Figure 5. Effect of Ti-addition on B_T .

increasing sample thickness. Although the shift of field invasion is natural in low field region before showing the peaks, remarkable is that the applied field which indicates drastic decrease due to flux jumps clearly shifted to high field region as well. This means that the flux jump might be suppressed in thick or well-shielded sample.

In Figure 5, the field trapping property is apparently different. One sees no significant changes in the data except for the resultant trapped field between different Ti-content samples in the higher field region more than 1.0 - 1.1T. We observed the apparent improvement in field trapping in Ti-5.0wt% sample. This surely suggests the suppression of flux jump by Ti addition. The field-trapping B_T strongly relates to the applied field B_A . On the other, the penetrated flux B_P at the center should affect the local heating and resultant flux jumps. We need to estimate the effect between B_P and B_T soon after.

3.3 Flux motion during PFM

The time-varying profiles of PFM operations were shown in Figure 6, referring to B_T data in g. The motions exhibit clear classifications to we call no-flux flow (NFF) behaviour and flux jump (FJ) regions at high and low trapping phenomena, respectively. NFF means the flux behaviour which shows no apparent decay in B after showing B_P . FJ means the state which shows apparent sudden drops in B on the profiles. NFF suggests us the most ideal flux trapping with less heat generation, showing no-significant differences between for the flux motion. This shows that the flux motions are all similar in

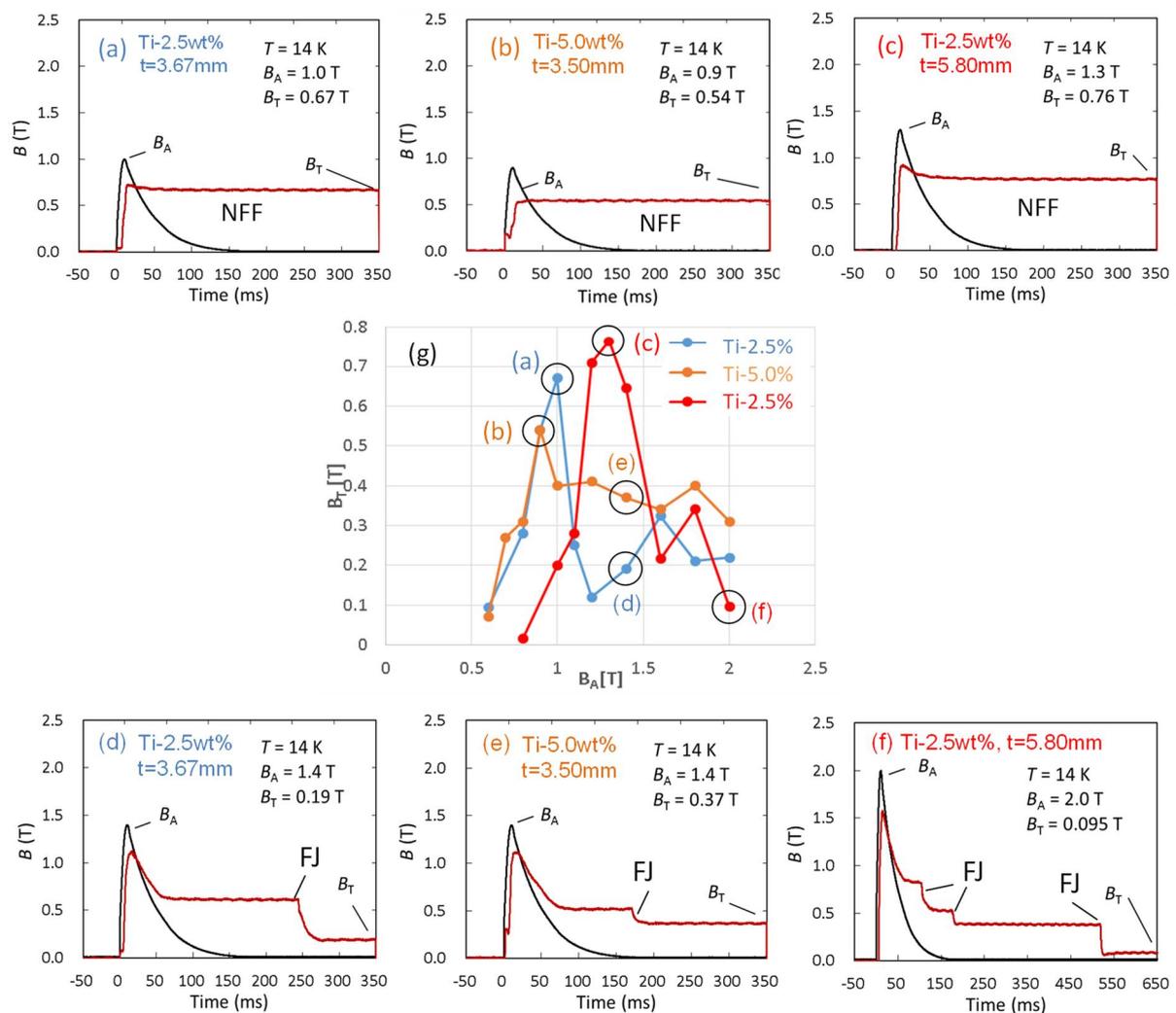


Figure 6. Flux motion in NFF (a-c) and FJ (d-f) in field trapping profiles (g).

low field application regions. However, flux jumps frequently happen to degrade B_T values in high field region with crucial heat generation.

There are two things to note. The shielding effect by elevating sample thickness has shifted the FJ region to high field region. It would be understandable in the low field region at the very beginning of flux invasion. But, all the data including FJ region shifted to high field with sample thickness even in high field regions. This is consistent to the gaps between the paralleled lines in Figure 3. This may suggest that the shielding effect affects over the range of field application in the experiment. Since sufficient flux invasion causes the high B_p and resultant high B_T , the shielding effect and diamagnetic effect should continue to the high field region until FJ appears. Furthermore, we may note that the FJs in Ti-5.0wt% sample exhibit a bit smaller drop than those of others in Figure 6. This may imply that Ti-addition might have suppressed the flux-jump occurrence. We should investigate the thermal properties like specific heat of Ti-added materials should be precisely studied in near future. In the present study, we inspected flux motion only at the centre point of the sample. As the heat generation affect FJ happening, we should detect the FJ on various points on the sample surface in the future.

4. Conclusion

Trapped field data during and after the PFM procedure were estimated on the sample thickness and metal Ti-added samples with 2.5 and 5.0wt% at cryocooled 14 K. The field invasion to the sample were influenced by the sample thickness by the shielding effect. The shielding effect remained to high field regions where FJ frequently happened. All the high field trappings in these data exhibited NFF region in all the samples regardless of sample thickness or Ti-content. Even in the FJ region of high field application, flux jumps happened with showing a bit difference between the sudden B_T decreases by FJ.

Acknowledgments

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