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Occurrence of Flux Jumps in MgB₂ Bulk Magnets during Pulse-Field Magnetization

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Abstract. The magnetic flux capturing of MgB₂ bulk magnets made by spark plasma sintering process has been precisely investigated to clarify the mechanism of flux motions during the pulse-field magnetization processes. The field trapping ratio B_T/B_P was evaluated as a key parameter of field trapping ability which strongly relates to the heat generation due to the rapid flux motion in the samples. The time dependence of magnetic flux density revealed the actual flux motion which penetrated the samples. The trapped fields B_T and field trapping ratios B_T/B_P of various samples were classified into three regions of 'no flux flow', 'fast flux flow' and 'flux jump' according to the generation of heat and its propagation. A flux jump was observed late at 280 ms from the beginning of PFM process, while the field penetration B_P showed its peak at 10 ms. Considering the heat propagation speed, the long-delayed flux jump should be attributed to the macroscopic barriers against the heat propagation to the surface centre of bulk magnet.

1. Introduction

It is well known that the largely-grown high temperature superconducting (HTS) bulk materials are capable of capturing the magnetic flux under their superconducting state, and of acting as the trapped field magnets (TFM) or bulk magnets [1], [2]. Since the field-trapping ability is linearly improved with lowering temperature, it is quite important to cool the materials beneath 77 K. When we employ the cryo-coolers instead of liquid nitrogen, T_c values of HTS materials are not serious issues to worry about any more, because we can easily attain certain low temperature conditions merely by turning on the switches of cryo-coolers [3].

In addition to the RE-Ba-Cu-O (RE: rare earth elements) family, a simple metallic compound, MgB₂, whose $T_c = 39$ K, is regarded as a promising candidate with various unique characteristics superior to other TFMs [4]. Sintered MgB₂ bulk superconductor is a sort of very homogeneous metallic compounds, which may bring us more uniform magnetic field than RE-Ba-Cu-O bulk magnets. This advantage is attributed to longer coherence length than that of oxide superconductors. This would overcome the weak-link problem. Magnesium is one of the common metals, which suggests us low material cost [5], [6]. When considering the magnetic field intensity, the bulk magnets are feasible candidates as intense



field generators for NMR/MRI (Nuclear Magnetic Resonance/Magnetic Resonance Imaging) devices [7], [8].

The low specific heat of MgB_2 and the narrow temperature margin between T_c and operating temperature causes serious flux jumps, which dissipate the trapped flux in the pulsed field magnetization (PFM) processes [9], [10]. The authors have reported the experimental results on the magnetic flux capturing in the PFM process for the MgB_2 bulk magnets made by hot-pressing. Miyazaki *et al.* reported that the flux invasion depends on the thickness of the piled-up MgB_2 plates [11]. Next, the authors showed that the field trapping ratios systematically shift with increasing thickness of stacked samples due to the field-shielding effect [12]. Furthermore, the authors discussed the frequent flux jumps during PFM for the MgB_2 samples made by hot-pressing and spark plasma sintering (SPS) [13]. In the paper, we focus on the samples made by SPS, and discuss the high field trapping ratio and its variations. In near future, we would analyze various flux jump phenomena and clarify the mechanism.

2. Experimental procedure

2.1. Preparation of MgB_2 bulk samples

We employed MgB_2 bulk magnets selected among the samples which were synthesized by SPS. Table 1 shows the sample specifications. These samples are all genuine MgB_2 compounds without any additives. The precursors were sintered by SPS with applying pressure of 50-100 MPa and heat-treated at 900-1200 °C for 1-20 min. The fabrication conditions were different among sintering temperatures, holding time at the highest temperatures, sample thickness, resulted in different densities from 1.45 to 2.62 g/cm³. The sample density strongly depended on the sintering temperature, while the pressure does not affect the density of the materials. Among these five samples, the highest density reached 2.62 g/cm³. Some samples were not adopted to the experiments because of cracks.

2.2 Pulsed field magnetization and magnetic flux motion

Figure 1a shows the illustration of the experimental setup for the PFM, employing the 2-stage GM cooler, which are capable of cooling the cold head to 15 K. The magnetic field data were measured at the center of the bulk surface by a Hall sensor (F. W. Bell, BHT 921), as shown in Figure 1b.

The parameter B_T/B_P was defined as shown in ref. [13]. B_P means the highest penetration field measured by the Hall sensor at the center of the bulk surface during the PFM. B_T means the final trapped field after PFM. The value of B_A means the peak value of applied field, which were calculated from the

Table 1 Specifications of bulk MgB_2

Sample	Diameter [mm]	Thickness [mm]	Pressure [MPa]	Temperature [°C]	Time [x60s]	Density [g/cm ³]
E116	19.95	12.90	90	1200	—	2.05
F526	19.90	9.60	50	1150	15	2.62
I258	19.60	12.70	75	950	1	1.45
I689	19.60	13.78	100	900	20	1.47
I690	19.83	9.26	100	1100	20	2.62

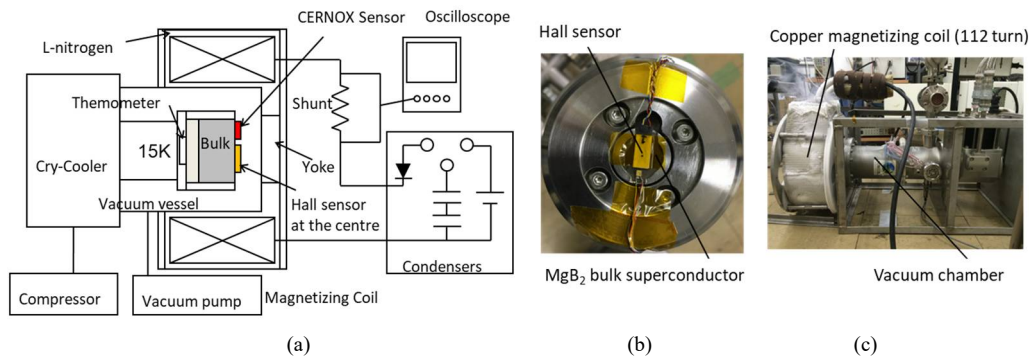


Figure 1 Experimental set up of PFM at 15 K

voltage at the shunt resistor. The ratio of B_T/B_p indicates the field-trapping ability, and is strongly affected by the generation of heat and its propagation in the sample. The pulse-fields of 0.4 - 2.2 T with a rise time of 10 ms were applied by feeding current from 60 mF condenser to the cryo-cooled bulk MgB₂ samples with use of 112-turn copper coil. The coil is cooled in the liquid nitrogen vessel to reduce the resistance, as shown in Figure 1c. The coil constant is 1.26 mT/A.

3. Results and Discussion

3.1 Trapped fields and field trapping ratios

Figure 2 and 3 show the trapped fields of five bulk samples and the field trapping ratios B_T/B_p for the samples of various thickness and density. In Figure 2, the data shows the trapped fields B_T after PFM which were measured at the centre of the bulk surface, as shown in Figure 1. One sees three levels in the data plots. The highest trappings were observed at about 0.7 T, while one sees insufficient field trappings of around 0.4 T for two samples and low field trapping of 0.15 T in wide field range from 0.4 to 2.0 T. We should discuss whether the flux has reached at the centre of the sample or not. Or, we may assume three kinds of J_c values in three levels of 0.7, 0.4, and 0.1 T class field capturing abilities. One may notice that the thickness of the sample would affect the shielding effect to prevent the flux to invade.

These profiles clearly exhibited the flux jump regions where the applied fields exceeded 1.6 T. The low field capturing of I689 might be attributed to a couple of reasons. One might be the strong shielding effect which prevent the flux to invade, and the other might be attributed to low J_c values which could let the flux dissipate. We need further observation on the flux motion throughout the field applications at various locations on the sample surface.

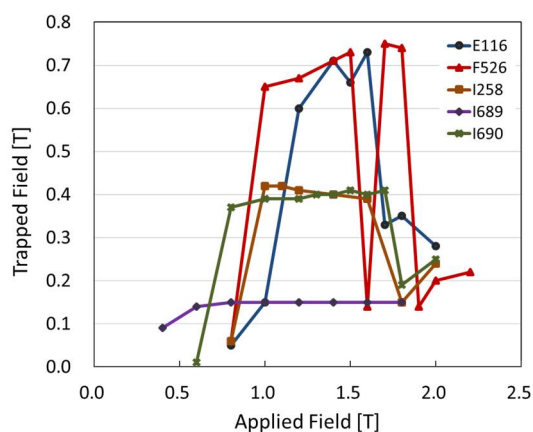


Figure 2 Trapped field after PFM

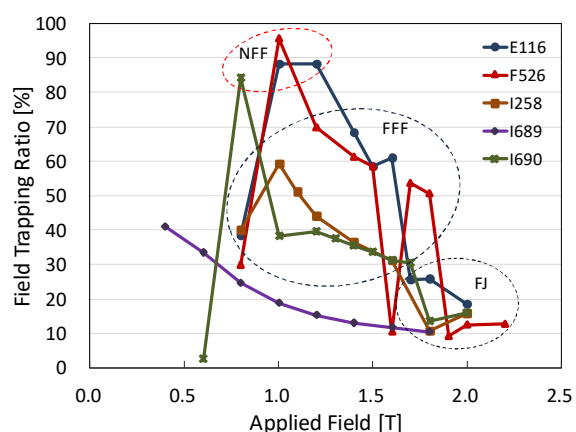


Figure 3 Field Trapping Ratio

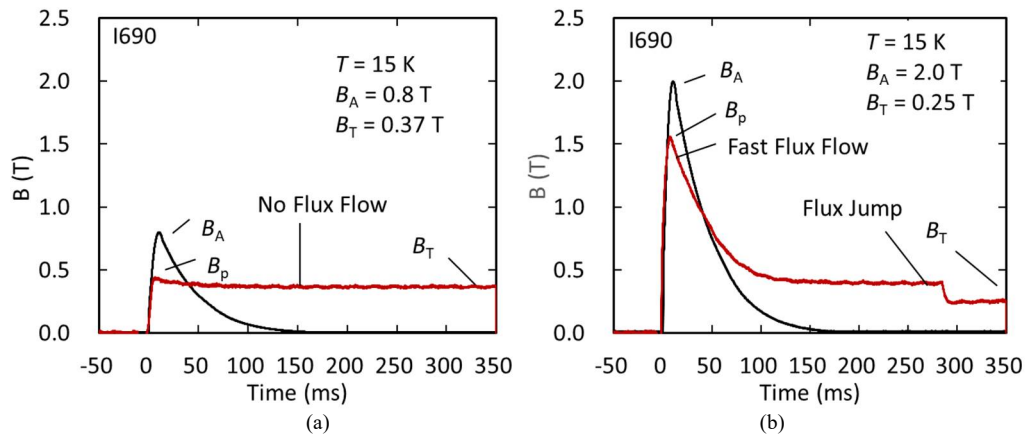


Figure 4 Time evolution profiles of flux motion at the center of sample surface

Figure 3 shows the field trapping ratios derived from Figure 2. The data plots exhibit three categories, which reflects the field trapping performances. All the data tends to decrease with increasing applied field, following the shielding effect which was roughly attributed to the thickness of the samples. The highest value reached 95.6% and 88.4% at 1.0 T and 1.2 T for F526 and E116, respectively. As for I690, the value of B_T/B_P reached 84.1% at 0.8 T. This means that the flux penetration causes no serious heat generation in this excitation process, which we call as ‘no flux flow (NFF)’. The NFF regions are observed in other samples and instances. On the contrary, low B_T/B_P ratios less than 20% were clearly attributed to low J_c value of I689. In Figure 3, I add the dashed circles showing three regions of NFF, FFF, and FJ regions.

3.2 Flux motion measurement in the PFM process

Figure 4 shows the typical flux trapping behaviours which reflect the flux motion and resultant heat generation. We classified the flux motion regions as NFF, “fast flux flow (FFF)”, and “flux jump (FJ)”. In Figure 4a, NFF means that the magnetic flux which invaded in the sample are kept as it was without any degradation and heat generation during PFM. As shown in Figure 4b, the drastic decreases of B_T/B_P with increasing applied field shown in Figure 3 are likely attributed to FFF which are responsible for heat generation. In the FFF region, flux jump would suddenly happen at long-delayed 280 ms at around 1.6 T. Although the mechanism is not precisely clear, yet, the lately-happening flux jump may likely be attributed to the long propagation time of heat, which is responsible for the macrostructure such as cracking, inclusions, dispersion of the second phases, and so on.

4. Conclusion

The authors have estimated the magnetic flux trapping property of MgB_2 samples made by SPS in Caen University by analyzing the parameter of field trapping ratios B_T/B_P with various values in thickness and density. The field invasion was suppressed in thicker sample than those of thinner ones because of the shielding effects. The invading flux motion is classified to three patterns of NFF, FFF, and FJ regions. Although the applied fields were kept as same intensity as applied in NFF region, the flux trapping drastically decreased in the FFF region with sudden occurrences of FJs. To expand the NFF region to high applied fields, we need further works both in the microstructural material designing and macroscopic development of heat draining techniques in the future.

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