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# Strong Influence of Pressure on the Magnetic Properties of $MgB_2$ Bulk Superconductors

Burcu SAVAŞKAN *1

## Abstract

The influence of the pressure on the magnetic and superconducting properties of polycrystalline $MgB_2$ bulks was studied. Bulk $MgB_2$ samples were prepared using conventional in-situ solid state reaction and hot-pressing methods. The structural and electromagnetic properties of $MgB_2$ samples were studied by using x-ray diffraction (XRD), scanning electronic microscope (SEM), magnetic hysteresis (M-H) and magnetic levitation force ($F_z$, $F_x$) measurements. XRD measurements proved high quality of $MgB_2$ bulks with only small traces of MgO impurity phase. The zero-field $J_c$ value reached 240 kA/cm$^2$ for $MgB_2$ sample produced by hot-press while 23 kA/cm$^2$ for $MgB_2$ sample produced by conventional in-situ at measurement temperature of 25 K. The max. levitation force values were obtained as 11.60 N and 15.42 N for $MgB_2$ bulk samples produced by in-situ and hot-press methods at 25 K, respectively. All these magnetic measurements result indicate that pressure acts like driving force for manufacturing highly dense and high levitation capability $MgB_2$ bulk superconductors.

**Keywords:** $MgB_2$ superconductor, magnetic levitation force, in-situ, hot-press, critical current density

## 1. INTRODUCTION

$MgB_2$ bulks may have innovative engineering applications as permanent magnets due to their ability to higher trap magnetic fields than conventional neodymium (Nb-Fe-B) permanent magnets and critical temperature of nearly 39 K make it an attractive candidate for use in liquid He-free systems [1-3] The cheap raw material cost, light weight, relatively easy fabrication, shorter processing time, large coherence length and lower anisotropy are the additional advantages of $MgB_2$ [4, 5]. Furthermore, unlike its high temperature superconductors (HTS) counterparts, the grain boundaries in $MgB_2$ don't form strong barrier to supercurrent flow, and also don't show weak-link behaviour. The ceramic nature of high temperature materials, like YBCO, causes brittleness and low mechanical strength on the contrary $MgB_2$ allows large dimensions and different shapes manufacture including ring, type,

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wire and bulk. All these advantages make $MgB_2$ its use as a strong candidate in the new generation applications such as electric motors, MRI, NMR, magnetic drug targeting devices and magnetically levitated transportation system (Maglev) [6, 7].

A record trapped magnetic field for a single $MgB_2$ bulk have attained $B_z = 5.4$ T at 12 K, therefore which are expected to be applicable in levitation applications such as Maglev trains and magnetic bearings [8, 9]. However, $MgB_2$ bulks use in Maglev trains has not yet been seriously considered for Maglev projects. Besides that, compared to the classes of cuprates, the works on magnetic levitation and guidance force of $MgB_2$ bulks are rather rare.

The in-situ processing method, elemental Mg and B precursor powders is heat treated to produce $MgB_2$ phase at moderate temperatures between 600-800 °C under inert atmosphere at ambient pressure [10]. Bulk $MgB_2$ samples produced by this technique exhibit high porosity (50 % dense) due to volatility of Mg and reaction induced shrinkage and also results in poor mechanical properties [5, 10]. Although the use of high pressure processing methods; such as spark plasma sintering (SPS), hot isostatic pressing (HIP) and hot pressing (HP) is effective to obtain dense, compact $MgB_2$ samples these techniques require specialist, large industrial presses and not preferable for the mass-production. Various authors have reported that the use of either sintering or pressure is not sufficient to obtain dense, high performance $MgB_2$ bulk superconductors. Use of pressure is carried out two different ways; first is while making a green body precursor, second is during heating cycle and results more particle-particle contact and so minimise porosities.

In this study, high quality $MgB_2$ bulk superconductors were fabricated using in-situ and hot-pressing process together. The effects of using pressure while making green body precursor on the structural, micro and bulk magnetic properties of $MgB_2$ bulk superconductors were investigated detailed.

## 2. EXPERIMENTAL DETAILS

### 2.1. Preparation of $MgB_2$ bulk samples

Two bulk $MgB_2$ polycrystalline samples were fabricated by in-situ solid state reaction and hot-press method. Elemental Mg powder (purity: 99.8%, 325 mesh, Alfa Aesar) and amorphous nano-B powder (purity: 99 %, d50 < 400 nm, supplied from Pavezyum Turkish co.,) have been used for the $MgB_2$ bulk synthesis.

The starting powders were weighted 1.5 g and rigorously mixed in an agate mortar for 30 min. To compensate magnesium evaporation during heat treatment and to obtain higher density and lower impurities in the bulk, 10 wt.% of excess Mg was used [11]. The powder mixture was pressed into a pellet with 20 mm in diameter and 3.5 mm in thickness using a uniaxial press. The sample named as $MgB_2$-I. The other powder mixture was pressed into pellet with 20 mm in diameter and 3.5 mm in thickness at 250 °C for 10 minutes using a hot-pressing mould with a temperature controller to improve the pellet density. The sample named as $MgB_2$-IP. Following the pressing process, two pellets were wrapped in titanium (Ti) foil and sintered at 775 °C for 2 h in a tube furnace in 1.5 bar argon atmosphere with heating and cooling rates of 10 °C/min.

### 2.2. Measurement processes

The phase components of the $MgB_2$ samples were acquired by using the X-ray diffraction (XRD) with a Rikagu D/Max III diffractometer with $Cu_{k\alpha}$ radiation ($\lambda$=1.5406 Å) in the range of 15°-80°.

The surface morphology imaging of the samples was performed by using a scanning electron microscope (SEM, Zeiss Evo LS10).

The vertical levitation force measurements ($F_z$) versus vertical distance ($z$) and the lateral (guidance) force ($F_x$) versus lateral distance ($x$) between the $MgB_2$ sample and cylindrical Nd-Fe-B permanent magnet (PM) were performed using "Low Temperature Magnetic Levitation Force Measurement System" [12]. The vertical levitation force measurements were taken under zero-field-cooling (ZFC) and field-cooling (FC) regimes at 25 K.

In the ZFC measurements, the sample was cooled in the cooling height (CH) of 51.5 mm, i.e., the magnetic field of the permanent magnet (PM) can be accepted as zero, while the CH was 1.5 mm in FC measurements.

In the ZFC regime, the measurements were taken while the gap between the sample and the PM is changing from the initial CH of 1.5 mm to the maximum gap of 51.5 mm, and the CH again.

In the lateral (guidance) magnetic force ($F_x$) measurements, the samples were cooled in CH=1.5 mm which was also fixed as the working height (WH). After the cooling process, the data were taken while the superconductor samples move ±9 mm laterally in the $x$ direction.

The critical current density ($J_c$, in A/cm$^2$) was calculated from the measured magnetic hysteresis loops $m(H)$ using Bean model for a plate-like geometry [13]

$$J_c = 20|m\uparrow - m\downarrow|/\{l[1-(l/(3L))]\} \qquad (1)$$

(samples dimensions ~ 0.15× 0.15 × 0.10 cm$^3$) in the presence of magnetic field perpendicularly to the surface of the sample. Where $m\uparrow$ and $m\downarrow$ are the magnetic moments in emu/cm$^3$ for the ascending and descending magnetic field, respectively, and $L$, $l$ are sample sizes perpendicular to the applied field.

## 3. RESULTS AND DISCUSSIONS

XRD patterns in Figure 1 (a) and (b) describe XRD patterns of $MgB_2$-I and $MgB_2$-IP samples prepared with in-situ and hot-press processing methods, respectively. It can be clearly seen that all two samples show $MgB_2$ as the major phase with peaks of (100), (101), (002), (110), (102) and (201) with small amount of MgO as impurity phase. As can be seen clearly compared to $MgB_2$-IP sample, the peak intensities of $MgB_2$ phase in $MgB_2$-I sample are significantly lower.

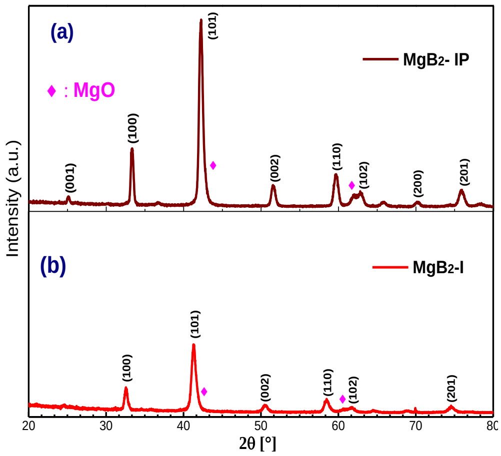

Figure 1 XRD patterns for the two $MgB_2$ samples fabricated by (a) hot-press (b) in-situ routes.

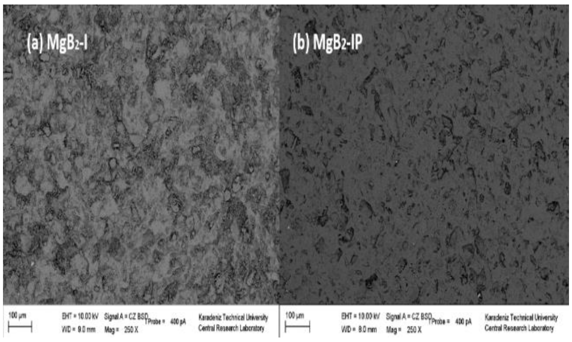

Figure 2 Backscattered SEM images (250 ×) for $MgB_2$ bulk samples fabricated by (a) in-situ (b) hot-press, routes.

Figure 2 shows microstructures of the two MgB$_2$ bulk samples sintered by in-situ and hot-press processing methods, respectively. The hot-press MgB$_2$ sample has a dense microstructure with little porosity pores, in contrast with the in-situ sample contains a large fraction of pores.

One of the engineering applications of the bulk superconductors (MgB$_2$ or YBCO) is the magnetically levitated transportation system (Maglev) and the most important parameters of this system is accepted as magnetic levitation force for loading capacity and lateral (guidance) force for lateral stability [14].

Figure 3 shows the vertical levitation force ($F_z$) versus vertical gap ($z$) between the PM and the MgB$_2$ samples under the ZFC and the FC regimes at 25 K. The arrows (1) and (2) show the movement of the PM to and away from the sample in the ZFC condition, respectively. In the FC regime, the arrows (1) and (2) show the movement of the PM away from the sample, while the arrows (3) and (4) show the movement of the PM to the sample.

The vertical levitation force curves of all two MgB$_2$ samples in the ZFC regime indicate repulsive (positive) character while in the FC regime they show very dominant attractive (negative) character due to the trapped magnetic flux inside the samples. The variation of vertical levitation force indicates a hysteretic behaviour that is known as the most common feature of the magnetic levitation [15].

As can be seen in Figure 3, the maximum levitation force values ($F_{z,max}$; those values were taken for a 1.5 mm vertical distance between the MgB$_2$ sample and PM) are strongly dependent on fabricating method of the MgB$_2$ samples. The $F_{zmax}$ values were found to be 11.60 N and 15.42 N at 25 K for the MgB$_2$-I and MgB$_2$-IP samples, respectively (Figure 3(a)). The maximum attractive force values were obtained as -4.13 and -4.67 N at 25 K for the MgB$_2$-I and MgB$_2$-IP samples, respectively (Figure 3(b)).

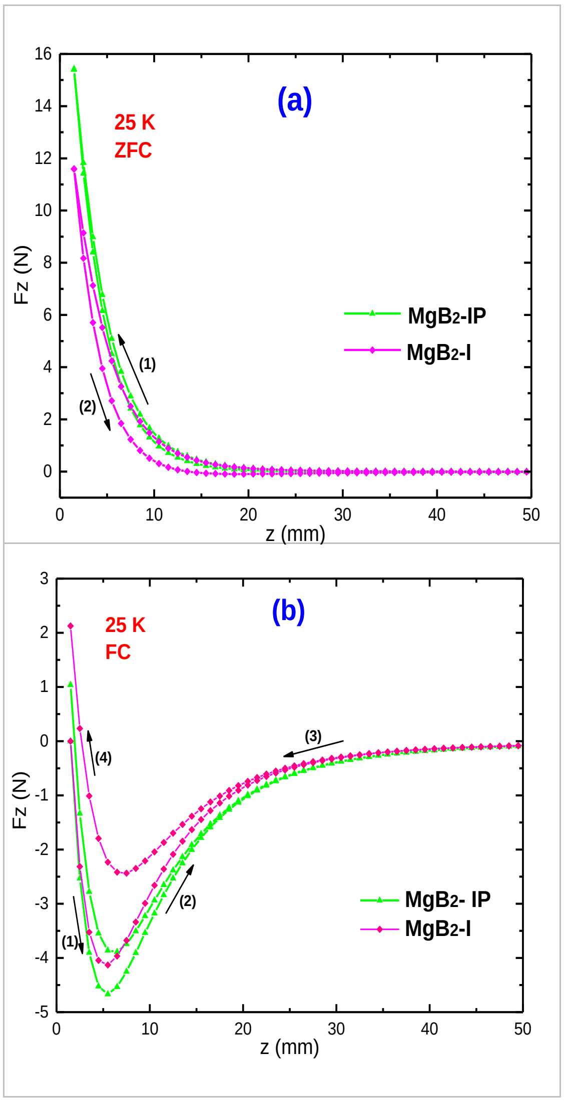

Figure 3 The vertical levitation force ($F_z$) versus vertical gap ($z$) between the PM and the MgB$_2$ samples under the ZFC (a) and the FC regimes (b) at 25 K. The marks (1)–(4) indicate the movement of the PM toward to and away from the MgB$_2$ sample.

In addition, one can see from Figure 3 that the levitation force curve of the in-situ MgB$_2$ sample is distinctly wider than that of the hot-press MgB$_2$ sample in both ZFC and FC regimes. In bulk superconductors, as reflecting the bulk material properties, magnetic levitation force is given as $F = (ArJ_{sc}V)$ dH/dz [16, 17]. The term in parenthesis represents the magnetic moment of the superconductor ($m$), where $J_{sc}$, A and V respectively represent the shielding current density with radius of $r$ circulating on the superconductor, A constant depending on the sample geometry and volume of the sample. dH/dz is external magnetic field gradient of the PM which is same for all levitation force measurement processes. The wider curve of the $MgB_2$-I sample is attributed to the poor connectivity between the grain boundaries and thus smaller shielding current ($J_{sc}$) and current radius ($r$) as consistent with the lower $J_c$ value of this sample.

The lateral guidance force is another critical parameter for Maglev trains since avoiding derailment of the vehicle on curved rails strongly depends on it. Figure 4 shows the lateral (guidance) force curves of the $MgB_2$ samples at 25 K. It is clearly seen from the Figure 4 that the guidance force curve of the in-situ $MgB_2$ sample is broader than the hot-press sample as consistent with the levitation force curves in Figure 3.

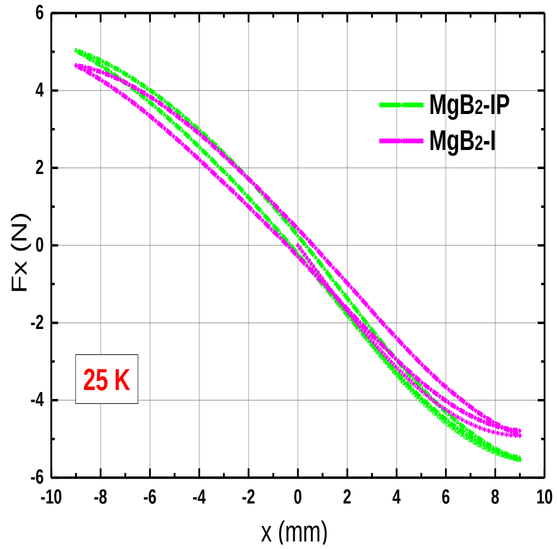

Figure 4 Lateral (guidance) force ($F_x$) depending on lateral displacement ($x$) for $MgB_2$-I and $MgB_2$- IP samples in FC regime at 25 K and at WH of 1.5 mm.

Figure 5 compares the critical current densities ($J_c$) at 25 K as a function of external field for $MgB_2$- I and $MgB_2$-IP samples. The self-field $J_c$ at 25 K for in-situ and hot-press $MgB_2$ bulk samples were calculated to be 23 kA/cm$^2$ and 240 kA/cm$^2$, respectively. Self-field $J_c$ increased more than 10 fold by fabricated with hot-press $MgB_2$ sample compared to fabricated by conventional in-situ $MgB_2$ sample. This result is consistent with the analysis SEM (Figure 2) showing that the microstructure of the produced by hot-press $MgB_2$ sample sintered to greater than produced by in-situ $MgB_2$ sample.

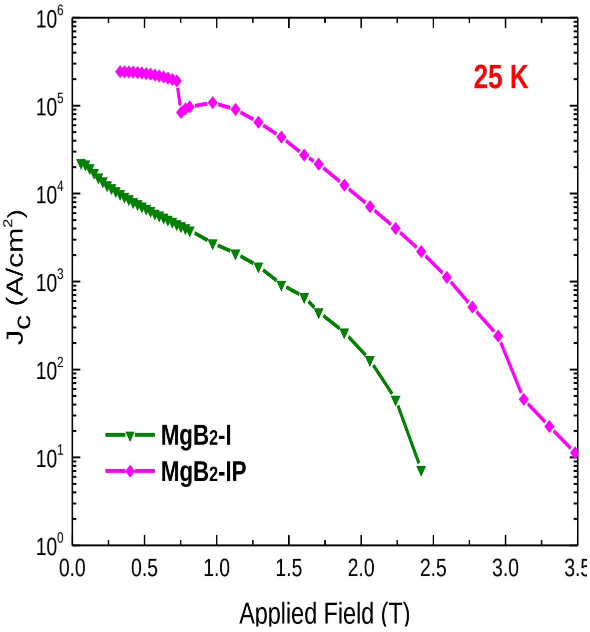

Figure 5 Magnetic field dependence of the critical current density ($J_c$) of the $MgB_2$-I and $MgB_2$-IP samples at 25 K.

## 4. CONCLUSION

The relationship between fabrication method and magnetic levitation performance of bulk $MgB_2$ superconductors was investigated using two processing routes; conventional in-situ solid state and hot-press. The bulk superconductor properties were investigated magnetic levitation ($F_z$) and lateral ($F_x$, guidance) force and also micro properties were investigated by XRD, SEM and critical current density ($J_c$). The zero-field $J_c$ value reached 240 kA/cm$^2$ for $MgB_2$ sample produced by hot-press while 23 kA/cm$^2$ for $MgB_2$ sample produced by conventional in-situ at 25 K. The max. levitation and max. attractive force values were obtained as 11.60 and -4.13; 15.42 and -4.67 N at 25 K for $MgB_2$ bulk samples produced by conventional in-situ solid state and hot-press method, respectively. All these magnetic measurements result demonstrate the importance of applied pressure in which acts like driving force in the production of dense $MgB_2$ bulk superconductors.

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***The Declaration of Conflict of Interest/ Common Interest***

No conflict of interest or common interest has been declared by the author.

***The Declaration of Ethics Committee Approval***

This study does not require ethics committee permission or any special permission.

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