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# Magnetic levitation and lateral forces in $MgB_2$ bulk superconductors fabricated by co-sintering process, in-situ and ex-situ

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**ABSTRACT**

The objective of this work is to enhance the magnetic levitation effect of bulk $MgB_2$ by exploring the potential of different in-situ and ex-situ mixtures. This could help to elucidate the role of these mixtures on the magnetic levitation force and the lateral force. We explored the potential of 0, 5, 10, 20, 30, and 40 wt % ex-situ $MgB_2$ powder concentrations by mixing them with 1.5 g of in-situ powder through a solid-state reaction method. An analysis of the vertical levitation force (Fz) and lateral guidance force (Fx) was conducted at 20 K and 25 K under field-cooled (FC) and zero-field-cooled (ZFC) conditions. It can be observed that the sample with the 20 wt% ex-situ addition amount achieved the largest vertical levitation force, reaching 17.03 N. Similarly, the sample with the 10 wt% ex-situ addition amount demonstrated the largest lateral force, reaching 6.31 N. These findings suggest that incorporating some ex-situ $MgB_2$ powder into the mixture of 2B and Mg during synthesis may enhance the magnetic vertical levitation force and lateral force.

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## 1. INTRODUCTION

The discovery of superconductivity in magnesium diboride ($MgB_2$), an intermetallic compound with a critical temperature of approximately 40 Kelvins, was made in 2001 [1]. Compared to high-temperature superconductors (HTS) such as cuprates, $MgB_2$ exhibits several advantageous properties, including a lower material cost, lower anisotropy, a long coherence length, a relatively straightforward fabrication process, and a low density of use. These characteristics make it a promising alternative for magnetic suspension device applications. Moreover, its relatively high critical temperature (Tc) renders it more suitable for LHe-free applications than low-temperature superconductors (LTS), such as conventional NbTi and $Nb_3Sn$. As fabrication methods have advanced, significant strides have been made in the generation of high trap magnetic fields [2-4] and the achievement of large magnetic levitation forces with $MgB_2$ bulk samples [5-7]. To utilize $MgB_2$ bulk materials in magnetic superconductor equipment, such as magnetic bearings or maglev trains, it is necessary to further enhance the lateral guidance force and levitation force in sintered bulk materials in Figure 1 [1-8].

When the levitation force is considered in a single dimension, it is given by $F_z = m(dH/dz)$; $m = MV$, $M = r.A.J_c$, $A$ is a geometric factor, $V$ is the volume of the superconductor, $r$ is the radius of a shielding current loop, $J_c$ is the critical current density of the superconductor and $dH/dz$ is the magnetic field. As can be observed, an increase in $dH/dz$, $J_c$, and $r$ results in a corresponding enhancement in buoyancy. The magnitude of $r$ and the critical current density ($J_c$) are contingent upon the potency of the flux pinning centres within the sample [9]. In addition to the $J_c$ and the magnetic field distribution of the magnet, numerous parameters influence the levitation force. These include the particle radius, particle orientation, sample thickness, distance between superconductor and magnet, cooling distance, relative motion speed of permanent magnet concerning superconductor, and dimensions and type of permanent magnet (PM) [10-13]. As the distance between the magnet and the superconducting material is reduced, the buoyancy increases [14]. Similarly, an increase in the thickness of the superconducting sample results in a corresponding rise in the buoyancy [15]. Furthermore, it has been established that the magnetic levitation force is enhanced as the temperature of the superconducting sample is reduced [16, 17].

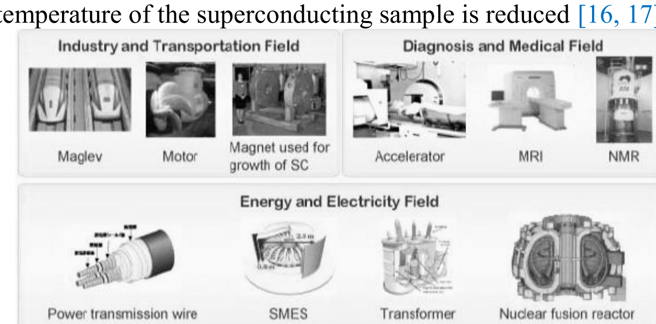


Fig. 1. Magnetic superconductor systems [1-8].

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The production of $MgB_2$ bulk materials frequently entails the use of powder synthesis, with the resulting materials typically falling into two categories: ex-situ and in-situ sintering routes. In the in-situ process, magnesium and boron precursor powders, in a ratio of 1:2, are typically subjected to heat treatment at temperatures between 650 and 850 °C under an inert atmosphere, to obtain the $MgB_2$ phase. In the ex-situ process, pre-synthesized commercial $MgB_2$ powder is subjected to high-temperature heat treatment, typically between 900 and 1300 °C. In a typical in-situ reaction process, magnesium melts at 650 °C and diffuses into boron grains, resulting in the formation of a $MgB_2$ phase with a high degree of purity. However, the $MgB_2$ sample typically exhibits a porous structure and low connectivity, estimated at approximately 50%, due to the volatility of Mg and the shrinkage associated with the formation of $MgB_2$ from Mg and B [18]. Bulk $MgB_2$ produced by the ex-situ process exhibits a significantly higher density, which is consistent with the findings that the powder of pre-synthesized $MgB_2$ is complementary in terms of the density of the bulk. These findings are supported by the literature, as evidenced by references [8,18-20]. However, the elevated sintering temperature in the ex-situ process is financially expensive and facilitates the formation of boron-rich phases, such as $MgB_4$, which reduces the overall superconducting fraction in $MgB_2$ bulk. In-situ sintered $MgB_2$ bulks exhibit a higher critical current density than ex-situ sintered bulks and are capable of carrying larger currents. In a previous study [21], we examined the impact of incorporating excess Mg in in-situ produced $MgB_2$ bulks on magnetic levitation and critical current density performance. The results of our study, as well as those of similar studies [22, 23], indicate that the incorporation of excess Mg up to 15 wt% markedly enhances the magnetic levitation performance and critical current density.

In this study, we employed a fabrication process combining in-situ and ex-situ co-synthesis to enhance the magnetic levitation force performance of bulk $MgB_2$ . The impact of utilizing the in-situ and ex-situ co-synthesis methodology was investigated. In this study, the effects of ex-situ $MgB_2$ adding into $MgB_2$ bulk samples on the vertical and the lateral levitation force properties were experimentally studied at 20 and 25 K by using a low-temperature magnetic levitation force measurement system (MLFMS).

## 2. EXPERIMENTAL

### *2.1. Fabrication Processes of $MgB_2$ Bulks*

Amorphous nano-B powder and elemental Mg powder (purity: 99.8%, 325 mesh, Alfa Aesar) were prepared as precursors. The $MgB_2$ powder was prepared ex-situ (99%, d50 < 400 nm; 95%, 100 mesh, provided by Pavezyum Turkish company, respectively) and used as a precursor. The ex-situ $MgB_2$ powder was doped to the in-situ powder at varying quantities, namely 0, 5, 10, 20, 30, and 40 wt%, via a solid-state reaction method. To compensate for the evaporation of Mg during the heating process and enhance the bulk density, an excess of 10 wt% Mg was employed [24]. The powders were blended in an agate mortar for 30 minutes under atmospheric conditions. The mixture was compressed into pellets measuring 3.5 mm in thickness and 20 mm in diameter using a pressing machine. Subsequently, the pellets were coated in titanium (Ti) and sintered at 850 °C for 1.5 hours in a tube furnace with a 1.5 bar argon atmosphere, with heating and cooling rates of 10°C/min. The final $MgB_2$ bulk samples were designated as *x* wt% ex-situ, where *x* represents the varying ratio of the ex-situ powder added, which was 0, 5, 10, 20, 30, and 40 wt %. Figure 2 illustrates the conventional sintering procedure.

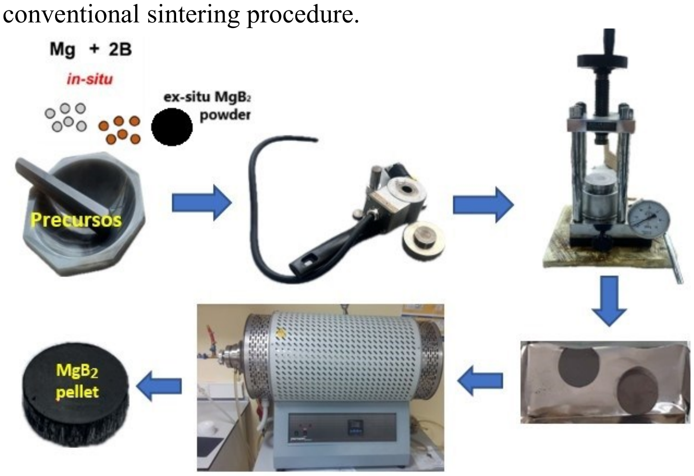
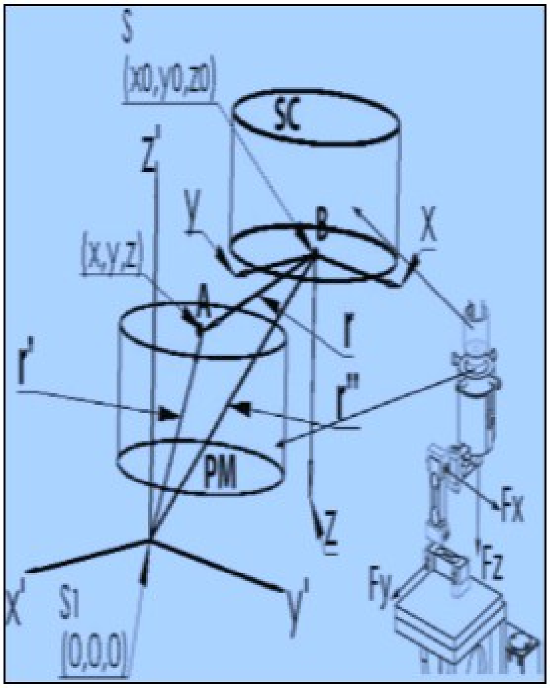



Fig. 2. Demonstration of the $MgB_2$ bulk synthesis.

### *2.2. Magnetic Levitation Force Measurements*

It is respectfully proposed that magnetic levitation force measurements between a cylindrical bulk MgB(20.95 mm in diameter and 4 mm in thickness mm) and a cylindrical NdFeB permanent magnet (19 mm in diameter and 10 mm in thickness) be performed by the MLFMS [25]. The system comprises a range of mechanical components and machinery, including a stainless steel vacuum chamber, a close-cycle cryostat, a high-level pumping station system, an electronic component, a three-axis load cell, precision three-dimensional movable axes, and software as seen in Figure 3(a) and 3(b). Nd-Fe-B PM with a magnetic field of 0.48 T in Figure 4, is designed to be placed on top of the $MgB_2$ bulk sample in both a vertical and a lateral position.

(a)




(b)

Fig. 3. (a) Low-temperature magnetic levitation system picture (b) Inside of MLFM system [25].

It is respectfully proposed that the vertical levitation force ($F_z$) measurements be performed under ZFC and FC conditions at 25 K. In the zero field cooling regime, it is believed that the temperature of the $MgB_2$ bulk could be decreased to 20 or 25 K in a cooling height (CH) of 51.5 mm. This would permit the magnetic field of the PM to be designated as zero, given that the CH was 1.5 mm in FC measurements. In the field cooling regime, the measurements were conducted while the distance between the $MgB_2$ bulk and the permanent magnet was incrementally also fixed as the working height (WH). Subsequently, data were collected while the $MgB_2$ bulks were observed to travel ± 9.5 mm laterally in the x direction seen in Figure 5.

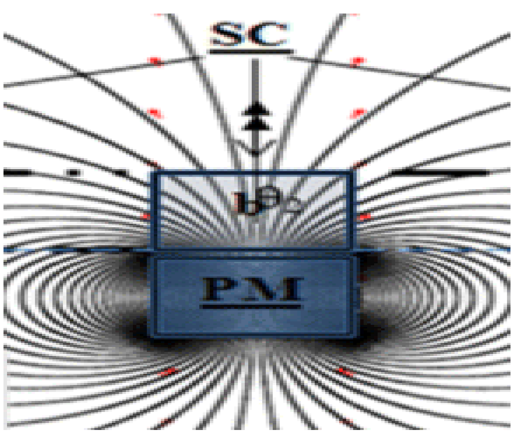



Fig. 4. A schematic representation of a superconductor under the influence of an applied magnetic field.

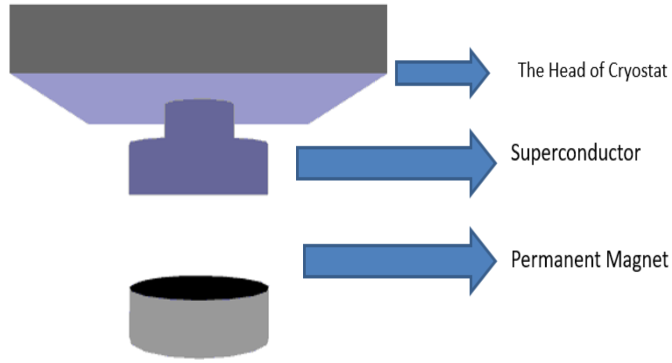



Fig. 5. The following schematic representation depicts the sample-PM movement and the distance relationship between the permanent magnet and the superconducting sample during the measurement of the magnetic levitation for ZFC and FC conditions.

## 3. RESULTS

Figure 6 depicts the vertical levitation force ($F_z$) about the vertical displacement (z-direction) for ex-situ powder doped in wt% of $MgB_2$ samples under ZFC conditions at 25 K and 20 K, respectively. It may be useful for the reader to note that the marks 1and in Figure 6 indicate the cycle of the PM towards (moving up) and away from (moving down) the $MgB_2$ bulk, respectively. From an analysis of the $F_z$ curves, it can be inferred that there may be a repulsive character, with the levitation force increasing exponentially with the reduction in vertical distance between the PM and the sample. It can be observed that there is a discrepancy in the levitation force, which suggests the possibility of hysteretic performance, which is widely recognized as the most prevalent characteristic of that force [26, 27]. In the opinion of Bernstein et al. [28], the phenomenon of hysteresis may be associated with alterations in the field and field gradient occurring at the superimposed current layers. As illustrated in Figure 6, it appears that the levitation force ($F_z$) values may have been enhanced for all samples that included the ex-situ $MgB_2$ powder. It can be seen that the maximum repulsive force ($F_z$) was approximately 17.03 N at 25 K for the 20 wt% ex-situ added sample, in comparison to the $F_z$ of 8.81 N for the ex-situ powder-free sample. It appears that optimization was achieved with the addition of 20 wt% ex-situ powder. A comparison of Figure 6(a) and 6(b) suggests that hysteresis loops are narrower at 20 K. This behavior has been explained in terms of current distribution inside the superconducting $MgB_2$, for the simple case of a cylindrical PM levitating on an $MgB_2$ disc [29].

Figure 7(a) and (b) show the vertical levitation force ($F_z$) about the vertical displacement (z-direction) for the bulk ex-situ powder added in wt% of $MgB_2$ samples under FC cooling at 25 K and 20 K, respectively. Figures 5 indicate the direction of movement of the PM towards (upward) and away from (downward) the sample, respectively. In the FC conditions, the temperature of the $MgB_2$ bulk samples was decreased to 20 or 25 K in the absence of a magnetic field, which resulted in a notable impact on the magnetic flux within the samples.

As illustrated in Figures 6 and Figure 7, it can be observed that the attractive (negative) force in the FC regime appears to be more pronounced than in the ZFC regime, where the repulsive (positive) force seems to be more prominent. This observation is consistent with the findings documented in the literature. It appears that the maximum attractive force values at 25 K and 20 K are observed for the $MgB_2$ sample with 10 wt% ex-situ added sample, with Figures 6 and Figure 7, -5.70 N and -6.04 N, respectively.

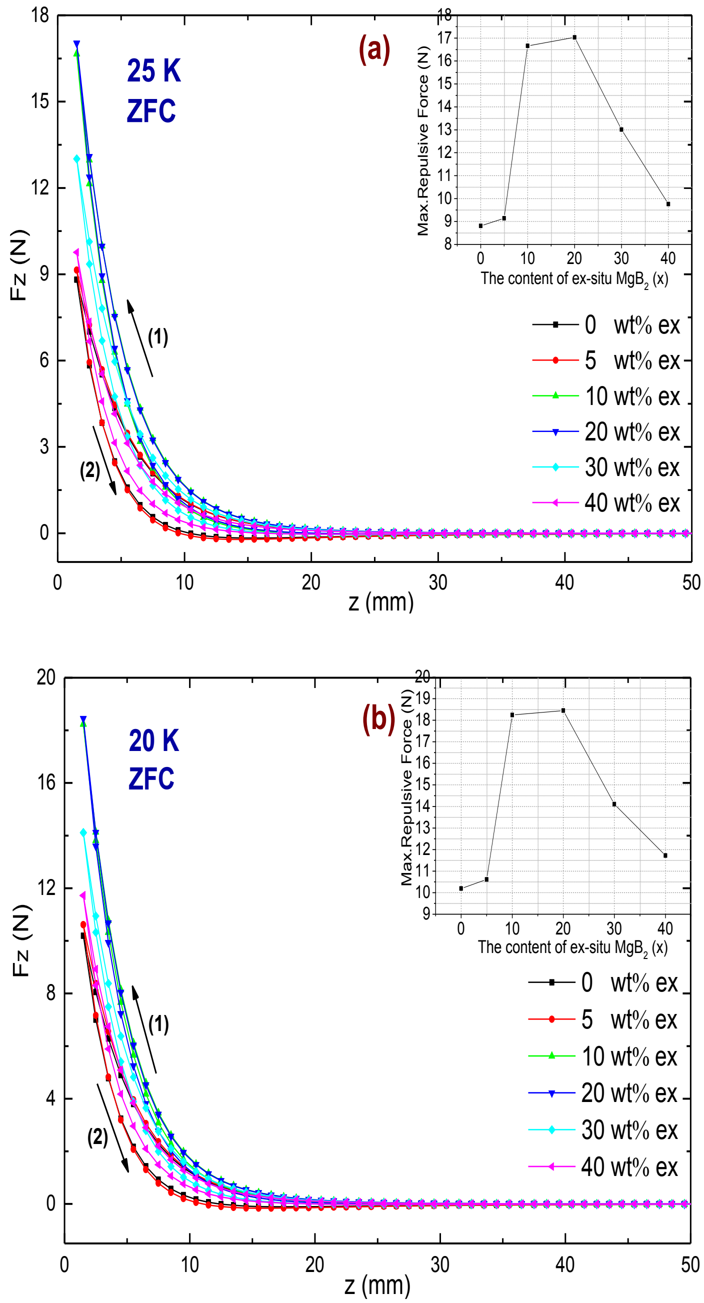



Fig. 6. $F_z$ versus z direction for $MgB_2$ + x wt% ex-situ (x = 0, 5, 10, 20, 30, and 40) bulk samples under ZFC condition at the temperatures (a) 25 K and (b) 20 K. Insets indicate those samples' maximum repulsive force values at 25 K and 20 K.

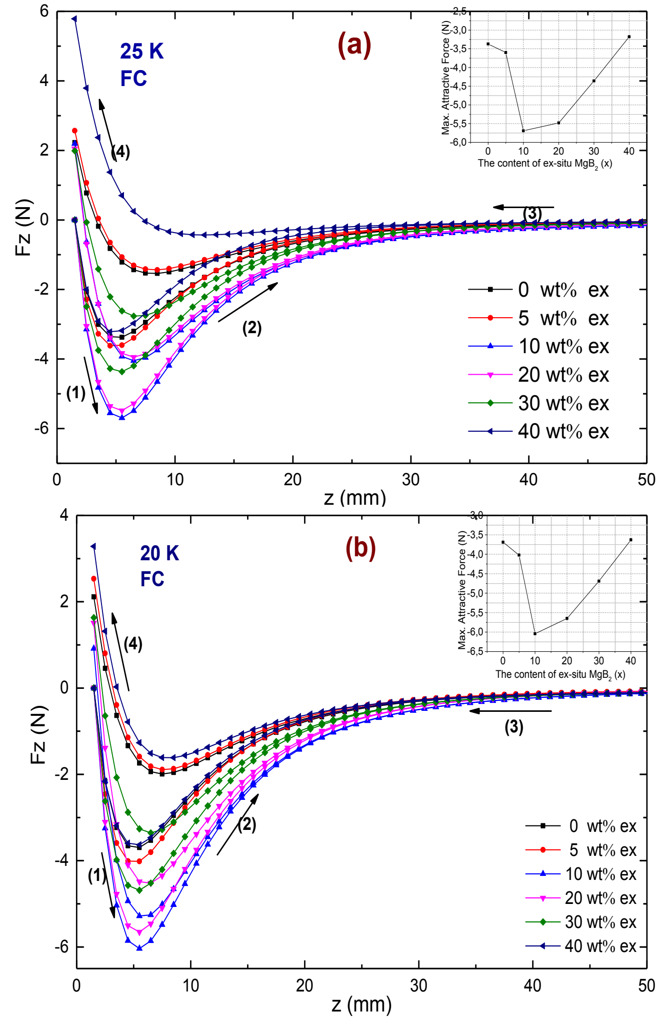



Fig. 7. $F_z$ versus z direction for $MgB_2$ + x wt% ex-situ (x = 0, 5, 10, 20, 30, and 40) bulk samples under FC condition at the temperatures (a) 25 K and (b) 20 K. Insets indicate those samples' maximum attractive force values at 25 K and 20 K.

It appears that the lateral force plays a pivotal role in the Maglev train, as it is essential for the transportation capability in curl organization and the filling ability of lateral influence [30]. The objective of this investigation is to present the results of our analysis of the lateral force ($F_x$) as a function of the lateral distance (x) for $MgB_2$ samples, conducted at 25 and 20 K in the FC cooling regime. For further details, please refer to Figures 8(a) and 8(b). In the $F_x$ measurement, the vertical distance is taken as 1.5 mm between the permanent magnet and the $MgB_2$ bulk through the lateral movement. As can be seen in Figure 8, it appears that the samples that were added ex-situ powders display a higher lateral force than the ex-situ powder-free sample. Although the critical current densities of the $MgB_2$ samples have not been measured yet, it can be said that the sample having the maximum levitation force has the highest critical current density. Because $F_z$ is directly proportional to $J_c$ ($F_z = m(dH/dz)$; m = MV, M = r.A.$J_c$) [31-35]. In addition, the vertical levitation force was measured to be 23.5 × $10^{-3}$ N/$mm^3$ at 25 K, which is a significant value compared to previous works [17, 21, 26].

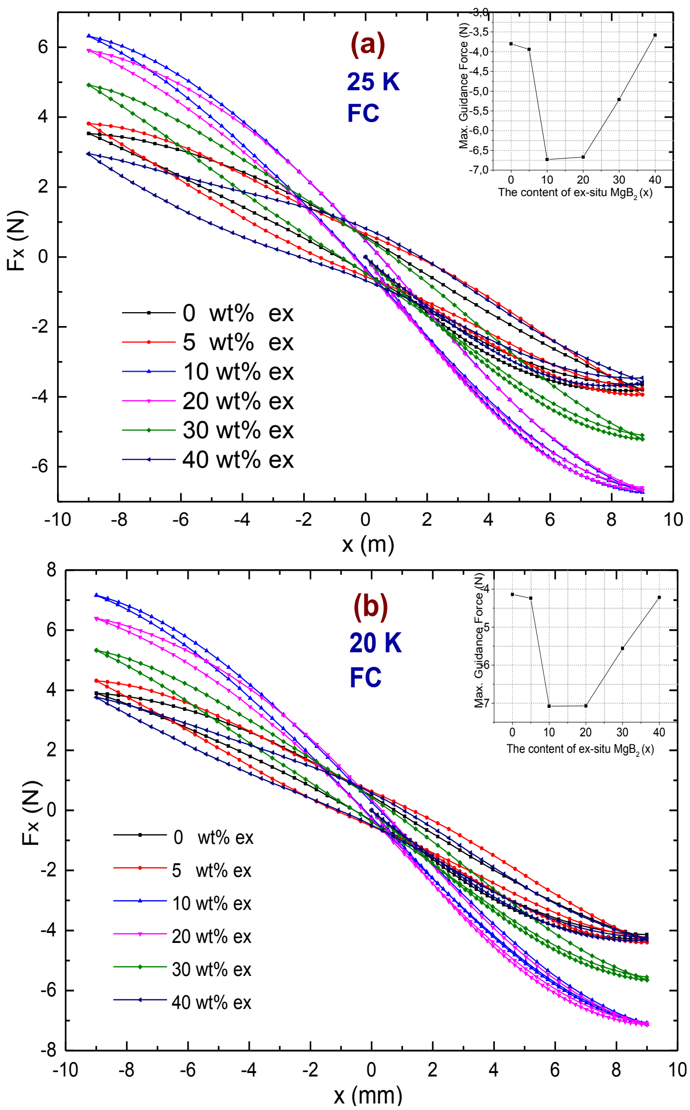



Fig. 8. $F_x$ versus $x$ direction for $MgB_2$ + x wt% ex-situ (x = 0, 5, 10, 20, 30, and 40) bulk samples under FC condition at the temperatures; (a) 25 K and (b) 20 K. Insets indicate those samples maximum lateral attractive force values at 25 K and 20 K temperatures.

## 4. CONCLUSION

The objective of this study is to present a technique for optimizing in-situ bulk $MgB_2$ Furthermore, we examine the and its impact on the magnetic levitation force and lateral force characteristics. It is encouraging to note that the addition of ex-situ powder has also had a positive effect on the magnetic levitation performance, with the 20 wt% ex-situ added sample showing an improvement over the ex-situ powder-free sample. For the next work; the enhancement of ex-situ $MgB_2$ doped $MgB_2$ samples can be improved with some dopants by using optimum ex-situ addition. As our understanding of the current magnetic levitation performance deepens, we are optimistic that this will open up new possibilities for the use of $MgB_2$ bulk superconductors in superconducting magnetic transportation systems, such as maglev trains.

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