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The Investigation of Magnetic Levitation Performance of Bis (2-methoxy-4-allylphenyl) Oxalate (I) ($C_{22}H_{22}O_6$) Doped MgB_2 Bulk Superconductor

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Abstract – In this work, the effects of bis (2-methoxy-4-allylphenyl) oxalate (I) on levitation (*Fz*) and lateral forces (*Fx*) of bulk MgB_2 superconductor has been investigated and reported for the first time. All samples were prepared from magnesium powder (Mg, 99.8 %), amorphous boron powder (B, 98 %), and bis oxalate ($C_{22}H_{22}O_6$) powder by using "Solid State Reaction Method". It is used as a dopant because it is a good candidate to be a carbon source material for doping MgB_2. The amount of $C_{22}H_{22}O_6$ was varied between 0 and 9 wt % (0, 1.5, 3.0, 4.5, 6.0 and 9.0 wt%) of the total MgB_2 bulks. Vertical levitation and lateral force measurements were carried out with both Zero-field-cooled (ZFC) and Field-cooled (FC) regimes at temperatures of 25 and 30 K. It was found that the bis oxalate adding has a positive impact on the levitation and guidance properties of MgB_2 bulk. Based on observed values of levitation and guidance force, it can be concluded the 3 wt% $C_{22}H_{22}O_6$ added sample is the best of the studied samples. This results of this study are useful for the practical application in Magnetic Levitation Devices.

Keywords *– MgB_2 superconductor, $C_{22}H_{22}O_6$ adding, Vertical levitation force, Lateral force*

I. Introduction

The magnetic levitation force between a superconductor (SC) and a permanent magnet (PM) arises from interaction between the induced currents, **J**, and applied magnetic field, **B**, from the magnet [1]. This unique property is attractive for various industrial applications such as noncontact superconducting bearings, wind turbine generator systems, flywheel energy storage systems, motors and magnetic levitation transportation system (Maglev). Vertical levitation force (F_z), lateral force (F_x) are two components of Lorentz force and two most important parameters for the maglev system [2, 3]. In the levitating system like Maglev, high temperature superconductors (HTCs) in the form of one single-seeded or multi-seeded (RE)BCO generally used due to their ability to trap large magnetic fields and to provide stable magnetic levitation [3]. Although bulk (RE)BCO is currently the most widely used material due to the advantages of high H_{irr}, J_c and T_c, its limitations are a production process that is time-consuming and expensive given the need for a single domain and its brittle mechanical properties as well as low thermal conductivity. Magnesium diboride (MgB_2) is a metallic HTS discovered in 2001. Although the critical temperature, Tc ~ 40 K, of MgB_2 is much lower than that of (RE)BCO bulks, it has generated tremendous interest due to its peculiar characteristics. In practice, the distinct advantage of MgB_2 is that its light weight, rare-earth free, low-cost, larger coherence length and metallic superconductivity drives a weak-link-free supercurrent flow across grain boundaries [4, 5, 6]. MgB_2 has been demonstrated to be a promising candidate for superconducting applications; magnetically levitated transportation system (Maglev) and high magnetic field applications for LHe-free operation in MRI.

The main advantage of MgB_2 is that it displays a critical current density, Jc, three orders of magnitude higher than polycrystalline HTS [7]. The typical Jc value of the polycrystalline MgB_2 samples is over 10^5 A.cm^{-2} below 20 K in the self-field, which is as high as that of (RE)BCO bulks at 77 K [8]. However, the Jc of pristine MgB_2 drop-off rapidly with applied magnetic field, which is mainly a lack of naturel defects, poor pinning and low upper critical field, H_{c2} [9, 10]. It is, therefore, essential that the in-field performance of bulk MgB_2. In the literature, a great deal of work includes of various methods such as elemental addition or doping, addition of nanoparticles and the introduction of defects by neutrons irradiation have been carried out with the aim of improving of pinning properties, Jc and irreversibility field, H_{irr} [11]. In particually, among these methods, chemical addition with Carbon (C) or C-based compounds is one of promising technique for enhancing Jc/H_{c2} in bulk MgB_2. Increased intra-band scattering, degradation of crystallinity, enhanced vortex and k pinning, reduced anisotropy in critical fields are some of the mechanism that have led to much improved Jc (B) performance in C-doped in bulk MgB_2 [12]. In recent years, alternatively the other forms that include SiC, C-nanotube, organic compounds have been considerably interest.

Many studies have shown that the magnetic levitation force depends on the cooling regime, different measurement temperature, the size and the shape of the interacting permanent magnet (PM) and the superconductor [13, 14]. Furthermore, large levitation forces can be achieved using a superconductor with high Jc.

It is important to note that the investigation on the levitation and guidance force of doped MgB_2 sample is almost rare. Our research group was first to investigate the effect of malic acid ($C_4H_6O_5$) addition on levitation force and guidance force of bulk MgB_2 [6, 11].

In the present work, we have investigated the effect of new organic compound bis oxalate ($C_{22}H_{22}O_6$) adding into MgB_2 bulk superconductors synthesized by solid state reaction method at 775 C under Ar atmosphere, on the vertical levitation force (*Fz*) and guidance (lateral, *Fx*) force properties in zero field cooling (ZFC) and field cooling (FC) regimes.

II. Materials and Method

Sample Preparation

Disk-shaped $C_{22}H_{22}O_6$ (0, 1.5, 3.0, 4.5, 6.0 and 9.0 wt%) added polycrystalline MgB_2 superconductors with 20 mm in diameter and 4 mm in thickness, were produced from commercially available high purity powders of Mg (-325 mesh, 99.8%, Alfa Aesar), amorphous nano B (<250 nm, >98.5%, Pavezyum) and $C_{22}H_{22}O_6$ by using solid state reaction method. We used 10 wt % excess Mg powder to compensate Mg evaporation during heat treatment. The $C_{22}H_{22}O_6$ added MgB_2 pellets weighing about 1.5 g were prepared. The sintering process was carried out at 775 °C for 3 h following vacuum process. During the heat treatment, high-purity argon gas was maintained 10 bar in a stainless steel tube. The heating and cooling rates were used 10 °C/min and 5 °C/min, respectively.

Levitation Force Measurements

Levitation force measurements in zero-field-cooled (ZFC) and field-cooled (FC) regimes were performed at temperatures of 25 K and 30 K using a low temperature magnetic levitation force measurement system in Solid State Research Laboratory in RTE University and designed by Sukru Celik and financially supported by TUBITAK with project no 110T622. Magnetic levitation force system consists of modular parts such as a stainless steel vacuum chamber, close cycle cryostat, high vacuum pumping system (rotary pump and turbo molecular pump), precision three-dimensional movable axes, three-axis load cell, electronic part and software (Figure 1).

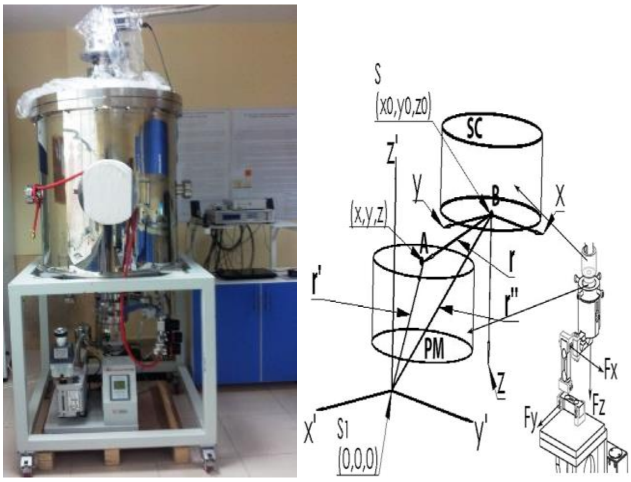

Figure 1. The photo and schematic diagrams of magnetic levitation force measurement system.

Cylindrical Nd-Fe-B permanent magnet (PM) polarized axially with a magnetization of μ_0M=0.48 T (with 19 mm diameter and 10 mm thickness) was used as a magnetic field source in this system. The PM was free to move on the bottom of MgB_2 samples both in the axial and the radial direction. Further details and schematics of the levitation force system can be found elsewhere [15].

In ZFC regime, firstly, the sample was fixed approximately on the central axis of the PM. Then the system was vacuumed and the cooling distance between sample and PM was chosen as z = 50 mm. When the sample was cooled at z = 50 mm above, the PM (where PM's magnetic field is negligible), the Fz (z) measurements were carried out during the vertical traverse of the PM from z = 50 mm to a minimum distance of z = 1.5 mm, followed by a vertical traverse of z = 1.5 mm.

In FC regime; the *Fz (z)* measurements were performed by cooling the sample at z = 1.5 mm above the PM. Then, the measurements were carried out during the PM was vertically moving from z = 1.5 mm to a maximum vertical of z = 50 mm, followed by a traverse to z = 1.5 mm.

The lateral (guidance) force (Fx) versus lateral distance (x) measurements in the FC regime were carried out by first cooling the sample at z = 1.5 mm distance above the PM after the centres of the sample and the PM were overlapped at x = 0 mm. Then, the measurements were performed and the PM was horizontally moving from the centre of the sample x = 0 to x = 50 mm (right), then to x = − 50 mm (left), and finally to x = 50 mm (right) while the fixed measurement height was chosen as 1.5 mm in vertical direction.

III. RESULTS

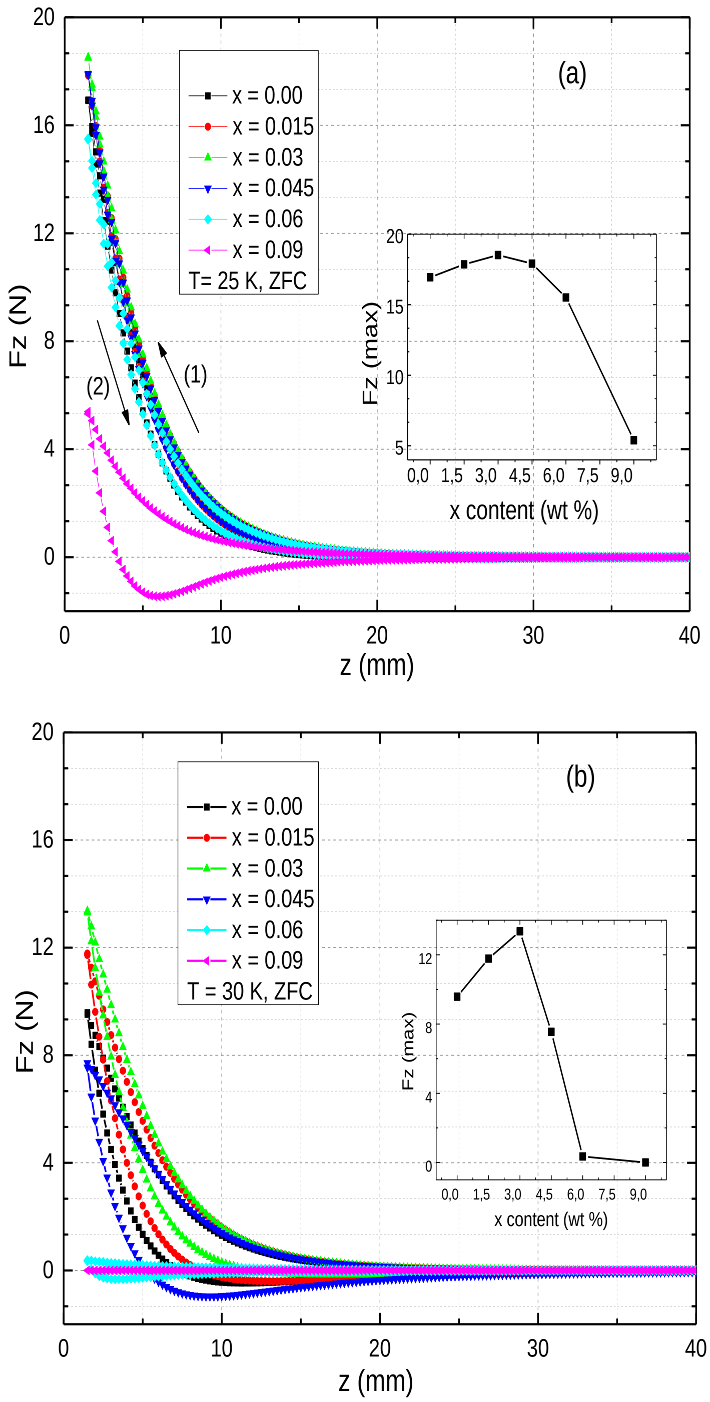

Figure 2. The vertical levitation force *(Fz)* versus vertical distance (z) for MgB_2+ x wt % $C_{22}H_{22}O_6$ bulk samples (x = 0, 1.5, 3, 4.5, 6, 9) during ascending (row 1) and descending (row 2) process under ZFC regime at (a) 25 K (b) 30 K.

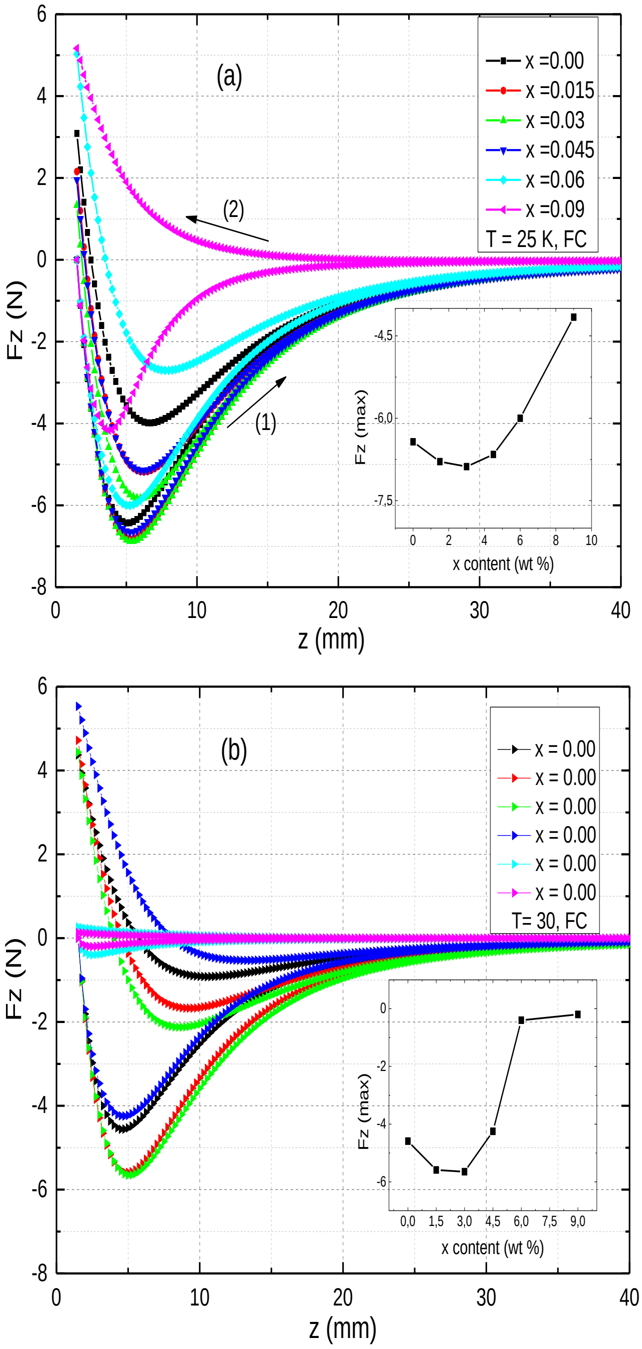

Figure 3. The vertical levitation force *(Fz)* versus vertical distance (*z*) for $MgB_2 + x$ wt % $C_{22}H_{22}O_6$ bulk samples (*x* = 0, 1.5, 3, 4.5, 6, 9) during descending (row 1) and ascending (row 2) process under FC regime at (a) 25 K (b) 30 K.

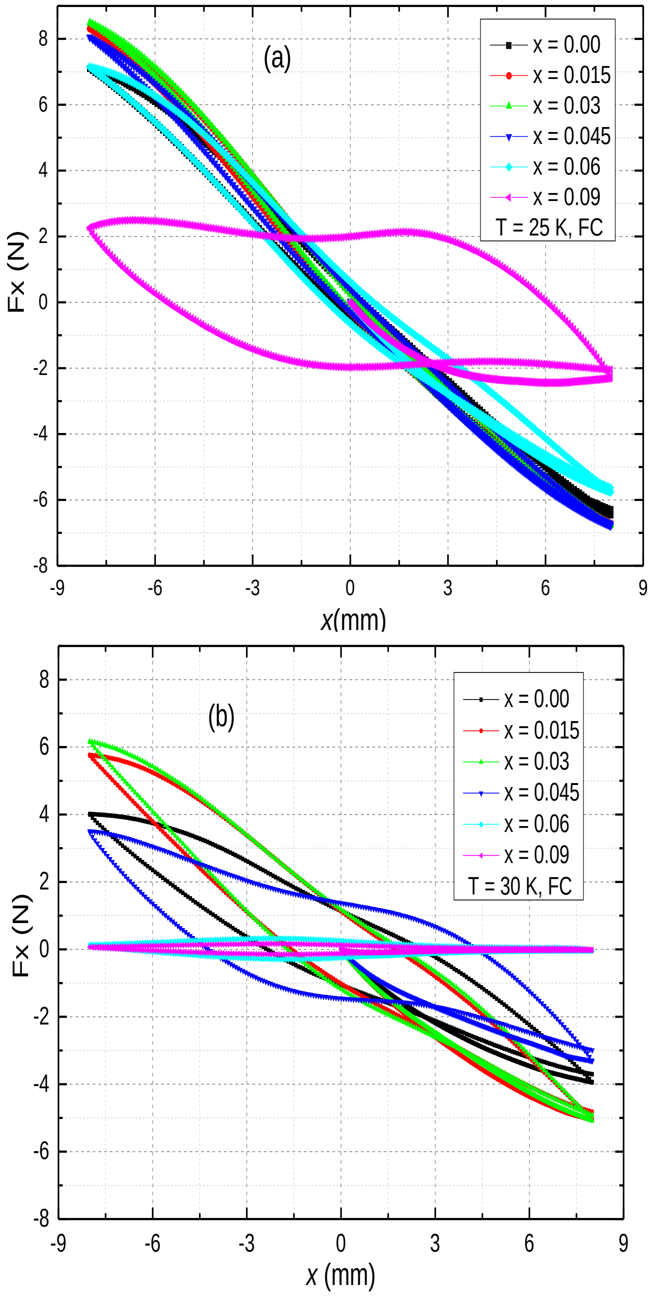

Figure 4. Lateral force (*Fx*) versus lateral displacement (*x*) for $MgB_2 + x$ wt % $C_{22}H_{22}O_6$ bulk samples (*x* = 0, 1.5, 3, 4.5, 6, 9) under FC regime at (a) 25 K (b) 30 K. The gap between sample and PM was kept 1.5 mm during the test.

III. DISCUSSION

Figure 2 shows the vertical levitation force (*Fz*) as a function of the vertical displacement (*z*) for the pure and 1.5, 3, 4.5, 6, 9 wt % $C_{22}H_{22}O_6$ added MgB_2 samples at temperatures of 25 and 30 K under ZFC. The maximum levitation forces (that values were taken for a 1.5 mm gap between sample and PM were collected and they were redrawn into the inset plot. The marks 1 and 2 in Fig. 2(a) indicate the movement of the PM toward to (ascending) away from (descending) the sample, respectively. As shown in Fig. 2, the Fz curves indicate repulsive character and increase exponentially with the decrease in vertical distance at fixed temperature. The variation of levitation force shows a hysteretic behaviour that is known as the most common feature of the magnetic levitation. A significant levitation force was observed at 24 and 28 K temperatures. As can be seen from the inset plot in Fig. 2, the maximum levitation force is not a linear function of the adding of $C_{22}H_{22}O_6$ level. In Fig. 2(a), the maximum *Fz* value increase from 16.95 to 18.57 N when the $C_{22}H_{22}O_6$ content increases from 0 to 3 wt% and decreases gradually up to 6 wt% and after that decreases rapidly with increase of adding content. The optimum $C_{22}H_{22}O_6$ content for the maximum *Fz* value is determined as 3 wt % at 25 and 30 K. The 9 wt % added sample do not present appreciable levitation force because of the decreasing superconductivity properties by the reason of the flux flow. The enhancement of *Fz* for 1.5 and 3 wt% samples at 24 K and 28 K compared with the pure sample is attributed to the lattice distortion resulting from incorporation of C atoms into the MgB_2 crystal lattice. This is an indication of C substitution for B sites, with the C coming from $C_{22}H_{22}O_6$, resulting in enhancement of levitation force.

However, when the $C_{22}H_{22}O_6$ content is above 4.5 wt%, levitation force shows an opposite effect. In Figure 2, rapid decrease of levitation force values with 9 wt % sample can be clarified as excess $C_{22}H_{22}O_6$ adding.

The vertical levitation force (*Fz*) as a function of the vertical displacement (*z*) for the pure and 1.5, 3, 4.5, 6, 9 wt % $C_{22}H_{22}O_6$ added MgB_2 samples at temperatures of 25 and 30 K under FC regime is shown in Fig 3. The marks 1 and 2 in Fig. 3(a) indicate the movement of the PM away from (descending) and toward to (ascending)the sample, respectively. It is seen from Fig. 3 that the *Fz* curves show attractive character because the produced magnetic field of the PM can be easily penetrated into normal regions in the samples. The hysteresis loops broaden FC case during the cycle with increasing measurement temperature because of trapped flux and induced currents circulating inside the samples [16]. Comparing Figs. 2 and 3, it can be seen that the attractive force in FC regime is stronger than in ZFC regime while the repulsive force in ZFC regime is stronger than in FC regime, consistent with the literature [11]. The 1.5, 3 and 4.5 wt% $C_{22}H_{22}O_6$ added samples show higher attractive force at 25 K, compared with that of the pure one. The maximum attractive force values at 25 and 30 K are seen for 3 wt% $C_{22}H_{22}O_6$ added sample as -6.90 N and -5.70 N, respectively.

In an actual maglev vehicle system, the guidance force is an important process because it is a key to the horizontal stability of the levitation system and it is essential for the traffic ability in curve way, and the loading capacity of lateral impact [17]. The lateral force (*Fx*) as a function of the lateral distance (*x*) for the pure and 1.5, 3, 4.5, 6, 9 wt % $C_{22}H_{22}O_6$ added MgB_2 samples are measured at 25 K and 30 K in FC case. In guidance force measurements, the vertical distance is kept constant at 1.5 mm from the PM when the PM is moved laterally. When the PM is moved laterally relative to the centre of the sample as observed in Fig. 4 (a), the lateral repulsive force increased from zero to the maximum values of 4.00, 5.77 and 6.24 N for pure, 1.5 and 3 wt % added samples, respectively.

IV.CONCLUSIONS

In this study, as different from the literature, the effects of bis (2-methoxy-4-allylphenyl) oxalate, $C_{22}H_{22}O_6$, one of the organic compounds, addition on levitation and guidance force properties of bulk MgB_2 superconductor have been reported.

$C_{22}H_{22}O_6$ synthesized by Kantar et al. [19]. Vertical and lateral levitation force measurements under both ZFC and FC regimes were carried out at different temperatures of 25 K and 32 K for various adding content. Addition of $C_{22}H_{22}O_6$ in MgB_2, finally results in C substitution at boron (B) sites. It was found that the $C_{22}H_{22}O_6$ adding has a positive impact on the levitation properties. At 25 and 30 K, the 1.5 wt % and 3 wt % $C_{22}H_{22}O_6$ added samples exhibit a higher levitation and guidance force than pure sample. The enhancement of *Fz* and *Fx* by the addition of $C_{22}H_{22}O_6$ to MgB_2 might be attributed to decomposition $C_{22}H_{22}O_6$ might exhibit higher *Fz* and *Fx*. As a result, this work might be helpful for studying the technological applications of Maglev and contactless bearing systems.

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