#### **ORIGINAL PAPER**



# Effect of Compaction Pressure on the $J_{\rm c}$ of Superconductor Bi-2212 in Bulk

Ismael Martínez Ramírez<sup>1</sup> · Elvia Díaz Valdes<sup>1</sup> · Concepción Mejía García<sup>1</sup> · Jaime Santoyo Salazar<sup>2</sup> · Agustin Conde Gallardo<sup>2</sup> · Ángel Guillén Cervantes<sup>2</sup>

Received: 23 May 2022 / Accepted: 5 October 2022 / Published online: 8 November 2022 © The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2022

### Abstract

The aim of this work was to study the effect of compaction pressure on the growth of the crystalline structure of the Bi-2212 phase and on the current density of the material. Ceramic samples were prepared by conventional solid-state reaction method, sintered at 840 °C after compacting at five different pressures that were 300, 450, 600, 750, and 900 MPa. The obtained samples were characterized by X-ray diffraction (XRD), scanning electron microscopy (SEM), resistivity vs. temperature ( $\rho$  vs. *T*) by the four-point probe method, critical current density vs. magnetic field ( $J_c$  vs. *H*) at 4 K, and by mass density vs. pressure ( $\rho_m$  vs. *P*). The XRD patterns show the main reflections of the Bi-2212 and Bi-2223 phases for all samples, varying slightly in intensity and with the presence of approximately 95.77% and 4.23% of each phase. The highest critical temperature values, at the beginning of the superconductor transition,  $T_{c,on1}$ , and for R = 0,  $T_{c,0}$ , are noted to be about 111.63 K and 101.20 K, respectively. For the calculations of critical current density, we used the Bean model, obtaining 6.84x10<sup>7</sup>  $Am^{-2}$  (the lowest for 300 MPa). The optimal conditions that improve the electrical, physical, and morphological behavior of the Bi-2212 superconducting material occur when the compaction pressure is 600 MPa and the lattice parameter *c* of the crystal structure is increased.

Keywords Bi-based superconductors · Compaction pressure · Current density · SEM · X-ray diffraction

## 1 Introduction

New horizons in technological applications have been reached thanks to the increase in current density in high critical temperature superconducting materials. Nowadays, scientists are seeking to reduce defects in polycrystalline superconducting materials, as for example disorders, dislocations, lattice strains, misorientations, and local structural distortions in the material. Through doping or adding foreign materials such as nanoparticles, it has been possible to reduce these defects [1]. Additionally, the effects caused by the modification of the microstructural grain size in polycrystalline superconducting materials, the Josephson unions that cause the "weak link" between grains, and many more difficulties that exist when trying to reach the local depairing current density ( $J_D(B, T)$ ), which is the theoretical limit associated with the density of Cooper pairs [2, 3], have been studied [4].

Recently, research groups and companies have modified or added steps in the classic solid-state reaction process, in order to mitigate the morphological defects mentioned above. Two new metallurgical processes, in the synthesis of the Bi-base superconducting material, that have been primarily used to reduce the "weak link" are (1) application of pressure and heat, simultaneously; and (2) annealing in controlled atmospheres at high pressures [2, 5].

When the superconducting material is synthesized by solid-state reaction, unwanted compounds are always obtained, since it is a procedure to obtain polycrystalline materials. Hence, the importance that the process guarantees the maximum formation of the desired compounds, as reported [2, 5, 6].

Elvia Díaz Valdeś ediazva@ipn.mx

<sup>&</sup>lt;sup>1</sup> Department of Physics, Escuela Superior de Física y Matemáticas, Instituto Politécnico Nacional, UPALM, Edif. 9, Col. San Pedro Zacatenco, GAM, Mexico City C. P. 07738, Mexico

<sup>&</sup>lt;sup>2</sup> Department of Physics, Centro de Investigación y de Estudios Avanzados, Instituto Politécnico Nacional, Mexico City C. P. 07360, Mexico

We have worked from 300 to 900 MPa, since from 100 to 300 MPa there are no significant changes in the magnetic and electrical properties of the superconducting material Bi-2212, as reported in refs. [7, 8]. On the other hand, it is taken into consideration that for the superconducting material with Bi-2223 phase, a significant affectation has been reported in the electrical and magnetic properties when compacted with pressures greater than 900 MPa [9].

Now, talking about the crystalline structure, it is known that the *c* lattice parameter value for the Bi-2212 phase is 30.78Å, and that *c* for Bi-2223 phase is 37.082Å [10]. The value of the lattice parameter *c* characterizes the superconducting phase.

When the compaction pressure is increased in the processing of the bulk superconducting material, in general, the content of the superconducting phase increases. It is logical to associate that by having a greater presence of Bi-2223 phase the  $J_c$  is greater. However, two things are experimentally demonstrated: the first, that there are better  $J_c$  behaviors in pure phases than in materials with the presence of combined phases [11]; and second, that samples with a lower percentage of Bi-2223 phase but with lower porosity and higher apparent density have better behavior in their electrical properties than samples with a greater presence of such phase [12]. Each of those research gives chemical, physical, or phenomenological justifications in the improvement of the properties of the superconducting material.

Previous studies indicate that applying high compaction pressure (between 1.5 and 6 GPa), in the precursor powders, affects the kinetics of formation of the superconducting phases, leaving the presence of impurities or non-superconducting phases, such as  $Bi_2CaO_4$  and  $Bi_{0.75}Sr_{1.25}O_3$ , even when the annealing temperature is high ~ (850 °C) [9, 13]. In other words, if high compaction pressure is applied to the precursor powders (>1.5 GPa), these are directly forced to react with their immediate neighbors, hindering the formation of more complex compounds such as superconducting phases [2, 5], hence the importance of obtaining greater knowledge about the formation of superconducting phases and the junction between grains.

To explain the behavior of  $J_c$  in polycrystalline superconductors, the effects of grain boundaries [14], the weak and strong bond between grains [8], the chemical composition (for example [13, 15]), and the effect of compaction pressure in the Bi-Sr-Ca-Cu-O system (BSCCO) in general [7–9, 14, 16] have been analyzed.

In this article, we report our recent results. We show how the compaction pressure influences the  $J_c$  in material with the Bi-2212 superconducting phase, all supported with measurements of X-ray, SEM, resistance versus temperature, and DC magnetization.

We have mainly found that the compaction pressure of the precursor powders of the bulk superconducting material, for 5 min and before the last heat treatment at 840 °C, reduces defects that naturally arise in polycrystalline superconducting materials.

The processing of the superconducting material allowed us to obtain  $T_{c,0}$  values around 100 K in the Bi-2212 phase, above of those reported for the same phase by Ali I. Al-Janabi et al. [17]. They estimated values of the critical onset temperatures for the Bi-2212 and Bi-2223 phases at 104 K and 110 K respectively.

# 2 Preparation of Bi-2212 Ceramics and Experimental Procedures

The bulk ceramic samples used in this study were prepared by the ordinary process of solid-state reaction, using  $Bi_2O_3$ , CuO,  $CaCO_3$  brand J. T. Baker,  $SrCO_3$  of Aldrich Chemistry, and PbO of Técnica Química, with 99.2, 99.2, 100, 98, and 100 % of purity, respectively. The powders of these oxides and carbonates were mixed in cation molar ratio 1.6:0.4:2:2:3 in order to obtain  $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_{9.8}$  of nominal composition. In this work, our interest was to obtain the Bi-2212 phase, but with the possibility of subsequently increasing the reaction temperature to obtain the Bi-2223 phase. The growth of the Bi-2212 phase was controlled by the reaction temperature.

After mechanically mixing for 20 h in a planetary mill inside an agate mortar, the powders were heat treated at 400 °C, 600 °C, and 750 °C for 106 h, 12 h, and 12 h, respectively, with a heating rate of 5 °C/min in porcelain crucibles. Then, 5 tablets of an equal quantity of powder were prepared, applying a constant load for 5 min to obtain rectangleshaped samples of  $10 \times 6 \times 2 \text{ mm}^3$ . The compaction pressures used were 300, 450, 600, 750, and 900 MPa. Finally, to obtain the Bi-2212 phase, we run a last treatment at 840 °C for 36 h with the same heating rate mentioned above.

The X-ray diffraction measurements of samples were performed in a Siemens D5000 diffractometer with source of  $CuK_{\alpha}$  ( $\lambda = 1.54$  Å), in Bragg-Brentano configuration, 36 kV, in air at room temperature, in the 2 $\theta$  range of 3–60° at a scan speed of 2 °/s with step increment of 0.02.

Analysis of morphology was performed in a scanning electron microscope model JEOL JSM-7401F with an external voltage of 20 kV and resolution power of 10 nm. The SEM images allowed us to study the morphology of the top face surface and measure the grain size. It was also possible to survey porosity, crystallinity, local structural distortions, disorders, dislocations, defects, and the weak grain boundary connection between grains that are created during the synthesis process utilized. Grain size was measured with the Zen Blue software from Zeiss, on the surface shown in the micrographs obtained at 2000 amplifications. A statistical average of the length of the flake-shaped particles was obtained.

Evaluation of mass density was performed by Archimedes water displacement technique. The experimental density findings enable us to evaluate the relative densities, of the processed material, and the variation of the degree of granularity with the variation of the compaction pressure in each of the samples with the same annealing temperature at 840 °C.

The DC resistivity as a function of temperature was measured by the standard four-point probe method, in the interval of 70–150 K. The electrical contacts were made with silver paint, and the measurements were performed with a quantum design physical property measurement system (PPMS). In the same way, the magnetization measurements were performed by using the vibrating sample magnetometer (VSM) option installed in the PPMS. The samples were zero field cooled to 4 K, and then the magnetization vs. applied magnetic field (M vs. H) curves were measured in the interval of  $\pm$  2 T. The critical current  $J_c$  as a function of the applied field was calculated from the hysteretic curves using Bean's model [18, 19].

## **3 Results**

### 3.1 X-ray Diffraction Analysis

Figure 1 shows the X-ray diffraction patterns between 3 and  $60^{\circ} (\theta - 2\theta)$  for the samples at five different pressure conditions. The Bi-2212 and Bi-2223 phases are identified. The Bi-2212 phase peaks with the Miller indices (*hkl*) are shown as L. These are peaks that do not overlap with those of Bi-2223 phase. In the same way, Bi-2223 phase peaks are shown as H (hkl). All the samples studied in this work exhibit the polycrystalline superconducting phase. Tiny unassigned peaks at the  $2\theta$  positions  $20^{\circ}$ ,  $37^{\circ}$ ,  $38^{\circ}$ , and 54° have a very low intensities, at noise level. They do not belong to any of the superconducting phases identified. They probably belong to impurities that were not identified. In all samples, the Bi-2212 phase is the dominant one and the Bi-2223 phase only appears as traces. In Table 1, the cell parameters for the Bi-2212 superconducting phase are shown. This phase exhibits a Pb-dependent solubility, which causes the transformation of the tetragonal structure to an orthorhombic one when the Pb content increases, being identified with the appearance of the peak in position  $2\theta$ =  $33.65^{\circ}$  in addition to the peak at  $33.15^{\circ}$  [13]. In the processed samples in this work, the stoichiometric relationship of Pb and the annealing temperature led to the formation of the orthorhombic structure, evidenced by the presence of both peaks mentioned above. It is observed, from the relative intensities (hkl)/(0010) as a function of the compaction

 Table 1
 XRD measurement results of cell parameters for the Bi-2212

 phase and phase fractions, at different compaction pressures

Compaction pressure,	Cell parameters, Å			Fraction of phases, %	
MPa	a	b	с	Bi-2212	Bi-2223
300	5.4091	5.4019	30.8608	95.71	4.29
450	5.4043	5.3981	30.8705	95.49	4.51
600	5.4127	5.3966	30.9255	95.77	4.23
750	5.4139	5.4028	30.9208	95.19	4.81
900	5.4101	5.4026	30.9033	94.06	5.94

pressure, that at 600 MPa, in the family  $\{00l\}$ , the intensities are of the highest and, on the other hand, the family  $\{11l\}$  presents a minimum in intensities. This indicates that the cell mostly grows in the *c* direction.

The volume fraction, of Bi-2212 and Bi-2223 phases in all the samples, was calculated using Eqs. (1) and (2) [1, 11, 20] and the relative percentages are tabulated in Table 1.

In Eqs. (1) and (2), the relative percentage of each phase is the ratio, in percentage, of the sum of the intensities (*I*) of the peaks of one phase, with respect to the sum of the intensities of the peaks of both phases, in the range of  $2\theta$  from 3 to 60°. The results in Table 1 show that the Bi-2212 phase grew as the main phase as a result of the reaction temperature at 840 °C. Also in Table 1, the lattice parameters of the pseudotetragonal structure are presented.

$$f(2212) = \frac{\sum I_{L(hkl)}}{\sum I_{H(hkl)} + \sum I_{L(hkl)}} * 100$$
(1)

and

$$f(2223) = \frac{\sum I_{H(hkl)}}{\sum I_{H(hkl)} + \sum I_{L(hkl)}} * 100$$
(2)

## 3.2 Mass Density

In order to quantitatively show the behavior of the density change at each pressure of compaction, the mass density analysis of all the samples was carried out in the same way as in [1, 16] and the values are tabulated in Table 2. The formula of the Archimedes water displacement method was used,

$$\rho_m = \frac{W_a \times \rho_{fl}}{W_a - W_{fl}} \tag{3}$$

where  $\rho_m$  is the mass density of the sample,  $\rho_{fl}$  is the mass density of the liquid,  $W_a$  is the weight of the solid in the air, and  $W_{fl}$  is the weight of the solid in the liquid. The synthesized superconducting pellets have a lower mass density

Table 2Mass density ofsuperconducting materialat different pressures. Theexperimental error of massdensity is  $\pm 0.34$  g/cm<sup>3</sup> for eachmeasurement

Compaction pressure, P	Mass density, $\rho_n$	
MPa	g/cm <sup>3</sup>	
300	4.66	
450	4.83	
600	4.95	
750	5.03	
900	5.09	

compared to the theoretical of the pure Bi-system phases (~  $6.302 \ g/cm^3$ ) [21, 22]. The reason the compaction pressure was not raised so much was because the precursor pellet would have a mass density much higher than the theoretical density of the superconducting material, which could more significantly affect the formation kinetics of superconducting phases (Bi-2212 and Bi-2223) as already mentioned above.

## 3.3 DC Electrical Resistivity

Figure 2 shows the behavior of the resistivity vs. temperature ( $\rho$  vs. T) curves, in the temperature interval of 70–150 K, of the superconducting samples under study, prepared at different compaction pressures. It is clearly visible that all the samples show a metallic behavior above the  $T_{c,on1}$  value and that the sample compacted to 600 MPa is less resistive than the other samples. The critical transition temperatures at zero resistance ( $T_{c,0}$ ) of the samples studied in this work are around 100 K. The maximum  $T_{c,0}$  value was 101.2 K for sample at 600 MPa. On the other hand, the minimum  $T_{c,0}$ 



Fig. 1 Diffraction patterns of the samples at 300, 450, 600, 750, and 900 MPa. Heat treatment at 840  $^{\circ}\mathrm{C}$  for 36 h

 
 Table 3
 Electrical parameters of the superconducting material at different pressures

Compaction pressure, P	$T_{c,on1}$	$T_{c,on2}$	$T_{c,0}$	$\Delta T_c$
MPa	К	Κ	Κ	Κ
300	109.09	104.57	99.00	10.09
450	110.72	106.21	99.50	11.22
600	111.63	106.49	101.20	10.43
750	111.22	106.35	100.00	11.22
900	110.52	105.89	99.10	11.42

value is noted to be about 99 K for the sample at 300 MPa. In addition, the variations of  $\Delta T_c (T_{c,on1} - T_{c,0})$  are shown in Table 3. There, it can be observed that the minimum  $\Delta T_c$  is about 10.09 K for the sample at 300 MPa, while the maximum  $\Delta T_c$  is about 11.42 K for the sample at 900 MPa. This phenomenon can be explained by the compaction pressure and the reduction of the grain limits.

The behavior of the  $\rho$  vs. *T* curves shows two shoulders in the resistance drop, which is typical when there is a combination of phases [23]. The point where the transition to the superconducting state begins, first shoulder, corresponds to the  $T_{c,on1}$  of the samples and the values of these temperatures belong to the phase with the highest critical temperature. The  $T_{c,on1}$  values range from 109.09 to 111.63 K. The second shoulder belongs to the phase with the lowest critical temperature. Its critical temperature is identified as  $T_{c,on2}$ and varies between 104.57 and 106.49 K. All the mentioned values are shown in Table 3. The  $T_{c,on1}$  and  $T_{c,on2}$  values are close to the critical temperatures of the Bi-2212 and Bi-2223 phases estimated in [17], as 104 K and 110 K respectively.



Fig. 2 Resistivity vs. temperature behavior of superconducting samples at different compaction pressures

In addition, as reported by Aytekin et al. [9], if the compaction pressure increases when processing the superconducting material above 1.5 GPa, as for example, the  $T_{c,on1}$  decreases, and the transition width  $\Delta T_c$  increases.

#### 3.4 DC Magnetization and J<sub>c</sub>

The isothermal magnetization was measured in the four quadrants in the range of  $\pm$  2T (see Fig. 3). The shape of each of the curves shows a minimum that indicates a strong field dependence in  $J_c$ , which is usually described by a modified Bean model in the cuprates [18, 19]. In order to obtain the samples for this measurement, a very careful mechanical cutting milling was performed on them to avoid fractures and defects. The masses of the samples were 45.2, 24.1, 42.2, 65.3, and 60.0 mg and their volumes 5.52, 6.9, 8.97, 10.8, and 9.9 mm<sup>3</sup> for 300, 450, 600, 750, and 900 MPa respectively. Figure 4 shows the tendency of the values of critical current density obtained from the loops of Fig. 3. The formula used to calculate the critical current was

$$J_c = \frac{2(dM)V}{w(1 - (w(3b)^{-1}))}$$
(4)

where  $dM = M^+ - M^-$  and V is the volume, w is the length, and b is the width of the tablets. The critical current density values at 0 T of applied field were  $9.71 \times 10^6$ ,  $1.17 \times 10^7$ ,  $6.84 \times 10^7$ ,  $1.18 \times 10^7$ , and  $1.32 \times 10^7 \text{ A/m}^2$ , and at approximately 0.15 T the maximum values of  $J_c$  were  $1.06 \times 10^7$ ,  $1.33 \times 10^7$ ,  $7.29 \times 10^7$ ,  $1.23 \times 10^7$ , and  $1.36 \times 10^7 \text{ A/m}^2$ , for samples compressed at 300, 450, 600, 750, and 900 MPa, respectively, and the ramping rate of the magnetic field for the magnetic hysteresis measurement was  $1.2 \ \mu\text{T}$ . The high values of critical current density at 4 K are slightly lower than those reported



Fig. 3 Magnetic hysteresis loop at 4 K



Fig. 4 Critical current density at 4 K

in the references by Guanmei Wang et al. [2], G. Wang et al. [4], and Y. Yuan et al. [5]. This shows that not only does the processing of the superconducting material influence high  $J_c$  values, but also, the percentage of superconducting phases present in the processed material. This is because they have a significant role when it comes to mitigating defects in the electrical phenomena mentioned in [2] and this breaks the goal of achieving the predicted theoretical values.

#### 3.5 SEM Analysis

Figures 5, 6, 7, 8, and 9 show the images of the top face surface of all the samples in bulk. As seen from the figures, the granular morphology of the samples consists mainly of layers of flakes with a structure similar to



Fig. 5 SEM micrograph of the sample pelletized at 300 MPa



Fig. 6 SEM micrograph of the sample pelletized at 450 MPa



Fig. 8 SEM micrograph of the sample pelletized at 750 MPa

large randomly distributed platelets. There are significant changes in the morphology of the material when the pressure of compaction is increased in its processing. In Fig. 7, it can be clearly seen that the most regular morphology is obtained for the sample with a compaction pressure of 600 MPa. In all samples, the dominant structures are plate-like grains and flakes randomly distributed due to the presence of pores between the grains. This is a direct observation of the texture with increasing compaction pressure. Fine particles are visible on the top surface of the grains, which may be a result of their fragmentation with a high degree of deformation occurring at a high pressure from 450 to 750 MPa, as mentioned in the same way by Kocabas et al. [16]. It is also evident from the micrographs that the grains of the samples compacted from 450 to 750 MPa are smaller and more uniform compared to those of the samples compacted to 300 MPa. We were able to corroborate this with the statistical measurement, for each compacted sample, of the length of the two types of grain observed. The results are shown in Table 4. The sample compacted at 900 MPa has few fine particles on the top surface of the granules, very low porosity, and larger grains. This can be attributed to the effect of compaction in the samples as already mentioned above. Regarding the morphology of the samples, it can be observed that the samples at 450 and 750 MPa have a similar grain structure, while the sample at 600 MPa has a more homogeneous structure with smaller grains,



Fig. 7 SEM micrograph of the sample pelletized at 600 MPa



Fig. 9 SEM micrograph of the sample pelletized at 900 MPa

 Table 4
 Grain size from two types of morphology of superconducting material processed at different pressures

Compaction pressure, P	Flakes length, L1	Platelet-like structure length, L2
MPa	μm	μm
300	1.78	5.67
450	1.16	4.31
600	1.05	2.39
750	0.71	2.88
900	2.17	5.27

which directly affects the superconducting state transition modifying the  $T_{c,0}$ ,  $T_{c,on1}$ , and  $T_{c,on2}$  [22].

## 4 Discussion

The diffractograms of the processed material indicate the presence of the superconducting phases Bi-2212 and Bi-2223, in a content around of 95% and 5% respectively. In this work, for the Bi-2212 phase, the effect of compaction pressure on the value of  $J_c$  was studied. We observed that increasing the pressure up to 600 MPa increases the value of  $J_c$ , but as the pressure continues to increase, the value of  $J_c$  decreases. It has been reported that the behavior of  $J_c$  is not related with the content of the superconducting phases. Rather, it is related to the local excess or deficiency of oxygen in the crystal lattice of the Bi-2212 phase, similarly to what was mentioned in the studies carried out in the (Bi, Pb)-2223 phase by Khulud Habanjar et al. [12], and with the interplanar distance [2, 4, 12, 14, 24]. We have shown that the behavior of the critical current density  $J_c$ , at 4 K, with respect to the variation of compaction pressure is directly associated with the increase or decrease of the lattice parameter c and specifically with the variation in the intensity of the planes (001) and (111). In the same sense, the intensity of the family of planes  $\{00l\}$  is due to the excess or deficiency of oxygen locally in the entire crystalline lattice as indicated in [12]. The greatest increase in c and  $J_c$  is obtained at a compaction pressure of 600 MPa.

The improvement in  $J_c$  between the samples compacted at 300, 450, 750, and 900 MPa can be justified because the weak-link between grains improves, more than with the growth of the lattice parameter c. The values of  $J_c$  do not increase significantly because they can only be improved up to a certain percentage as mentioned in [2]. But at 600 MPa,  $J_c$  increases almost by an order of magnitude. This could be explained through a strong link between grains. However, this increment is outside the limits of the improvement of the strong bond, leaving as a primary option, the growth of the lattice in c due to its local oxygen content in the crystal lattice, as well as it has been shown in [12] and [14].

The compaction pressure of the precursor powders for 5 min causes the superconducting material to be formed with a different morphology when the last heat treatment at 840 °C is applied. At this temperature, the compaction pressure generates changes in the material, such as micropores and nanopores, among others, that are typical microstructural morphologies other than normal [7–9, 12].

According to the electrical results, the existence of two shoulders in the  $\rho$  vs. *T* measurements has been justified by the presence of two phases. The first fall,  $T_{c,on1}$ , belongs to the phase with the highest critical temperature Bi-2223 and the second fall,  $T_{c,on2}$ , to the phase Bi-2212 with a lower critical temperature.

# **5** Conclusions

The study presented in this work of the effect on  $J_c$ , when the compaction pressure is varied in the processing of bulk superconducting material, indicates that the application of pressure for 5 min directly impacts its crystalline structure, on the relative content of the superconducting phases, and in its electrical behavior mainly in  $J_c$ .

The pressure raise locally increases the oxygen content in the entire crystal lattice up to 600 MPa compaction, while causing oxygen deficiency when the pressure continues to increase. The excess or deficiency of oxygen in the crystal lattice has a proportional effect on the lattice parameters b and c, on the values of the critical temperatures and on  $J_c$ . The greatest effect is obtained at 600 MPa that can be explained by the increase in interplanar distance due to the natural incorporation of oxygen in certain planes of the crystalline lattice.

The study on the processing of material in bulk reflects that the behavior of the critical current density can be improved by increasing the Bi-2212 phase content by exploring the compaction pressure around 600 MPa.

Now, according to the results obtained, a simple way to reduce the phenomena that affect to reach the theoretical values  $J_D(B,T)$ , on different scales and in large proportions, is with an adequate reticular growth in the parameter *c*, specifically in planes of families {00*l*} and {11*l*}, since these are among the most important in increasing  $J_c$ .

Finally, we can say that the variations in the content of the phases Bi-2212 and Bi-2223, in the values of the critical temperatures, in the lattice parameters b and c, and in  $J_c$  (0 T, 0.15 T), are a reflection of the content of oxygen in the crystal lattice. This is exclusively due to the variation of the compaction pressure applied during 5 min, since the superconducting material was prepared with the same composition and at the same reaction temperature. Acknowledgements We thank the support of Escuela Superior de Física y Matemáticas — IPN under project SIP Nr. 20221217. We would like to express our sincere thanks and appreciation to Profesor Dr. Roslan Abd. Shukor for his constant support and theoretical and practical guidance, about the Bi-based superconducting system, during the execution of this project. Finally, we appreciate the technical support given by P.E. Marcela Guerrero and M.Sc. Blanca Estela Zendejas Leal in the development of this project.

### Declarations

Conflict of Interest The authors declare no competing interests.

## References

- Saritekin, N.K., Pakdil, M., Bekiroglu, E., Yildirim, G.: Examination of effective nucleation centers for flux pinning of vortices and optimum diffusion annealing temperature for Au-diffusion-doped Bi-2212 polycrystalline compound. J. Alloy. Compds. 688, 637-646 (2016)
- 2. Wang, G., Raine, M.J., Hampshire, D.P.: The cause of "weak-link" grain boundary behaviour in polycrystalline  $Bi_2Sr_2Ca2U_2O_8$  and  $Bi_2Sr_2Ca_2Cu_3O_{10}$  superconductors. Supercond. Sci. Technol. **31**, 024001 (2018)
- Wang, G., Raine, M. J., Hampshire, D.P.: How resistive must grain boundaries in polycrystalline superconductors be, to limit Jc?. Supercond. Sci. Technol. 30, 104001 (2017)
- Sánchez-Zacate, F.E., Conde-Gallardo, A.: Particle size effect on lower critical field and full penetration field in the *SmFeAsO*<sub>0.91</sub>F<sub>0.09</sub> superconductor. Physica C: Superconduct. Appl. 563, 16-21 (2019)
- Yuan, Y., Jiang, J., Cai, X.Y., Larbalestier, D.C., Hellstrom, E.E., Huang, Y., Parrella, R.: Significantly enhanced critical current density in Ag-sheathed (*Bi*, *Pb*)<sub>2</sub>Sr<sub>2</sub>Ca<sub>2</sub>Cu<sub>3</sub>O<sub>x</sub> composite conductors prepared by overpressure processing in final heat treatment. Appl. Phys. Lett. 84, 2127 (2004)
- Yahya, S.Y., Jumali, M.H., Lee, C.H., Abd-Shukor R.: Effects of gamma-*Fe*<sub>2</sub>O<sub>3</sub>) on the transport critical current density of (*Bi*<sub>1.6</sub>*Pb*<sub>0.4</sub>)*Sr*<sub>2</sub>*Ca*<sub>2</sub>*Cu*<sub>3</sub>O<sub>10</sub> superconductors. J. Mater. Sci. New York **39**, 7125-7128 (2004)
- Tepe, M., Avci I., Abukay, D.: Effect of pelletization pressure on structural properties and critical current hysteresis of ceramic superconducting *Bi*<sub>1.7</sub>*Pb*<sub>0.3</sub>*Sr*<sub>2</sub>*Ca*<sub>2</sub>*Cu*<sub>3</sub>*O<sub>y</sub>*. Physica Status Solidi (a). **198**, 420-426 (2003)
- Fradina, I.A., Alekseev, A.F., Gridasova, T. Ja., Morozov, V.V., Jurchenko, D.O.: Influence of pelletization pressure on magnetic susceptibility samples of ceramics Bi (Pb)-Sr-Ca-Cu-O. Physica C: Superconduct. **311**, 81-85 (1999)
- Aytekin, M.E., Ozkurt, B., Sugozu, I.: Physical, magnetic and mechanical properties of Bi-2212 superconductors prepared by high pelletization pressure. J. Mater. Sci. Mater. Electron. 26, 1799-1805 (2015)
- Shamray, V.F., Mikhailova, A.B., Mitin, A.V.: Crystal Structure and Superconductivity of Bi-2223. Crystallogr. Rep. 54, 584-590 (2009)

- Yildirim, G., Varilci, A., Akdogan, M., Terzioglu, C.: Role of annealing time and temperature on structural and superconducting properties of (Bi, Pb)-2223 thin films produced by sputtering. J. Mater. Sci. Mater. Electron. 23, 928-935 (2012)
- Habanjar, K., Najem, A., Abdel-Gaber, A. M., Awad, R.: Effect of pelletization pressure on the physical and mechanical properties of (Bi,Pb)-2223 superconductors. Physica Scripta. 95, 12p. (2020). http://dx.doi.org/10.1088/1402-4896/ab7f46
- Majewski, P.: Phase diagram studies in the system Bi Pb Sr -Ca - Cu - O - Ag. Superconduct. Sci. Technol. 10, 453-467 (1997)
- 14. Hermiz, G. Y., Aljurani, B. A., Thabit, H. A.: Effect of Pressure on the Superconducting and Mechanical Properties of  $Bi_{1.6}Pb_{0.4}Sr_{1.8}Ba_{0.2}Ca_2Cu_{2.2}Ni_{0.8}O_{10+\delta}$  Syst. Adv. Mater. Phys. Chem. **3**, 42-47 (2013)
- Sugawara, K., Sugimoto, C., Luo, T., Kawamata, T., Noji, T., Kato M., Koike, Y.: Superconductivity above 100 K in the Bi-2212 phase of (*Bi*, *Pb*)<sub>2</sub>Sr<sub>2</sub>CaCu<sub>2</sub>O<sub>8</sub>. J. Phys. Conf. Series. **1054**, 012008 (2018)
- Kocabaş, K., Gokç, Çiftçiolu, M., Bilgili, O.: Effect of compaction pressure on structural and superconducting properties of Bi-2223 superconductors. J. Superconduct. Nov. Magn. 23, 397-410 (2010)
- 17. Al-Janabi, A.I., Al-Shakarchi, E.K.: Synthesis and specification of superconductor compound  $Bi_2Sr_2Ca_{n-1}Cu_nO_{2n+4+\delta}$  (n = 2, 3, 4). J. Supercond. Nov. Magn. **28**, 1659-1664 (2015)
- Chen, D.X., Sanchez, A., Nogues, J., Muoz, J. S.: Bean's, Kim's, and exponential critical-state models for high-Tc superconductors. Phys. Rev. B. 41, 9510-9512 (1990)
- Poole, C., Farach, H., Creswick, R., Prozorov, R.: Superconductivity. San Diego ISBN:9780124166103 (2014)
- 20. Halim, S.A., Khawaldeh, S.A., Mohamed, S. B., Azhan, H.: Superconducting properties of  $Bi_{2-x}Pb_xSr_2Ca_2Cu_3O_y$  system derived via sol-gel and solid state routes. Mater. Chem. Phys. **61**, 251-259 (1999)
- Zalaoglu, Y., Yildirim, G., Buyukuslu, H., Saritekin, N. K., Varilci, A., Terzioglu, C., Gorur, O.: Important defeats on pinning of 2D pancake vortices in highly anisotropic Bi-2212 superconducting matrix with homovalent Bi/La substitution. J. Alloy. Compd. 631, 111-119 (2015)
- Kocabas, K., Ciftcioglu, M.: The effect of Sb substitution of Cu in Bi<sub>1.7</sub>Pb<sub>0.3</sub>Sr<sub>2</sub>Ca<sub>2</sub>Cu<sub>3-x</sub>Sb<sub>x</sub>O<sub>y</sub> superconductors. Phys. Stat. Solidi (A) Appl. Res. **177**, 539-545 (2000)
- Valdés, D., Mejía-Garcia, E., López-López, C., Jergel, J. L.M.: Influence of annealing on the critical temperature of Bi-Pb-Sr-Ca-Cu-O thin films. J. Mater. Sci. Mater. Electron. 18, 1167-1170 (2007)
- Hermiz, G.Y., Aljurani B.A., Thabit, H.A.: Mechanical properties of Bi<sub>1.6</sub>Pb<sub>0.4</sub>Sr<sub>1.8</sub>Ba<sub>0.2</sub>Ca<sub>2</sub>Cu<sub>3-x</sub>Ni<sub>x</sub>O<sub>10+δ</sub> superconducting system. J. Supercond. Nov. Magn. 25, 1629-1634 (2012)

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.