




A novel research on the subject of the load-independent microhardness performances of Sr/Ti partial displacement in Bi-2212 ceramics

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ABSTRACT

This work is interested in the critical changes in the load-independent microhardness performance parameters with the partial substitution of Sr²⁺ inclusions for the Ti⁴⁺ impurities in the Bi-2212 inorganic solids with the help of the theoretical approximations as regards Meyer's law (ML), proportional sample resistance (PSR), modified proportional sample resistance (MPSR), elastic/plastic deformation (EPD), Hays–Kendall (HK) and indentation-induced cracking (IIC) models found on the experimental microhardness tests applied to a variety of test loads between 0.245 and 2.940 N for the first time. Moreover, Ti-substituted Bi-2212 bulk ceramics (Bi_{2.1}Sr_{2.0-x}Ti_xCa_{1.1}Cu_{2.0}O_y) are prepared within mole-to-mole ratios of $x = 0.000, 0.010, 0.030, 0.050, 0.070, 0.100$ by the standard solid-state reaction method in the atmospheric pressure conditions. It is provided that Ti partial substitution in the superconducting system descends unsmilingly the mechanical durability, stability, strength, toughness, critical stress, stiffness and flexural strengths of Bi-2212 superconducting solids studied owing to the increment of crystal structural problems. Moreover, it is obtained that the degradation in the crystal structural leads to diminish the typical ISE characteristic of Bi-2212 superconducting ceramic compounds. At the same time, the results show that all the models (especially IIC approach) can serve as the suitable descriptors for the determination of the variation in the load-independent mechanical performances of the Bi-2212 superconducting materials.

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1 Introduction

Superconductivity phenomenon is defined as the state of zero electrical resistivity and perfect diamagnetism (expelling the magnetic flux from the material). No other physical phenomenon likes the superconductivity characteristic behavior; or in the literature there has been no strong clue on the relation to the atomic number, atomic weight, ionization potential, angular momentum, electron affinity, electronegativity, work function, electron binding energy or the related compounds such as the metals, halogens, metalloids, non-superconducting materials, noble gases, halogens, alloys, nonmetals, organic compounds, inorganic materials and dielectric materials [1]. Hence, it is just based on the last descriptors that the superconductivity phenomenon correlates scarcely with the characteristic properties such as normal resistivity, conductivity, physical and mechanical features. Accordingly, the phenomenon of superconductivity can be found in all the kinds of materials. In fact, non-superconducting compounds drive the superconductivity at even lower temperature (below the critical transition temperature values). At the same time, the second term of perfect diamagnetism has directly attracted great attention of the scientists for the usages of metallurgical and materials science engineering, power transmission, magnetic separation, motors, transformers, refrigeration, electro-optic, generators, particle accelerators, spintronics, innovative energy infrastructure sectors, future hydrogen society, medicine areas, levitated trains, imaging technology, sensitive process control, electric power cable, magnetic energy storage, heavy-industrial technology and large-scale areas application fields [2–8]. As well known that according to the magnetic carrying characteristics, the superconducting materials are differentiated into two types: Type-I/Type-II. Among the materials, the superconductivity driven in the Type-II cuprate materials is hardly any affected at even higher magnetic field applied. In fact, the latter superconducting compounds obtain much superior characteristics such as relatively smaller energy power consumptions due to the presence of losses or heat dissipations in the crystal structures, extremely larger operating temperature, extensively higher pinning ability/capacity (satisfactory size of critical fields), tremendously greater current and external magnetic field carrying capacity as compared to those of the former

superconductors. Besides, the other promising features regarding as optical and electronic behaviors are clearly mentioned in the same publications of [9–12]. Moreover, largely lower material-preparation procedures including the chemical costs, harmless chemical contents, light weight/size, simple availability of starting powders and easy phase formation as well as the environmental benefits can be listed as the advantages of Type-II cuprate ceramic materials in comparison with the Type-I superconducting materials. All the appealing features mentioned above provide the Type-II superconductors to utilize in the magnetic energy storage, innovative energy infrastructure, medical diagnosis, heavy-industrial technology, spintronics, hydrogen society, sensitive process control, future refrigeration and large-scale areas application fields [2–12]. All in all, the scientists have extensively studied especially on the Type-II cuprate materials. As for the theoretical researches in recent years [13–16], the magnetic, electronic and structural characteristics of 3d transition metal atoms, known as Zinc [Zn], Vanadium [V], Titanium [Ti], Scandium [Sc], Nickel [Ni], Manganese [Mn], Iron [Fe], Copper [Cu], Cobalt [Co], Chromium [Cr] respectively, have been a topic of great interest. Especially, these researches related with transition metal atoms are concentrated on the silicon-based electronic devices and technology. This is so because of the fact that the mass production and bandgap properties of new classes of two dimensional materials such as silicene are discovered. Also, defect formation, applying an electric field and impurity doping are some of the most used methods so as to fit the bandgap. As a result of the magnetic, optical and superconducting researches, a number of methods to modulate a bandgap for magnetic random access memory (MRAM), single-spin electron sources and field-effect transistors (FETs) have been attempted using silicene. Besides, the researchers are hopeful for understanding the heavy electron systems and anomalous behaviors in experiments and models. In this work, we want to determine experimentally and theoretically the vital role of partial displacement of Sr^{2+} inclusions by the Ti^{4+} inclusions in the host Bi-2212 ceramics on the original or true (load-independent) microhardness parameters by means of the available six theoretical models founded on the Vickers microhardness experimental tests to be exerted at the different applied loads starting from 0.245 N and ending with 2.940 N. It is to be

mentioned here that the Bi-2212 cuprates (from the parents of Type-II cuprate ceramic materials) exhibit extensively higher thermodynamic stability, compositional/oxygen stability, and invariant of oxygen stoichiometry among the Type-II cuprate superconducting materials [17–21]. Further, this comprehensive study with the experimental results focused on the performance and functionality of Ti nanoparticles in Bi-2212 crystal system. Also, sophisticated/phenomenological interpretations and theoretical approaches occurred on the characteristic aspects of mechanical and structural quantities may be primary work to construct the application-oriented material science, metallurgical, electro-optic, industrial, technological, engineering, commercial, refrigeration, sensitive process control, small scale applications of Bi-2212 particulate solid materials for the first time. Also, the analysis of dopant mechanism cooperating between the fundamental material sciences and engineering may be a progressive study to generate active, feasible and dormant areas for the Bi-2212 superconducting matrix.

2 Experimental processes for Ti-substituted Bi-2212 ceramic solids

In this scientific work, we prepare the Ti-substituted Bi-2212 cuprate-layered perovskite crystals ($\text{Bi}_{2.1-x}\text{Sr}_{2.0-x}\text{Ti}_x\text{Ca}_{1.1}\text{Cu}_{2.0}\text{O}_y$) in the different molar ratio in a range of $0 \leq x \leq 0.100$ with the aid of solid-state reaction method in the medium of air. Also, the crucial variations in the load-independent microhardness parameters with the substitution of Sr^{2+} inclusions for the Ti^{4+} impurities in the Bi-2212 crystal structure are searched using the six theoretical approximations mentioned above based on the Vickers microhardness tests applied at the various indentation loads in the interval of 0.245–2.940 N for the first time in this study. In this regard, we firstly purchase the powder of chemicals such as Bi_2O_3 , SrCO_3 , CaCO_3 , CuO , TiO_2 materials with the high purity (> %99.99) from Alfa Aesar company. Then, we weigh all the chemicals in terms of the stoichiometric ratios by means of an electronic balance (within four digits) and put the chemicals in a tube so that the ball milling process can be started immediately. Here, the process is done for 6-h duration in the atmospheric pressure conditions for the homogeneous mixture of chemicals. Then, the obtained

mixture is exerted to the manual grinding process in an agate mortar using a grinder for the duration of 30 min so as to minimize the chemicals into the intended particle sizes. Further, the mixture of powders is calcined at 800 °C for 36-h duration in porcelain crucibles in the air atmosphere. During the calcination process, the cooling/heating rates are arranged as 5 °C per min. Also, the mixture carried out calcination process (in the formation of the blackish color) is removed from the furnace and is again ground by the grinder in the agate mortar for about the duration of 30 min. Right after, we press the mixture of powder into the rectangular bars with the size of $1.5 \times 0.5 \times 0.2 \text{ cm}^3$ using 300 MPa press load at the normal atmospheric pressure conditions. The main-heat treatments of the solid bars for annealing process are performed at 850 °C for 24-h duration. The solid bars prepared in this work will thenceforward be presented as starting from Ti-0 and ending with Ti-5 according to the molar ratios of different x values such as 0.000, 0.010, 0.030, 0.050, 0.070, 0.100, respectively. Besides, the mechanical measurements are performed using the model digital microhardness tester of SHIMADZU HVM-2 in the different external test loads of 0.245–2.940 N for 10 s at the normal atmospheric pressure conditions. The critical changes in the original microhardness performance of Bi-2212 specimens with the Ti partial replacement process are surveyed by the way of the available theoretical models provided above (Table 1).

3 Results and discussion

In this part of the paper, we argued about the alterations of the mechanical characteristics and performances of the Sr-site Ti partial substituted Bi-2212 inorganic matrix regarding with the partial substitution level and indentation test loads applied to the samples between the range of 0.245–2.940 N. In this regard, we firstly have to describe the effects of Sr-site Ti partial substitution mechanism on the Vickers hardness (H_v) parameters. Thereafter, we will try to determine the indentation size effect (ISE) and reverse indentation size effect (RISE) behavior for all samples prepared for this study under the static compression loads. As well known, Vickers hardness (H_v) parameters at the different five indentation test

Table 1 Reasonable mean diagonal lengths and Vickers microhardness parameters at various applied indentation test loads of 0.245–2.940 N for bulk $\text{Bi}_{2.1}\text{Sr}_{2.0-x}\text{Ti}_x\text{Ca}_{1.1}\text{Cu}_{2.0}\text{O}_y$ ($0 \leq x \leq 0.100$) superconducting ceramics

Samples	F (N)	H_v (GPa)	d (μm)
Ti-0	0.245	4.94504	303.110
	0.490	4.68095	440.588
	0.980	4.54448	632.372
	1.960	4.43642	905.135
	2.940	4.41546	1111.188
Ti-1	0.245	4.75976	308.953
	0.490	4.45794	451.474
	0.980	4.29511	650.470
	1.960	4.21798	928.277
	2.940	4.20866	1138.160
Ti-2	0.245	4.59865	314.318
	0.490	4.26889	461.362
	0.980	4.08407	667.065
	1.960	4.02184	950.643
	2.940	4.01588	1165.159
Ti-3	0.245	4.51057	317.372
	0.490	4.14435	468.243
	0.980	3.94718	678.533
	1.960	3.91775	963.189
	2.940	3.91663	1179.829
Ti-4	0.245	4.39828	321.398
	0.490	3.97946	477.846
	0.980	3.81743	689.968
	1.960	3.79576	978.544
	2.940	3.79502	1198.584
Ti-5	0.245	4.14537	331.057
	0.490	3.66098	498.197
	0.980	3.42855	728.047
	1.960	3.41504	1031.649
	2.940	3.41448	1263.610

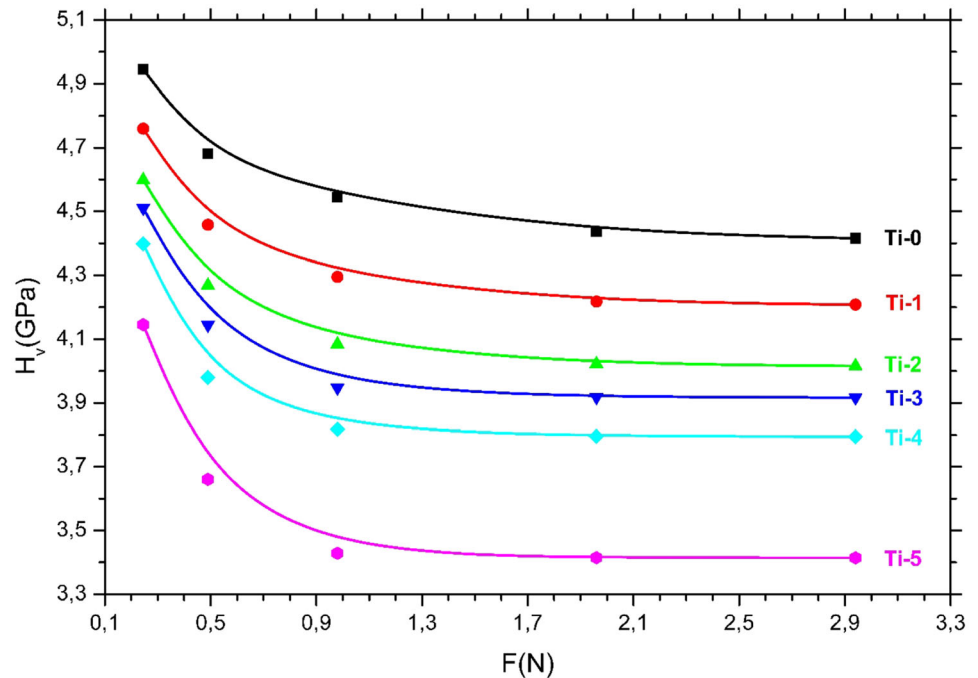
loads starting from 0.245 N and ending with 2.940 N are obtained from the sequent equation:

$$H_v = \frac{2F \sin(\alpha/2)}{d^2} = 1.8544 \left(\frac{F}{d^2} \right) \quad (1)$$

in the formula, H_v is the Vickers microhardness value, α demonstrates the indenter face angle (136°), d displays the mean diagonal length of the indentation impression and F is abbreviation of the applied indentation test load. In the equation, $2\sin(\alpha/2)$ equals to 1.8544, and so the right part of the equation is obtained. Also, the load-dependent microhardness values of the pure and Sr-site Ti substituted Bi-2212 ceramics is graphically depicted in Fig. 1. Based on

the experimental details, it can be obtained that the augmentation of Ti inclusions in the Bi-2212 superconducting matrix swiftly deteriorates the key mechanical features and microhardness values at the same compression test load. That is to say, the presence of partial substitution mechanism in Sr/Ti particles in the crystal system leads to disturb the key mechanical characteristics and general mechanical features due to the improvement in the stabilization of durable tetragonal phase. As for the numerical evidences, one can easily see from Table 1 that the microhardness values and features tend to diminish quickly from the value of 4.94504 GPa towards to 4.14537 GPa at the test load of 0.245 N. Moreover, the mechanical performances of the samples simultaneously are found to decrease depending on the enhancement of Ti partial substitution level. Besides, it can be noted that the microhardness values gradually diminish depending on the compression load in the increasing range of 0.245–2.940 N for each sample. Additionally, the microhardness value of the Ti-5 ceramic (3.41448 GPa) is ascertained as the smallest value as compared with the other values such as 4.41546 GPa (Ti-0), 4.20866 GPa (Ti-1), 4.01588 GPa (Ti-2), 3.91663 GPa (Ti-3), 3.79502 GPa (Ti-4) at the compression load of 2.940 N (Fig. 1). Meanwhile, it can be quite easily ascertained that the mechanical hardness parameters descend systematically up to the compression load of about 2 N, and so the hardness parameters almost remain constant above this applied load value. Then, the value of 2 N can be accepted as the saturation limit regions. In this regard, the optimum substitution amount of Sr^{2+} inclusions for the Ti^{4+} impurities takes the advantage of enhancement in the main structural problems. Among the samples studied, Ti-0 specimen is conspicuous as the least sensitive, the bulk Ti-5 sample can be determined as the most sensitive (response) in terms of the test load owing to the increment of induced permanent structural problems in the Bi-2212 superconducting system. Forthcomingly, the solid Ti-0 sample exhibits the highest key mechanical design properties. As for the determination of mechanical behaviors of the $\text{Sr}^{2+}/\text{Ti}^{4+}$ substituted Bi-2212 crystal system for the definite substitution level, all samples prepared for this detailed study exhibit the usual ISE nature, in which the materials simultaneously display not only irreversible (plastic) but also reversible (elastic) deformations in the matrix system as a result of the influential amelioration of

Fig. 1 Plots of Vickers hardness parameters (H_v) versus indentation test loads (F) for all $\text{Bi}_{2.1}\text{Sr}_{2.0-x}\text{Ti}_x\text{Ca}_{1.1}\text{Cu}_{2.0}\text{O}_y$ ($0 \leq x \leq 0.100$) ceramic samples



systems. Besides, the ISE characteristic descends remarkably with the improvement of the Sr/Ti partial substitution amount. That is, in fact, the ISE nature resides the least behavior for the highest substitution level of $x = 0.100$. Moreover, the load-independent (true) microhardness values in the saturation regions are examined with the help of the theoretical models regarding Meyer’s law (ML), proportional sample resistance (PSR), modified proportional sample resistance (MPSR), elastic/plastic deformation (EPD), Hays–Kendall (HK) and indentation-induced cracking (IIC) models.

3.1 Load-dependent Vickers performance parameters of Ti-replaced Bi-2212 solids with regard to ML approach

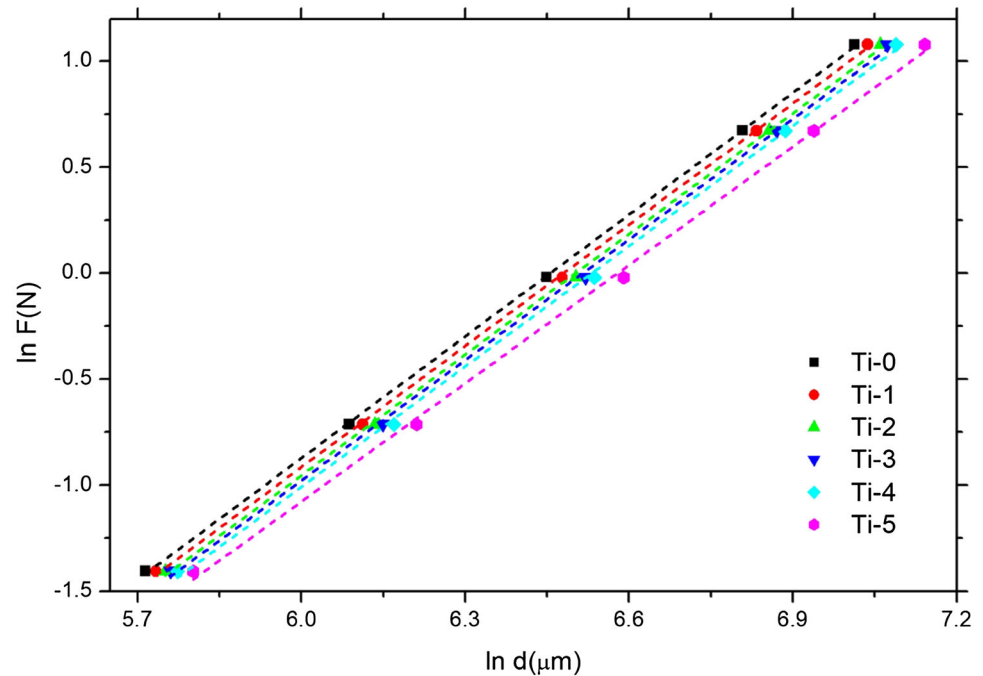
The theoreticians prefer the Meyer’s law to determine the differentiation in the load-independent mechanical performances of the superconducting ceramic compounds with any changes in the preparation conditions (doping, addition, partial substitution and the heat-treatment processes such as the, temperature, time, pressure, calcination and sintering ambient atmosphere), dopant type, dopant quantity, transition metal evaporation and chemical composition [22, 23]. That the model provides the reliable, valid and useful results for the superconducting material exhibiting both reverse indentation size

effect (RISE) and indentation size effect (ISE) behaviors is another advantage of the model. In the Meyer’s law there is a strong and sensitive link between the external test loads and exponential power of n related to the mean diagonal length. One can see the relation below [24]:

$$F = A_{\text{MEYER}}d^n \tag{2}$$

in the relation, A_{Meyer} is associated with the typical Vickers hardness parameters for the materials studied when the abbreviation of n coincides with the Meyer number for applied indentation test loads. Besides, one can anticipate the mechanical characteristic behavior of a sample with regard to the Meyer’s law. Namely, in case of $n < 2$ (n is lower than 2), the sample exhibits the characteristic ISE feature. As for the state of $n > 2$ (the exponential power value of n is greater than 2), the sample presents the unusual RISE nature. At the last condition of $n = 2$ (n is equal to 2), the material is known as Kick’s material whose mechanical characteristic behavior is totally independent upon the indentation test load [25, 26]. As for the examination with respect to this approach of our materials in Fig. 2 (linear differentiations of $\ln F$ over $\ln d$ curves), all the exponential power values of n are found to be lesser than 2 (Table 2). This is relied on the fact that every material prepared presents the ISE property with the enhancement of Ti

Fig. 2 Variation of external test loads $\ln F$ versus diagonal tracks $\ln d$ for every material studied in this work



impurity substitution level [27]. Numerically, the n value is found to decrease regularly from 1.914 (for the Ti-0 compound) until the value of 1.860 (bulk Ti-5 material) related with the Ti partial replacement level. The other values between 1.907 and 1.894 are calculated for the other materials. In this regard, it would be more precise to confirm that the formations of plastic (irreversible)/elastic (reversible) deformations emerge together in the Bi-2212 superconducting matrix but in the decrement trend. The degradation of Meyer number with the dopant level stems from the increased crystal structural problems, crack-producing omnipresent flaws, disorders, structural voids, porosity, defects lattice strains, misorientations distortions, cracks, strength quality and grain boundary couplings of connection between the grains.

3.2 Investigation based on PSR model of Ti partial substituted Bi-2212 specimens for real Vickers microhardness parameters

PSR, mostly called as the modified form of HK approach, is firstly introduced in 1993 by Bradt and Li [28]. Also, the basis of this model is the energy dispersion accompanied by the residual cracks, voids and flaws on the sample surfaces. Besides, the variation of surface energy brings about determining the

mechanical characterization of the materials. Additionally, the equation belonging to this model is related with two parameters to describe *ISE/RISE* nature of the superconducting compounds: (I) α , the surface energy and (II) β , the load independent microhardness constant. Besides, this model is identified via following relation [29]:

$$F = \alpha d + \beta d^2 \quad (3)$$

here, two constants (β , α) values are attained from the linear graphs of F/d over d for each sample prepared for this study (Fig. 3). Further, it can be clearly said that α and β parameters are directly correlated with the irreversible/reversible (plastic/elastic) deformation of the specimens [28]. Also, all findings acquired from F/d vs. d graph are pictured in Table 2. When examining the table, it is clearly illustrated that all the samples reveal *ISE* nature as a result of the positive α parameter. This statement strengthens the realization of plastic/elastic deformations at the same time. Indeed, the another crucial evidence obtained from the table is that the value of β parameter gradually descend depending on the enhancement of the partial substitution level, confirming that the grain boundary weak links and local structural distortions between the grains increase immediately. What's more, one can easily compute the load independent microhardness values at the saturation regions for

Table 2 Extrapolated parameters inferred from various theoretical models for bulk $\text{Bi}_{2-x}\text{Sr}_{2-x}\text{Ti}_x\text{Ca}_{1-x}\text{Cu}_2\text{O}_y$ ($0 \leq x \leq 0.100$) ceramic compounds

Samples	ML		PSR		MPSR		EPD		HK		IIC		
	$A_{\text{MEYER}} \times 10^{-6}$ (N/ μm^2)	N	$\alpha \times 10^{-4}$ (N/ μm)	$\beta \times 10^{-6}$ (N/ μm^2)	$W \times 10^{-2}$ (N)	$A_{0\text{MPSR}} \times 10^{-5}$ (N/ μm)	$A_{1\text{MPSR}} \times 10^{-6}$ (N/ μm^2)	$d_e \times 10^{-1}$ (μm)	$A_{2\text{EPD}} \times 10^{-2}$ (N/ $\mu\text{m}^{1/2}$)	$W \times 10^{-1}$ (N)	$A_{3\text{HK}} \times 10^{-6}$ (N/ μm^2)	$K \times 10^{-4}$ (N ³⁻⁵ mA) ^{3/} $\mu\text{m}^{(2-3 \text{ m})}$	m
Ti-0	4.306	1.914	1.139	2.273	1.768	4.920	2.321	0.361	0.151	0.325	2.355	13.526	-0.420
Ti-1	4.297	1.907	1.138	2.160	3.883	-2.603	2.261	0.369	0.147	0.308	2.244	8.226	-0.441
Ti-2	4.363	1.898	1.191	2.051	5.113	-6.167	2.180	0.394	0.143	0.318	2.139	3.684	-0.479
Ti-3	4.338	1.895	1.153	2.000	6.750	-12.139	2.166	0.385	0.142	0.289	2.087	8.684	-0.432
Ti-4	4.252	1.894	1.114	1.938	7.204	-13.858	2.112	0.378	0.139	0.273	2.023	24.160	-0.377
Ti-5	4.858	1.860	1.408	1.711	9.577	-17.843	1.923	0.498	0.131	0.356	1.814	71.701	-0.315

each superconducting sample with the aid of the relation below [30, 31]:

$$H_{\text{PSR}} = 1854.4\beta \tag{4}$$

H_{PSR} value computed are introduced in Table 3 clearly. As is seen from the table, the H_{PSR} hardness values are smaller than other load-dependent microhardness values in the saturation regions. This means that Vickers hardness evidences via this approximation is not practical to investigate the load independent microhardness parameters. Thus, it is fair to say that this approach performs the worst theoretical results to the load independent microhardness findings between theoretical models applied to Ti substituted Bi-2212 inorganic solid ceramics.

3.3 Determination of role of Sr/Ti partial substitution on original microhardness performance parameters with MPSR approach

After the proportional sample resistance model proposed by Bradt and Li to search the true mechanical performances of a superconducting material [28], the model needs to be modified by a new term of minimum applied test load leading to the impression track on the material (abbreviated as W_{MPSR} parameter in the model calculation). Moreover, MPSR model allows the scientists to search whether the polycrystalline compound studied exhibits the typical *ISE* feature or not. The calculation of model can be summarized as below [32]:

$$F = W_{\text{MPSR}} + A_{0\text{MPSR}}d + A_{1\text{MPSR}}d^2 \tag{5}$$

in the relation given, the $A_{0\text{MPSR}}$ and $A_{1\text{MPSR}}$ parameters ascribe to the dissipation energies founded on the plastic deformations due to the presence of residual flaws, porosities, cracks, voids on the sample surfaces in the unit volume. One can encounter the variations of external indentation test load against the impression lengths are depicted in Fig. 4 (linear differentiations of F against d curves). The curve slopes and crossing points on the y-axis are deduced according to the extrapolation method and all the values (W_{MPSR} , $A_{0\text{MPSR}}$ and $A_{1\text{MPSR}}$) obtained are numerically introduced in Table 2. Additionally, one can be seen obviously from the table that every calculation for the $A_{1\text{MPSR}}$ parameters is found to be in a range of 2.321×10^{-6} N/ μm^2 (for Ti-0 ceramic

Fig. 3 Linear graphs of F/d vs. d for all ceramic samples prepared

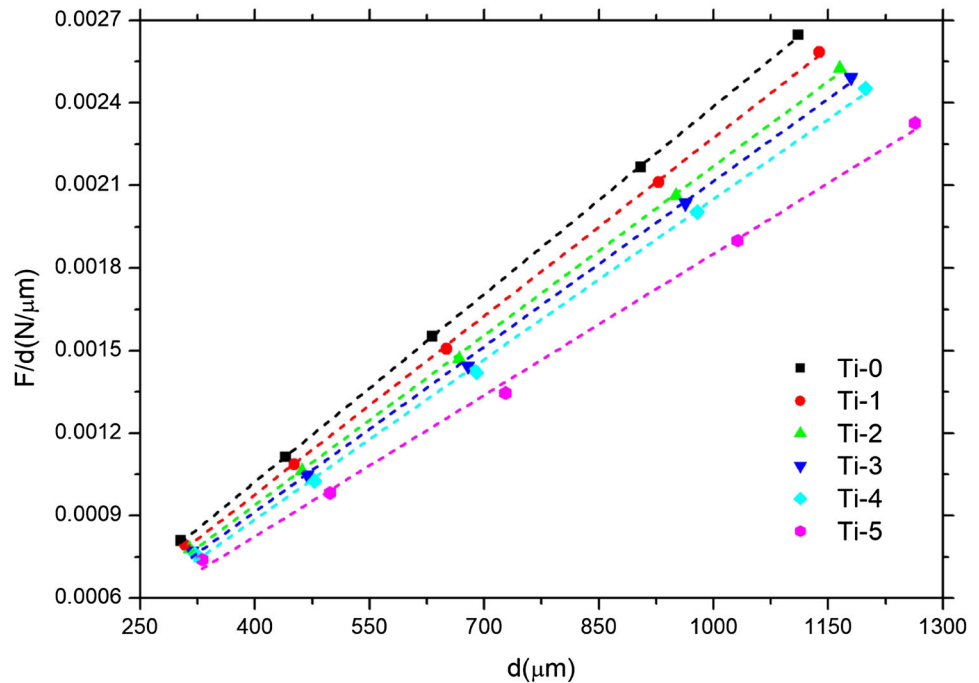


Table 3 Comparisons of load-independent microhardness parameters near saturation regions with the help of six theoretical approximations

Samples	H_{PSR} (GPa)	H_{MPSR} (GPa)	H_{EPD} (GPa)	H_{HK} (GPa)	H_{IIC} (GPa)	H_v (GPa)
Ti-0	4.215	4.304	4.228	4.367	4.627	4.945–4.415
Ti-1	4.006	4.193	4.007	4.161	4.364	4.760–4.209
Ti-2	3.803	4.043	3.792	3.967	4.225	4.599–4.016
Ti-3	3.709	4.017	3.739	3.870	4.050	4.511–3.917
Ti-4	3.594	3.916	3.583	3.751	3.915	4.398–3.795
Ti-5	3.173	3.566	3.182	3.364	3.599	4.145–3.414

instance) $- 1.923 \times 10^{-6} \text{ N}/\mu\text{m}^2$ (for Ti-5 specimen). Here, according to the values of A_{1MPSR} parameters the two important findings are obtained: (I) the specimens exhibit the ISE nature because of the positive A_{1MPSR} values and (II) the ISE feature tends to decrease systematically with the accrument of Ti partial displacement amount until the value of $x = 0.100$. Besides, according to this model, the load-independent microhardness values are computed via following relation:

$$H_{MPSR} = 1854.4A_{1MPSR} \quad (6)$$

The load independent microhardness values computed are served in Table 3. It can be easily point out that the Vickers hardness results of MPSR approach are found to be far the values with respect to the evidences by means of the IIC model in the saturation regions. Thus, we can say that whereas MPSR model is more successful for Ti-4 sample in accordance with

the other models, this model is generally invalid to compute relevantly the original load-independent values.

3.4 Survey of mechanical performances of ceramic materials studied in plateau regions with respect to EPD model

The EPD model is practical and reliable approximation to identify the mechanical performances of the solid bulk samples being subjected to compression load. Unlike the other known models, this is concentrated on the elastic recovery obtained in the vicinity of the indentation track. As a result, it is fair to point out that the indentation impression length is described by means of a new term defining the irreversible (plastic) deformation. Moreover, the equation including an extra new term are given below [33]:

Fig. 4 Linear plots of F versus d for Ti partial replacement Bi-2212 superconducting bulk ceramics

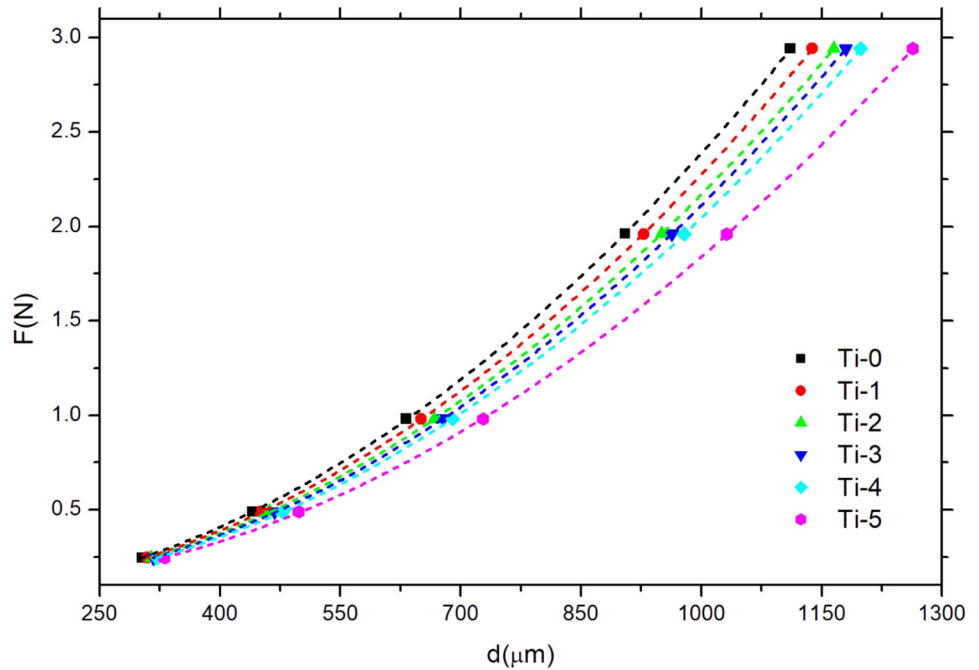
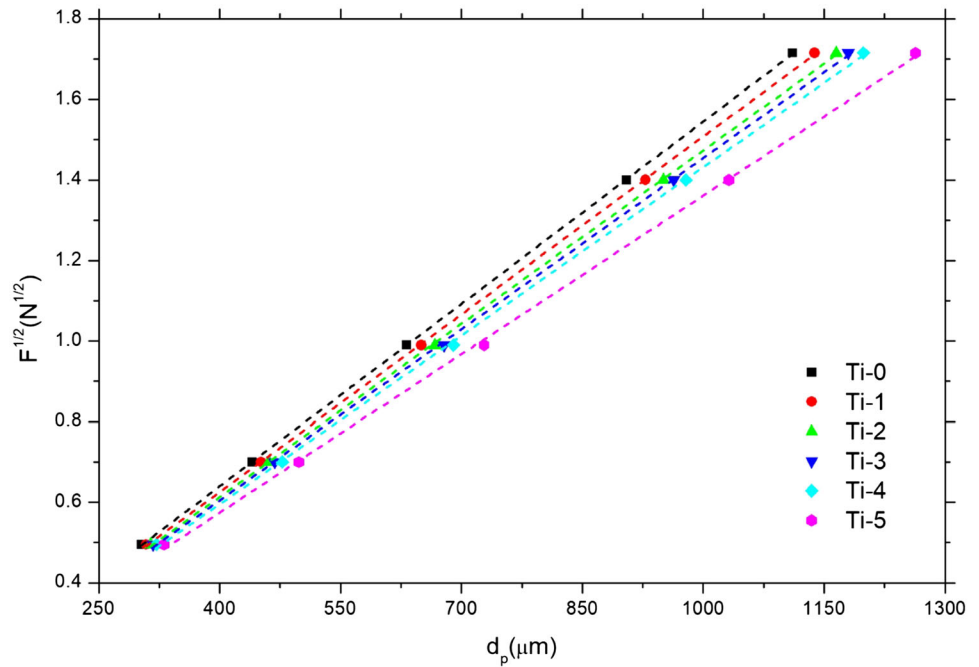


Fig. 5 Plots of the square root of test load $F^{1/2}$ against indentation length d_p for each solid samples prepared

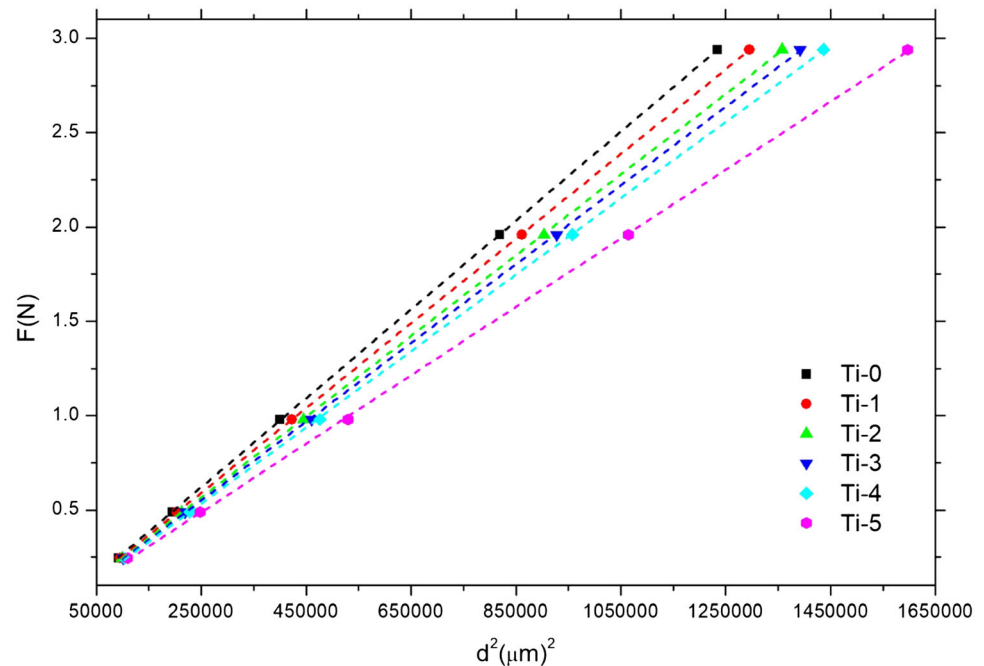


$$F = A_{2EPD}(d_e + d_p)^2 \tag{7}$$

here, A_{2EPD} illustrates the original microhardness parameter while the d_e and d_p variables presents plastic and elastic deformations, respectively. The values of A_{EPD} and d_e constants are deduced from the linear of $F^{1/2}$ vs. d_p graphs (Fig. 5). Also, all the

theoretical evidences of the specimens studied are depicted in Table 2. It is fair to say that all the d_e values extracted from the linear graphs are determined as positive in the increment trend from 0.361×10^{-1} to $0.498 \times 10^{-1} \mu\text{m}$ with the enhancement of the Sr-site Ti partial substitution level. This statement confirms that Ti substitution process into

Fig. 6 Linear plots of external indentation loads F over indentation lengths d^2 for $\text{Bi}_{2.1}\text{Sr}_{2.0-x}\text{Ti}_x\text{Ca}_{1.1}\text{Cu}_{2.0}\text{O}_y$ ($0 \leq x \leq 0.100$) ceramic materials



the Bi-2212 matrix destroy the mechanical features. In addition, this statement confirms that both the plastic and elastic deformations play dominant role along with the crystal because of the elastic recovery in the solid bulk materials prepared [34]. Based on the $A_{2\text{EPD}}$ computations depicted in Table 2, a regular decrement can be observed because of the increment in the boundary weak links and local structural distortions between superconducting grains. Likewise, we can also compute the true microhardness values via the relation specified below:

$$H_{\text{EPD}} = 1854.4A_{2\text{EPD}} \quad (8)$$

All the theoretical findings are gathered in Table 3. As for the results computed, it is fair to emphasize that EPD theoretical model is not adequate to describe the original Vickers hardness parameters. This is so because of the fact that the calculated values are far from the Vickers microhardness findings in the saturation regions.

3.5 Examination of true microhardness parameters for the Ti-substituted Bi-2212 bulk samples with respect to HK approach

HK model is another probable model to challenge the critical variations in the load-independent mechanical performances of Ti partial replacement of Bi-2212

materials produced in this work. In the approach, it is mentioned that there is a critic indentation test load (abbreviated as W) to start the plastic deformation in the crystal structure for every material [35]. In other words, an applied load higher than the critical value leads an indenter to penetrate deeply into the bulk compounds. Thus, the HK model describes an effective load ($F_{\text{eff}} = F - W$) to find the differentiation in the impression diagonal lengths over the applied indentation test loads as given below:

$$F - W = A_{3\text{HK}}d^2 \quad (9)$$

where the value of $A_{3\text{HK}}$ parameter is directly related to the microhardness when the abbreviation of W demonstrates the indentation test load resulting in the beginning of the plastic deformation in the crystal structure. In addition, it can be explicitly seen from the linear relation graphs of applied test loads vs. the square of impression lengths as shown in Fig. 6 (linear variations of F against d^2 curves). Further, all the extractions are given in Table 2. It is clearly founded from the table that all computations for the $A_{3\text{HK}}$ parameters are noted to be in a range from the value of $2.355 \times 10^{-6} \text{ N}/\mu\text{m}^2$ (for the solid Ti-0) to $1.814 \times 10^{-6} \text{ N}/\mu\text{m}^2$ (for the bulk Ti-5 compound). This confirms that the all superconducting ceramic materials studies exhibit the ISE characteristic due to the positive $A_{3\text{HK}}$ constants within the decrement trend. Namely, the degradation observed

in the constants with the substituted inclusions shows the regression the mechanical durability, stability, strength, toughness, critical stress, stiffness, flexural strengths of Bi-2212 structure studied owing to the increment of crystal structural problems. We also specify the changes in the load-independent performances of the Ti substituted Bi-2212 bulk ceramics using the following relations:

$$H_{HK} = 1854.4A_{3HK} \tag{10}$$

One can find out all the computations in Table 3. It is clearly seen from the table that the evidences of HK approximation are far to the load-dependent microhardness parameters as compared to those of the IIC model. In this respect, the HK model is unsatisfying so as to establish the original microhardness values for the samples produced for this work.

3.6 Analysis of original microhardness parameters of the ceramic samples prepared in terms of IIC Model

IIC model is the last approach in this study so as to analyze the real microhardness values along with the saturation regions. In this model, researchers are concentrated on the four parameters related with the indentation test loads applied on the specimen surface because of the total resistance at the maximum depth. These are given as;

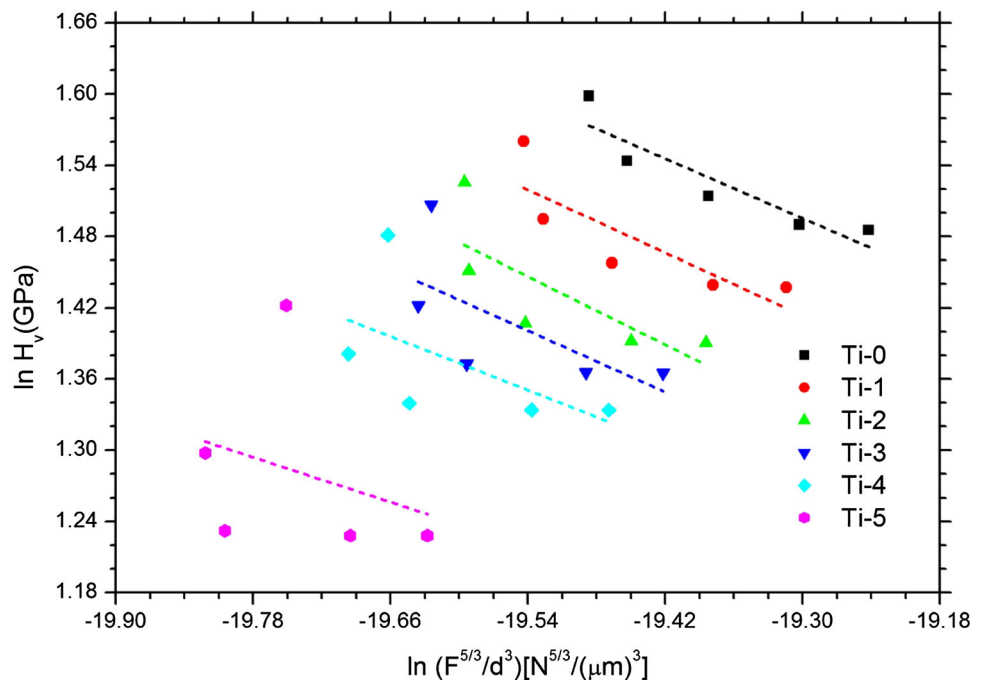
- (I) The friction occurred at the indenter/specimen facet interface.
- (II) Reversible /elastic deformation.
- (III) Irreversible/inelastic deformation.
- (IV) Cracking mechanism realized on the specimen

Herein, as the first two of the four parameters mentioned above are directly connected with the ISE characteristic, the last two ones commonly reveal the RISE feature. Hence, this model is determined as the sufficient approach to investigate the original microhardness values while the fundamental structural deformations or problems in the crystal gradually ascend. Moreover, the load independent true microhardness values of the specimens for this study are obtained from sequent relation:

$$H_{IIC} = \lambda_1 K_1 \left(F/d^2 \right) + K_2 \left(F^{5/3}/d^3 \right) \tag{11}$$

here, d presents the indentation impression size, λ_1 determines the constant, K_1 offers the geometry of indenter, K_2 gives the applied indentation load. In the relation given above, λ_1 is equal to 0 for an ideal perfect brittle solids like type-II superconductors. Therefore, the right-hand side of equation turns into $K_2(F^{5/3}/d^3)$. Further, the equation given above is reduced to following relation:

Fig. 7 Linear graphs of $\ln(H_v)$ over $\ln(F^{5/3}/d^3)$ for the bulk superconducting ceramics



$$H_{IIC} = K \left(\frac{F^{5/3}}{d^3} \right)^m \quad (12)$$

here, two constants, m and K , are attributed to the load-independent parameters. Besides, the graphs of $\ln(H_v)$ vs. $\ln\left(F^{5/3}/d^3\right)$ for Ti-substituted Bi-2212 ceramics are tabulated in Fig. 7. Also, two constants mentioned above for all samples inferred from the curves are introduced in Table 2. As for the evidences obtained from Table 3, all the real microhardness values concerning with Ti-substituted Bi-2212 inorganic ceramics are much closer to the load-dependent microhardness values as compared to the other approximations mentioned in the text. Further, according to the evidences obtained by means of this approach, it is clearly pointed out that the IIC is sufficient approach for the mechanical identification of Sr/Ti partial substituted Bi-2212 inorganic solids.

4 Conclusion

In this detailed study, the critical variation in the original mechanical performances of Ti-substituted Bi-2212 superconducting bulks produced with the molar ratio intervals $0 \leq x \leq 0.100$ via six theoretical approximations founded on the Vickers hardness experimental results obtained from the different external indentation loads (0.245–2.940 N) for the first time. It is observed that the superconducting materials produced for this study show ISE feature with the accrument of the Ti impurity displacement amount. Similarly, six theoretical approaches studied for this detailed work declare that the reversible (elastic)/irreversible (plastic) deformations appear together in the Bi-2212 superconducting solids because of the increased crystal structural problems. Moreover, the presence of Ti impurity in the Bi-2212 matrix leads to degrade considerably the mechanical durability, stability, strength, toughness, critical stress, stiffness, flexural strengths of Bi-2212 matrix studied. Additionally, it is revealed that six theoretical approaches studied in this exhaustive study are successful so as to notice the effect of substitution process on the general mechanical characteristic features and stabilization in the durable tetragonal phase. As for the comparison between the findings of models, IIC approach exhibits much closer results in terms of the load-independent microhardness

parameters Sr-site Ti substituted Bi-2212 superconducting ceramics in comparison to those of the other models.

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