Sakarya Üniversitesi Fen Bilimleri Dergisi
Sakarya University Journal of Science

e-ISSN : 2147-835X
Publisher : Sakarya University

Vol. 29, No. 6, 626-640, 2025
DOI: https://doi.org/10.16984/saufenbilder.1687983

Research Article

Examination of Load-Independent Parameters of $Bi_{2.1-x}Ba_xSr_{2.0}Ca_{1.1}Cu_{2.0}O_y$ Samples Depending on Semi-Empirical Mechanical Models

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ARTICLE INFO

Keywords:
Bi-2212 ceramic structure
Ba/Bi substitution
Original microhardness features
Mechanical models

Article History:
Received: 01.05.2025
Revised: 23.09.2025
Accepted: 25.09.2025
Online Available: 11.12.2025

ABSTRACT

This study investigates how the main mechanical properties and behavior of $Bi_{2.1-x}Ba_xSr_{2.0}Ca_{1.1}Cu_{2.0}O_y$ ceramic compounds change with different levels of barium substitution, using standard microindentation hardness (Hv) tests in the load range of 0.245-2.940 N. Results show that Hv values are strongly dependent on the substitution level that the sample with x = 0.1 molar ratio demonstrates the highest mechanical strength and durability under applied forces because of the formation of effective slip systems, force barrier zones, and stress regions within the Bi-2212 ceramic matrix. In other words, the presence of an optimal amount of barium ions lowers crack surface energy and reduces stored internal strains. In addition, load-independent hardness values in the saturation region were determined using five semi-empirical models; Hays-Kendall (HK), indentation-induced cracking (IIC), Meyer's Law (ML), proportional sample resistance (PSR), and elastic/plastic deformation (EPD) techniques for the first time. Among these, the IIC model provided the most accurate description of the microindentation hardness data for the mechanical characterization of $Bi_{2.1-x}Ba_xSr_{2.0}Ca_{1.1}Cu_{2.0}O_\gamma$ ceramic compounds.

1. Introduction

Superconductivity, defined as the coexistence of zero electrical resistance and the expulsion of magnetic flux fields, has long been a subject of significant scientific and technological interest. Since the discovery of Bi-based $Bi_2Sr_2Ca_{n-1}Cu_nO_{4+2n+x}$ ceramic superconductors, global research has focused on their superior current and magnetic field-carrying capacities, higher critical transition temperatures, enhanced thermodynamic stability, and reduced energy losses and power consumption [1-4].

These compounds crystallize in a multilayer perovskite structure consisting of alternating short-range ordered antiferromagnetic copper oxide layers and oxygen-deficient layers. They are categorized into three superconducting phases according to the number of conducting $Cu–O_2$ planes (n) per unit cell: n=1 (Bi-2201), n=2 (Bi-2212), and n=3 (Bi-2223). The $Cu–O_2$ planes directly determine superconducting

Cite as: A. Mercan, M. Öz, T. Turgay, G, Yıldırım, "Examination of load-independent parameters of $Bi_{2.1-x}Ba_xSr_{2.0}Ca_{1.1}Cu_{2.0}O_y$ samples depending on semi-empirical mechanical models," Sakarya University Journal of Science, vol. 29, no. 6, pp. 626-640. https://doi.org/10.16984/saufenbilder.1687983

behavior and strongly influence the c-axis lattice constant, which increases proportionally with the number of stacked antiferromagnetic layers.

Consequently, the high phase Bi-2223 has the longest c-axis length and the highest T_c (≈110 K), followed by Bi-2212 (≈85 K) and Bi-2201 (≈20 K) [5, 6]. Partial substitution in the Bi-2223 system can further enhance T_c [7].

Among these, Bi-2212 exhibits several advantages, including exceptional thermodynamic stability, faster and easier phase formation, strong compositional and oxygen stability, high critical magnetic field, and resistance to humidity [8-12]. The relatively simple melt-processing of its layered mica-like structure allows production in various shapes and lengths, making it suitable for a wide range of applications. Bi-2212 superconductors are frequently used in technology and industry, including metallurgy, particle accelerators, power transmission, transformers, electro-optics, spintronics, mobile devices, hydrogen energy systems, and large-scale industrial applications [13-19].

Hardness measures how well a material resists permanent damage and shows its wear resistance, strength, and durability [20]. Hardness tests are easy to prepare for, low cost, quick, accurate, and can also provide other mechanical information [21, 22]. Various methods like Rockwell, Brinell, and microindentation have been used to study metal-doped Bi-2212 superconductors, with Vickers and Knoop tests especially good for brittle materials like ceramics and mica-like structures. Microindentation uses small loads and diamond tips to precisely measure hardness differences and defects [23]. Modern automated Vickers tests give reliable results and help estimate other properties such as strength, stiffness, and toughness, making them essential for evaluating advanced ceramics [24].

In this study, we focus on the effects of Ba/Bi substitution in the Bi-2212 system on fundamental mechanical design parameters that are independent of applied load. These parameters are analysed using microindentation hardness data and evaluated through five established theoretical models: Meyer's Law (ML), Proportional Sample Resistance (PSR), Hays–Kendall (HK), elastic-plastic deformation (EPD), and Indentation-Induced Cracking (IIC).

2. General Methods

The influence of replacement of Bi^{3+} ions in the system with Ba^{2+} ions on the mechanical features of ceramics is investigated using hardness test experiments on the prepared samples via using a digital test machine (SHIMADZU HVM-2 model). Detailed impacts of barium atoms on primary mechanical properties and characteristic behaviors are explored. For the production process, the Bi-2212 superconducting material is prepared using high-purity powders ($BaCO_3$, $SrCO_3$, Bi_2O_3, $CaCO_3$, and CuO). Precise quantities of these high-purity chemicals (≥99%), supplied by Alfa Aesar, are accurately weighed to produce $Bi_{2.1-x}Ba_xSr_{2.0}Ca_{1.1}Cu_{2.0}O_y$ ceramicuprates with stoichiometric ratios varying within the range of $0.00 \leq x \leq 0.10$ and then electronically mixed for 6 hours to attain a uniform blend.

The resulting homogeneous mixture is subsequently ground in a mortar for approximately 45 minutes to improve particle size uniformity and enlarge the effective surface contact area, thereby facilitating enhanced solid-state reactivity and covalent bond formation. The uniform mixture, prepared with controlled particle growth, was subjected to heat treatment at 800 °C for 24 hours in a programmable furnace to ensure the effective removal of carbon and carbon-related impurities. To preserve the crystal structure, the rates for heating and cooling process for the calcination process are maintained under 5°C per minute. Following this, the powders are extracted from the furnace, shaped into rectangular prisms measuring 15x5x2 mm^3, and exposed to additional heating process under 840°C during 24 hours. Throughout the study, the produced samples, featuring various molar ratios of substitution (x=0.00, 0.01, 0.03, 0.05, 0.07, and 0.10), are denoted as pure, Ba-1, Ba-2, Ba-3, Ba-4, Ba-5, and Ba-6, respectively.

The fundamental knowledge established on mechanical characterization through microhardness measurements, focusing on load-independent mechanical performances in the plateau regions and the roles of Bi^{3+} impurities in the Bi-2212 crystal structure due to partial homovalent substitution of Ba^{2+} foreign residues. Experimental measurements (impression traces of indentations) are performed for 10 seconds in ambient air at room temperature using a calibrated microscope with the SHIMADZU HVM-2 model digital microhardness testing machine. Each measurement was performed five times at different regions of the sample surface to obtain an average value. The original hardness test results, together with their corresponding error bars derived from the standard deviations of five indentations, are presented in the microhardness plots. The machine was calibrated by HMV 700 standard block for hardness purchased from Yamamoto Chiba with applied 0.2 kgf before each measurement. Furthermore, we determine original performance parameters related to the mechanical features using existing theoretical models such as ML, EPD, PSR, HK, and IIC approaches for the first time.

3. Results and Discussion

We adapt to determine influence of aliovalent Ba/Bi replacement level intervals $0.0 \le x \le 0.1$ in the polycrystalline Bi-2212 ceramic compounds on the durable tetragonal phase, stored internal strain energy, crack surface energy, new formation of chemical bonds, slip systems, force barrier regions, and stress regions by the micro indentation H_v experiments under the forces changing 0.245 N-2.940 N.

The crucial relationships between the microhardness parameters and microscopic structural problems (permanent crystallinity problems, impurity residues, microvoids, degree of granularity, local problematic defects, concentration regions, internal problematic flaws, interior cracks, porosity, stress raisers, non-recoverable stress amplification sites, and weak-connection faults between adjacent layers) are also discussed in detail. Further, the changes in the microhardness parameters of aliovalent Ba/Bi partial replaced Bi-2212 compounds in the plateau sites are extensively examined by means of semi-empirical mechanical modellings including ML, EPD, PSR, HK, and IIC methods for the first time.

3.1. Variation of Vickers microinhardness parameters $Bi_{2.1-x}Ba_xSr_{2.0}Ca_{1.1}Cu_{2.0}O_y$ ceramics

The improvement of the main mechanical performance, mechanical strength, and durability of a material is extensively related to seven main mechanisms. These are arranged as follows: (i)- formations of new chemical bonds; (ii)- increase in the slip planes and slip directions; (iii)- reduction of granularity degree; (iv)- augmentation in the stress regions; (v)- decrease in the internal strain energy; (vi)- delay of propagations of dislocations and cracks along the system; (vii)- control mechanisms for crack velocity over the main matrix.

Fig. 1 indicates alteration of hardness results for the pure and $Bi_{2.1-x}Ba_xSr_{2.0}Ca_{1.1}Cu_{2.0}O_y$ ceramic compounds under the force applied of 0.245 N-2.940 N. As observed that the crystal quality, mechanical performances, mechanical strength, and durability are noted to improve with the substitution amount up to the amount of x=0.01 after which the mechanism converses totally as provided in Fig. 1.

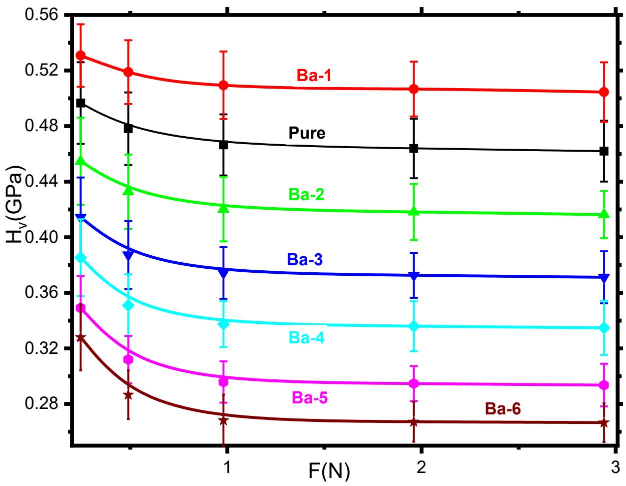

Figure 1. Alteration of hardness results for the pure and $Bi_{2.1-x}Ba_xSr_{2.0}Ca_{1.1}Cu_{2.0}O_y$ ceramic compounds with the applied test loads. Error bars represent the standard deviation of hardness values of 5 indentations under applied test loads

The numerical microhardness (H_v) values deduced from following Eq. 1 between the force (F) and notch diagonal lengths (d) are provided in Table 1 [25].

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

In this Eq. 1, d represents mean impression diagonal length, and F denotes the applied external forces. α signifies the angle for the indenter face.

According to the data in Table 1, values related to the H_v parameter values are recorded to vary meaningfully based on the Ba inclusions level. The variation reveals the barium inclusions were substituted successfully by the bismuth ions in the ceramic matrix. Obtained findings show that x=0.01 barium substitution amount is noticed to be ideal level in the matrix. In more detail, the pure one has 0.4966 GPa whereas the Ba-1 sample exhibits the global maximum H_v parameter of 0.5308 GPa at the force of 0.245 N. After x=0.01, the microhardness parameters are found to decrease dramatically.

At the highest replacement, the value belonging to H_v is noted to decrease against the smallest parameter of 0.2666 GPa for the bulk Ba-6 material. As to variation of hardness constants with the forces of $Bi_{2.1-x}Ba_xSr_{2.0}Ca_{1.1}Cu_{2.0}O_y$ ceramics, the H_v parameters were obtained to diminish systematically with augmenting the external forces applied. The decrement in the mechanical hardness constants with the forces stems from the ISE behavior of the pristine and aliovalent Ba/Bi partially Bi-2212 ceramics.

For the materials exhibiting characteristic typical ISE feature, reversible/irreversible deformations produce instantaneously within ceramic system under forces applied. Moreover, Fig. 1 indicates that the characteristic ISE property is recorded to rise with enhancing the Ba/Bi additional level until x=0.01 where there seems to be a degradation of the typical ISE behavior. This indicates that the Bi-2212 ceramics prepared at relatively lower barium particles present a more dominant ISE behavior. Consequently, the Ba-2 ceramic displays the highest characteristic ISE nature [26, 27].

Additionally, Fig. 1 demonstrates that the Vickers hardness parameters decrease nonlinearly with increasing test load until approximately 2 N, after this point the variation in the microhardness findings is recorded to remain nearly constant. This phenomenon is a result of plateau regions associated with increased microscopic structural problems in the ceramic matrix under applied test loads [28].

Table 1. Microindentation hardness findings for all the materials

Samples	*F (N)*	*d (µm)*	*H_v (GPa)*
Pure	0.245	30.24694	0.49662
	0.49	43.59537	0.47813
	0.98	62.41499	0.46655
	1.96	88.51514	0.46392
	2.94	108.63115	0.4623
Ba-1	0.245	29.25629	0.53085
	0.49	41.84638	0.51894
	0.98	59.72900	0.50942
	1.96	84.69432	0.50674
	2.94	103.95486	0.50455
Ba-2	0.245	31.60984	0.45473
	0.49	45.82011	0.43284
	0.98	65.76377	0.42026
	1.96	93.22615	0.41825
	2.94	114.43850	0.41632
Ba-3	0.245	33.11120	0.41444
	0.49	48.43686	0.38737
	0.98	69.67947	0.37435
	1.96	98.76619	0.37263
	2.94	121.19129	0.37122
Ba-4	0.245	34.33881	0.38534
	0.49	50.87989	0.35153
	0.98	73.38003	0.33757
	1.96	104.00641	0.33632
	2.94	127.60940	0.33484
Ba-5	0.245	36.07529	0.34915
	0.49	53.96628	0.3124
	0.98	78.38188	0.29583
	1.96	111.05540	0.29472
	2.94	136.26909	0.29365
Ba-6	0.245	37.21755	0.32809
	0.49	56.30690	0.28667
	0.98	82.31621	0.26828
	1.96	116.63033	0.26720
	2.94	143.00305	0.26668

Scientifically, the presence of optimal barium particles in the $Bi_{2.1}Sr_{2.0}Ca_{1.1}Cu_{2.0}O_y$ ceramics leads to dramatic reduction of the hardness parameters, mechanical durability and strength. This enhancement is due to the formation of new force barrier regions [29, 30]. Additionally, optimum barium ions induce new active operable slip systems and surface residual compressive stress areas along Bi-2212 matrix, leading to a suppression in stored internal strain energy, crack surface energy. Consequently, the durability is

maximized, corresponding to increased stabilization of durable tetragonal phase, deformation levels and especially critical stress constants.
The optimal barium ions also significantly enhance the mechanism of elastic recovery with both irreversible/reversible problems occurring instantaneously within the matrix under forces applied. Furthermore, improvement in crystallinity quality resulting from the optimal substitution is a key factor in the enhancement of microindentation hardness parameters. It is from Fig. 1 that the Ba-2 material shows the least sensitive to loads because of the higher H_v parameters and mechanical durability compared to other samples. Correspondingly, x=0.01 substitution level enables the ceramic system to present wholly all the main mechanisms provided above. In contrast, excess barium ions lead to the dominance of the stress-sourced phase [31]. Therefore, Ba-6 ceramic sample with the highest structural faults in the crystal system shows the most responsiveness to forces applied because of the prevalence of irreversible faults (plastic deformation problems), resulting in increased fatigue-induced fractures. In summary, the Ba-6 material is more prone to breaking in comparison with other ones. Similar experimental results can be found in the literature studies [32, 33].

At the same time, the incorporation of Ba impurities at the optimal concentration enhances chemical bonding and strengthens intergranular interactions between Ba and host matrix ions in the Bi-2212 crystal system. This modification results in a ceramic material with improved resistance to external stresses, corrosion, and fatigue as much as possible. Accordingly, among all investigated cermic samples, the bulk Ba-1 composition exhibits the lowest sensitivity to applied loads, reflecting superior mechanical performance. However, when the Ba impurity content exceeds the optimal molar ratio (x = 0.01), some problems such as reduced crystallinity, unfavorable crack orientation and geometry, weakened grain boundary coupling, and increased deformation become prominent along the Bi-2212 crystal system.

The presence of excess Ba impurity ions diminishes intergranular cohesion and accelerates structural degradation, thereby compromising the stability, durability, and integrity of the ceramic system.

In this respect, the novelty of the present study lies in demonstrating that Ba substitution can be finely tuned to engineer the mechanical hardness and ISE behavior of Bi-2212 ceramic structures. Unlike prior studies that primarily emphasized superconducting or electrical properties of Bi-based systems, this work systematically quantifies the correlation between Ba content, microstructural modifications (related to the formation of operable slip systems and surface residual compressive stress areas in the system) and mechanical stability under varying applied loads. Importantly, the identification of an optimal substitution level (x=0.01) that enhances both H_v and elastic recovery represents a new pathway for designing Bi-based superconducting ceramics with improved mechanical robustness, corrosion resistance, and fatigue tolerance, which are critical parameters for their industrial applications in power transmission, magnetics, and energy systems.

3.2. Evolution of mechanical behaviors of samples with semi-empirical mechanical approaches

The hardness findings are thoroughly inspected in the saturation limits by considering five available semi-empirical mechanical methods; viz, EPD, HK, MPSR, IIC, ML, and PSR techniques. We will also describe the best working method to analyze the change of mechanical durability and main mechanical characteristic property of materials.

3.2.1. Research of mechanical behaviors of samples with ML

One of the theoretical models preferred in this study is the ML being one of approaches used to investigate microhardness properties pertaining to the polycrystalline compounds. This method perfectly works for inspection of the fundamental mechanical characteristic feature (ISE or RISE) of Bi-2212 ceramics studied. The mechanical characterization of ceramics is defined by the Meyer number (*n*) that is totally related between the notched force load and the mean notch length. The formulation is shown below (Eq. 2) [34]:

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

Within this Eq. 2, the variable 'n' represents the Meyer constant while the number of A_{MEYER} signifies the hardness parameter.

Literature references reveal clearly three distinct scales for the 'n' constant. The scale's classification pivots around the value of n=2. Notably, if the material's 'n' value exceeds 2 (n>2) through extrapolation, the material demonstrates an unusual RISE feature (reverse indentation size effect). Conversely, for n<2, the material exhibits the typical ISE nature (indentation size effect), where microhardness constants decline with external forces. When n precisely equals 2, H_v parameters remain entirely independent of the applied load [35]. *n* constant values for all pristine and aliovalent Ba/Bi partially Bi-2212 ceramics in current work are recorded in graphs of lnF(N) against lnd(μm), as presented in Fig. 2. The computed values derived from extrapolation, along with the A_{MEYER} values (established as the y-axis intercepts when x=0) are outlined in Table 2.

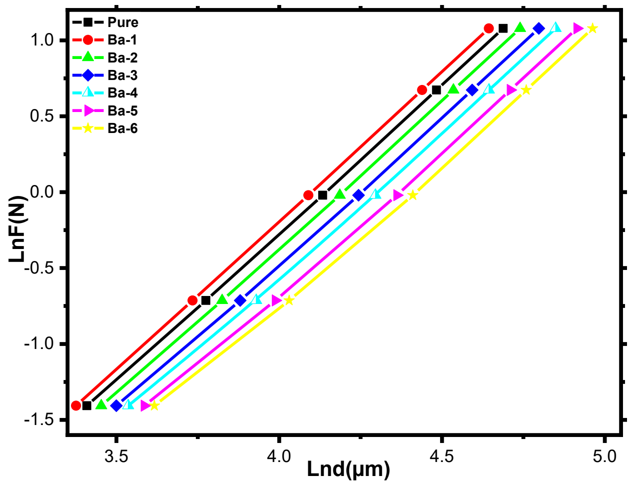

Figure 2. Graph of lnF(N) against lnd(μm) belonging to the pure and Ba added Bi-2212 ceramic compounds

According to the data provided in Table 2, the parameters found for the *n* parameters are significantly dependent on the aliovalent Ba/Bi substitution level. All calculated n parameters are less than 2. On this basis, all the studied products present the standard ISE characteristic [36]. Therefore, both the unsubstituted Bi-2212 material and all Ba/Bi replaced Bi-2212 ceramic materials are noted to simultaneously exhibit both reversible and irreversible deformations in the matrix. That is, when the forces are removed from material surface, Bi-2212 crystal system rapidly recovers. Evident from the table, the coefficient 'n' was computed to be 1.945 for the pristine product, while it was determined to be 1.961 for the optimally Ba-substituted Bi-2212 sample. After x=0.01 (critical substitution amount), there is a rapid reduction of *n* constant, and the minimum constant is calculated as 1.852 for the bulk Ba-6 ceramic material.

Table 2. Vickers microinhardness parameters calculated with different models for $Bi_{2.1-x}Ba_xSr_{2.0}Ca_{1.1}Cu_{2.0}O_y$ ceramic compounds

Samples	Meyer's Law		PSR Model	
	A_{MEYER} x10^{-4} (N/μm^2)	n	αx10^{-3}(N/μm)	βx10^{-4} (N/μm^2)
Pure	3.193	1.945	0.693	2.424
Ba-1	3.251	1.961	0.543	2.672
Ba-2	3.035	1.934	0.772	2.176
Ba-3	2.905	1.919	0.868	1.925
Ba-4	2.885	1.899	1.013	1.723
Ba-5	2.840	1.876	1.162	1.491
Ba-6	3.193	1.852	1.321	1.332

Samples	EPD Model		HK Model		IIC Model	
	d_ex10^{-1} (μm)	A_{2EPDX} 10^{-1} (N$^{1/2}$/μm)	Wx10^{-1} (N)	A_{3HK} x10^{-4} (N/μm^2)	Kx10^{-2} (N$^{(3-5mA)/3}$/ μm$^{(2-3m)}$)	m
Pure	0.216	0.155	0.1812	2.482	3.403	-0.212
Ba-1	0.163	0.163	0.1456	2.712	8.782	-0.144
Ba-2	0.253	0.147	0.2069	2.234	1.557	-0.264
Ba-3	0.300	0.138	0.1726	2.387	0.608	-0.325
Ba-4	0.364	0.131	0.2338	1.982	0.284	-0.373
Ba-5	0.446	0.122	0.2736	1.793	0.170	-0.398
Ba-6	0.526	0.115	0.3307	1.562	1.322	-0.232

The key result to be derived from this is that polycrystalline Bi-2212 structures show standard ISE features. However, the ISE behavior is noted to increase with the presence of optimal barium ratio in the Bi-2212 ceramics whereas the excess barium particles damage the characteristic ISE property. On this basis, in the case of x=0.10, the typical ISE behavior reaches its lowest level. The ML theoretical model clearly demonstrates why the overall mechanical properties improve with optimal Ba/Bi substitution. In this context, the presence of optimum barium ions in the crystal structure stabilizes the Bi-2212 system to the applied test forces. Oppositely, the increase of the amount of barium particles in the bulk Bi-2212 superconducting crystal structure increases the degree of sensitivity and responsibility to the forces applied.

To sum up, the ML model results indicate that the Ba/Bi-1 composition exhibits the highest resistance to external loads and deformation. This superior performance can be attributed to enhanced critical mechanical parameters, a more effective elastic recovery mechanism, and the stabilization of the durable tetragonal phase within the Bi-2212 lattice. In contrast, the Ba-5 and especially Ba-6 sample display the greatest sensitivity to applied loads, reflecting diminished structural integrity and reduced mechanical stability. Hence, the findings obtained highlight the capability of mechanical modeling approaches to reliably capture and predict the mechanical behavior of Ba/Bi substituted Bi-2212 ceramic structures, thereby providing valuable insights into the optimization of their structural and functional performance.

3.2.2. Alteration of mechanical features belonging to $Bi_{2.1-x}Ba_xSr_{2.0}Ca_{1.1}Cu_{2.0}O_y$ ceramic compounds using EPD model

The model of EPD is employed to scrutinize overall mechanical features, microhardness parameters, and actual hardness values within the material's plateau region. This model establishes a robust correlation between diagonal size and elastic recovery. Consequently, a novel verification term is integrated into the calculation module, encompassing plastic deformation, and its formula (Eq. 3) is as follows [37]:

$$F = A_{2EPD}\,(d_e + d_p)^2 \tag{3}$$

In the Eq. 3 above, the constant of A_{2EPD} and the related constants are observed with an extrapolation method using the curves of square root of applied microindentation test load ($F^{1/2}$) versus average indentation diagonal length (d_p) of Ba/Bi added Bi-2212 ceramics, as shown in Fig. 3 and the second parameter, d_e is a diagnostic coefficient for mechanical behavior. The numerical values obtained are detailed in Table 2. The coefficients deduced are observed as positive for all the pure and aliovalent Ba/Bi added Bi-2212 ceramic compounds. In this context, each sample is observed to exhibit ISE behavior. Similar to findings from other semi-empirical mechanical models, it has been observed that the manufactured products display both reversible and irreversible deformations simultaneously. Consequently, these systems exhibit recovery once the applied microindentation test loads are removed. Numerically, the coefficient of mean diagonal length for pristine sample is found to be 2.152x 10^{-2} μm while the d_p parameter is observed to decrease towards the value of 1.627x 10^{-2} μm for the polycrystalline Ba-1 sample, and in the case of further substitution amount a continuous increase in the coefficient is observed. The value is determined to be 5.263x x10^{-2} μm for the $Bi_{2.1-x}Ba_xSr_{2.0}Ca_{1.1}Cu_{2.0}O_y$ ceramics prepared by maximum replacement amount of x=0.1.

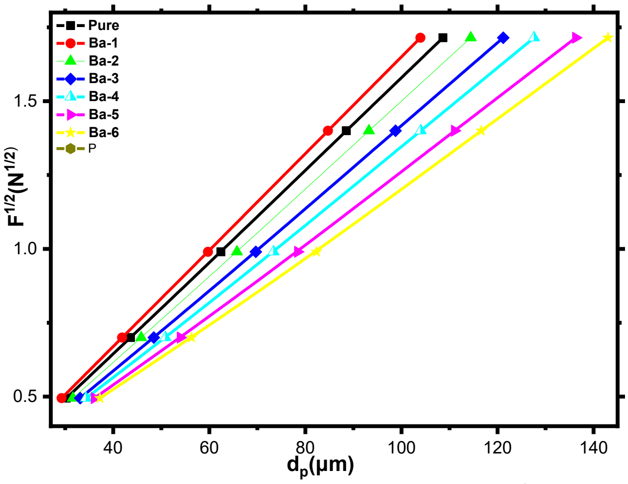

Figure 3. Graphs of notched test force ($F^{1/2}$) over diagonal length (d_p) for Ba/Bi added Bi-2212 ceramics

As for change in the constants of A_{2EPD}, the pristine ceramic is noted to possess 1.55x x10^{-2} $N^{1/2}$/μm followed by an increase in the coefficient to 1.63x x10^{-2} $N^{1/2}$/μm for the bulk Ba-1 superconductor. In the case of maximum addition, bulk Ba-6 ceramic is recorded to possess the global minimum A_{2EPD} constant of 1.15x x10^{-2} $N^{1/2}$/μm. The initial enhancement in the constants of A_{2EPD} stems from the improvement in the slip planes and slip directions, the crystallinity quality, and the surface residual compressive stress regions. On the other hand, with the enhancement of the aliovalent Ba/Bi replacement amount all the mechanism converses entirely. Thus, the constant of A_{2EPD} is noted to decrease dramatically depending on the degradation in the mechanism discussed above.

Moreover, the decrease in the value at x=0.01 substitution ratio is expressed as the applied force causing less damage to the material (due to the increase in the material's resistance to applied load). Therefore, it is found that Ba-1 presents the greatest mechanical performance among the materials studied. Conversely, the increase of the amount of Ba ions in the crystal structure adversely affects the hardness, critical constant for the stress, mechanical strength, and resistivity towards the test loads (the tetragonal phase durability) of the Bi-2212 material. Using this model, we also examine the load-independent microhardness constants in the saturation sites by following relation (Eq. 4):

$$H_{EPD} = 1854.4A_{2EPD} \tag{4}$$

The results of all calculations of true hardness constants are given in Table 3 numerically. According to Table 3, computed original hardness values in the saturation sites are considerably lower than the anticipated values. Within this context, while the EPD theoretical model effectively ascertains fundamental mechanical performance features and hardness characteristics of ceramics, it exhibits limitations in accurately determining the microhardness values within the plateau regions.

Consequently, although the EPD approach is found to be succesfull to obtain valuable information about mechanical strength parameters, critical stress values, elastic recovery mechanisms, crack initiation and propagation constraints, deformation behavior, stabilization of the tetragonal phase, sensitivity to applied test loads, and the overall mechanical characteristics of the Bi-2212 ceramics, the model exhibits minimal deviations in estimating the microhardness values within the plateau regions, indicating good agreement with the experimental data.

Table 3. Computations of Vickers hardness coefficients in plateau sites according to semi-empirical mechanical models (all the values are given in the unit of GPa)

Ceramics	H_{PSR}	H_{MPSR}	H_{EPD}	H_{HK}	H_{IIC}	H_V
Pure	0.449	0.460	0.450	0.460	0.473	0.462-0.496
Ba-1	0.495	0.499	0.495	0.503	0.514	0.504-0.530
Ba-2	0.402	0.417	0.403	0.414	0.428	0.416-0.454
Ba-3	0.356	0.375	0.357	0.441	0.384	0.371-0.414
Ba-4	0.319	0.341	0.319	0.367	0.349	0.335-0.385
Ba-5	0.276	0.302	0.276	0.332	0.309	0.294-0.350
Ba-6	0.247	0.278	0.248	0.289	0.283	0.266-0.328

3.2.3. Inspection of original mechanical properties of $Bi_{2.1-x}Ba_xSr_{2.0}Ca_{1.1}Cu_{2.0}O_y$ ceramics with the Hays Kendall approach

The Hays Kendall (HK) model is commonly used in literature to define the general mechanical performances, microhardness characteristic features, and real hardness constants in the saturation sites. The Hays Kendall (HK) model is frequently referenced in literature for delineating the overall mechanical performances, hardness characteristic features, and true hardness coefficients in plateau areas of solid compounds. Within the Hays Kendall (HK) calculation Eq. 5, there exists a coefficient pertaining to the elastic/plastic deformation occurring on the surface due to a critical force (represented as W) applied sample [38]. Hence, the model encompasses an effective l force that links the applied forces and irreversible deformation, which is denoted as $A_{eff} = F - W$. Consequently, the HK model formulation is depicted as follows (Eq. 5):

$$F - W = A_{3HK}\, d^2 \tag{5}$$

In this Eq. 5, the A_{3HK} coefficients are obtained by extrapolation method from average indentation diagonal length (d^2) graphs of forces applied (F) of aliovalent Ba/Bi partially substituted Bi-2212 ceramics, as shown in Fig. 4. According to the approach, the coefficient obtained is given numerically in Table 2. The values of critical test forces (abbreviated as W) are computed positively for the samples studied. Similar to other models, all $Bi_{2.1-x}Ba_xSr_{2.0}Ca_{1.1}Cu_{2.0}O_y$ compounds show standard ISE behavior (discussed above in detail).

In this context, all produced materials simultaneously exhibit reversible crystal structures and irreversible deformation in their crystal structures. In other words, it is observed that the systems recover quickly when the force applied to the studied materials is removed from the surface. As for the values of the W parameter, the pristine product is recorded to have $1.811x10^{-2}$ N, while this value is calculated as $1.451x10^{-2}$ N at optimum aliovalent Ba/Bi replacement amount of optimum value. On the other hand, a noteworthy augmentation of W coefficient is observed due to the presence of more Ba ions in the Bi-2212 ceramics.

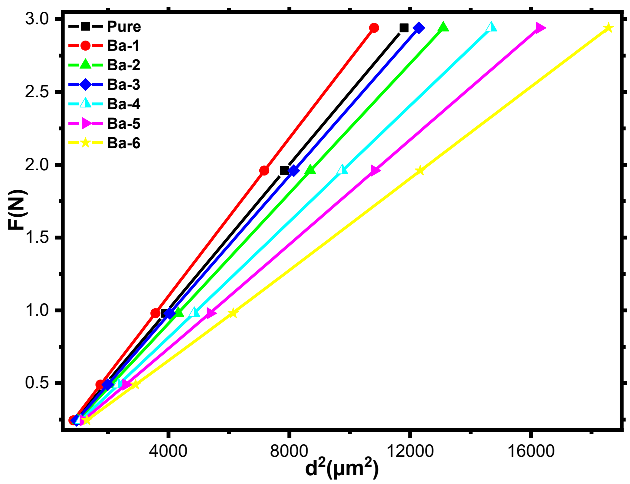

Figure 4. Average indentation diagonal length (d^2) graphs of forces applied (F) of aliovalent Ba/Bi partially substituted Bi-2212 ceramics

The W value for ceramic with the highest substitution level is determined to be $3.381x10^{-2}$ N. The primary rationale behind these variations lies in the fact that the Bi-2212 material exhibits heightened mechanical properties at the optimum substitution rate within the system. Conversely, an increase in the quantity of Ba ions significantly compromises the critical stress, mechanical strength, hardness, and resistivity to force of the ceramic materials. Similar to the outcomes obtained from other models, the theoretical approach of HK facilitates an assessment of the true hardness constants for all samples searched within saturation areas using Eq. 6:

$$H_{HK} = 1854.4A_{3HK} \quad (6)$$

All H_{HK} parameters determined with respect to Eq. 6 are numerically depicted in Table 3. Based on these values, the original hardness parameters calculated in saturation regions are close to the original hardness constants (compared to the calculations of other models).

In this context, the HK mechanical approach effectively establishes the overall mechanical properties and microhardness characteristic features of the $Bi_{2.1-x}Ba_xSr_{2.0}Ca_{1.1}Cu_{2.0}O_y$ ceramic compounds. However, it encounters challenges in accurately determining the original hardness constants computed within saturation areas. Despite this limitation, the model superior to other models, remains a valuable tool for assessing original hardness findings. In conclusion, similar to the other mechanical models including ML and EPD, the HK approach provides reliable insights into the key mechanical characteristics of Bi-2212 ceramics, with only minimal deviations in estimating microhardness values within the plateau regions, confirming good agreement with the experimental data.

3.2.4. Investigation of load-independent characteristics based on Proportional Sample Resistance Model (PSRM) of $Bi_{2.1-x}Ba_xSr_{2.0}Ca_{1.1}Cu_{2.0}O_y$ ceramic compounds

The Proportional Sample Resistance Model (PSRM) mehcnaical examination approach, introduced by Li and Bradt in 1993, serves as analyzing the load-dependent and original hardness properties of crystal-structured $Bi_{2.1-x}Ba_xSr_{2.0}Ca_{1.1}Cu_{2.0}O_y$ ceramic compounds prepared by varying molar ratios of Ba/Bi partial replacement levels [39]. (Within the calculation module, the approach accounts for energy distribution across the sample surfaces in structural analyses. Consequently, it establishes a surface energy linkage between the general mechanical characteristic properties (ISE and RISE) of a ceramic material and this energy value is automatically integrated into the formula of the method. Thus, the model's computation comprises two primary components: (I) surface energy coefficient (designated as α) and (II) hardness value (β) [40, 41]. The α value signifies the overall mechanical properties of the material studied. A positive α value indicates the material demonstrates the typical ISE nature, whereas negative values indicate the presence of the RISE property in the sample studied. This study calculates surface energy parameter of the prepared Bi-2212 ceramics using the following Eq. 7:

$$F = \alpha d + \beta d^2 \tag{7}$$

Where α, d and β are surface energy coefficient, mean impression diagonal length, microhardness coefficient, respectively. Fig. 5 illustrates the plot of notch forces (F/d) variation with average diagonal size (d) for bulk Bi-2212 ceramic samples with Ba/Bi partial substitution. As from Fig. 5, Bi/Ba partial replacement in crystal structure causes significant changes in the PSRM model graphs founded on the changes of critical stress value, mechanical strength, resistivity towards applied force (tetragonal phase resistance), and material integrity.

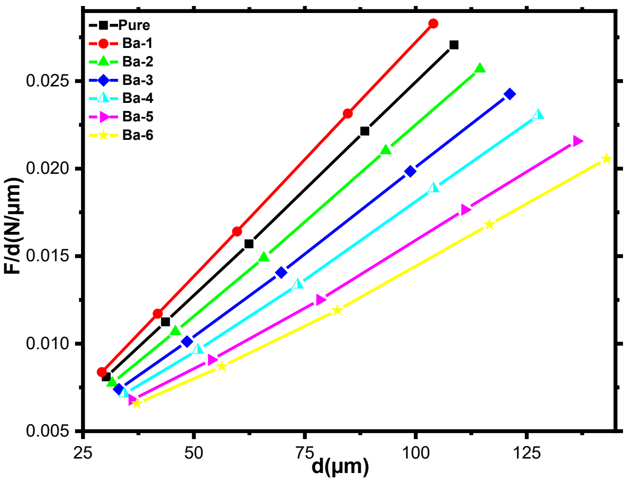

Figure 5. Variations in the notch test force and mean indentation diagonal length for the Ba/Bi partially substituted Bi-2212 products

In other words, Ba ions clearly cause to an increase or decrease of crystallinity problems in the Bi-2212 structures. α and β constants computed for the aliovalent Ba/Bi partially replaced Bi-2212 samples are inserted in Table 2. As observed from the table, the α calculations for the ceramics produced are computed as positive. Thus, all ceramics show ISE behavior. Accordingly, both pristine and $Bi_{2.1-x}Ba_xSr_{2.0}Ca_{1.1}Cu_{2.0}O_y$ ceramics exhibit crystal structures that simultaneously display both elastic and plastic deformation.

Consequently, when the test forces applied are removed from ceramic compounds, the systems recover rapidly. In more detail, for the pure sample the α constant is found to be about 0.693×10^{-3} N/µm while the coefficient is noted to decrease harshly for the bulk Ba-1 sample. After x=0.01, it is determined that there is a regular increase in the α parameter with the enhancement of Ba addition ratio. Therefore, the α value of the highest doped sample (Ba-6) is found to be 1.321×10^{-3} N/µm. As for the β coefficient of hardness features, parameter is determined as 2.424×10^{-4} N/µm^2 for un-substituted product. On the other hand, the value is found to be 2.672×10^{-4} N/µm^2 at the optimum doping rate. After this critical replacement value (x=0.01), the value of β exhibited a reduction parallel to the presence of barium ions amount. Thus, the lowest β parameter is found as 1.321×10^{-4} N/µm^2 (belonging to the Ba-6 product). Trend of changes in both constants (minimum value of α and maximum value of β coefficient at ideal doping amount; vice-versa in the case of largest substitution) shows that the critical stress value, mechanical strength, resistance to applied test load (tetragonal phase resistance), and material integrity of Bi-2212 superconducting samples significantly increases at the optimum replacement ratio.

Conversely, at the maximum substitution ratio, all the mentioned mechanical characteristic properties are noticed to dramatically decrease. Additionally, using this model, the load-true hardness parameters of $Bi_{2.1-x}Ba_xSr_{2.0}Ca_{1.1}Cu_{2.0}O_y$ ceramics in the saturation areas are examined by means of the equation provided below (Eq. 8).

$$H_{PSR} = 1854.4\beta \tag{8}$$

where H_{PSR} is proportional sample resistance model hardness and β is coeffecient. All the calculation data for the pure and Ba added Bi-2212 ceramics are inserted in Table 2. The original hardness values are far from the original hardness coefficients. On this basis, the PSRM model is thought to be unsuccessful for the investigation of true hardness constants of the Ba/Bi added Bi-2212 ceramics. All in all, the PSRM mechanical model reliably characterizes the mechanical behavior of Bi-2212 ceramics, showing minimal deviation from experimental microhardness data in the plateau regions.

3.2.5. Inspection of original mechanical features of Bi-2212 products with Indentation-induced cracking approach

The method is preferred to investigate the fundamental mechanical features of a material to determine whether it exhibits ISE/RISE nature. The formation of the indentation diagonal lengths in this mechanical modeling calculation is primarily based on four factors: (I) indentation friction; (II) and (III) elastic and plastic deformation; (IV) crack mechanism, and the relationship is symbolized by the following equation (Eq. 9):

$$H_{IIC} = K\left(\frac{F^{5/3}}{d^3}\right)^m \tag{9}$$

Here, the abbreviations of m and K constants represent the original Vickers microhardness constant where F is the force applied and d represents mean impression diagonal length. Fig. 6 shows variation of ln H_v-ln $F^{5/3}/d^3$ graphs of all the ceramic compounds studied. The calculated constants are shown in Table 2. As generally observed, it is noted that as the aliovalent Ba/Bi partial substitution amount increases, the values of K constants are recorded to systematically decrease. In this regard, it is determined that increasing the barium ions in Bi-2212 ceramics leads to an improvement in the crystalline quality of the materials.

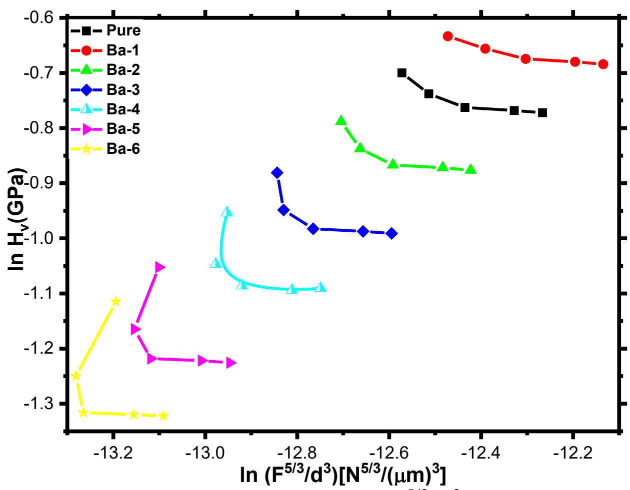

Figure 6. Variation of ln H_v-ln $F^{5/3}/d^3$ graphs of all the ceramic compounds studied

Another possible conclusion drawn from this study is that all samples have an m constant smaller than 0.6, which implies that ceramic compounds exhibit typical ISE behavior. In this context, the recovery mechanism dominates in both pure and Ba/Bi partially substituted Bi-2212 crystal systems. The observed increase in m values corresponds to improved crystalline quality with higher substitution levels. Notably, the Ba-1 sample shows superior mechanical performance, attributed to the formation of additional, active slip systems within the crystal structure. Consequently, barium impurities appear to hinder or redirect crack and dislocation motion, leading to fracture within trans-crystalline regions under sufficient load [11]. Furthermore, the original Vickers hardness parameters at saturation limits are theoretically examined with Eq. 9. The calculated H_{IIC} parameters can be seen in Table 3, where each calculation is performed to be closer to the actual microhardness parameters. In this context, it is evident that the IIC approach is the most important candidate to investigate the mechanical performance and characteristics of B-2212 ceramic materials.

4. Conclusion

We try to define the change in the main mechanical performance and mechanical characteristic behavior of $Bi_{2.1-x}Ba_xSr_{2.0}Ca_{1.1}Cu_{2.0}O_y$ ceramics with aliovalent Ba/Bi partial substitution in the $0.0 \leq x \leq 0.1$ range by using the standard microindentation hardness test measurements. The work provides an academically rigorous understanding of the interplay between substitution level, crystallinity quality, and indentation size effect (ISE) behavior by systematically integrating multiple semi-empirical mechanical models (ML, EPD, HK, PSRM, and IIC). The originality of this work lies in its combined use of several complementary modeling approaches to correlate optimal Ba substitution (x = 0.01) with peak mechanical performance, while also identifying the detrimental effects of over-substitution.

The experimental findings show that ideal barium ion amount is noted as x=0.01 for the largest mechanical durability and mechanical strength since the optimum barium particles leads to the induction of new slip directions and planes, barrier regions, and compressive stress sites in crystal lattice. At the same time, the Vickers hardness parameters are noted to reduce nonlinearly based on the increase in the test load up to approximately 2.00 N while microhardness parameters reach its plateau limit because of the enhancement in the crystallinity problems in the ceramic matrix under applied test loads. Results indicate that optimum barium content improves the standart ISE behavior and the IIC theoretical approach is the most effective method for accurately defining the microhardness parameters belonging to the ceramic compounds within the saturation regions.

From a technological and industrial perspective, the results have direct implications for the development of durable high-temperature superconducting (HTS) materials used in magnet systems, power transmission lines, fault-current limiters, and other applications requiring both superior mechanical strength and stable superconducting properties. Future work should explore substitution ranges beyond x = 0.1, conduct in-situ mechanical testing under cryogenic and high-field conditions, and combine advanced microstructural characterization with modeling to refine structure-property relationships. Overall, the original contribution of this work lies in establishing a quantitative connection between substitution ratio, crystallographic quality, and mechanical response, supported by multi-model analysis. The findings provide a design reference for high-temperature superconducting (HTS) components where both superconducting and mechanical properties are critical.

Article Information Form

Funding

This study was financially supported by Sakarya University, Scientific Research Projects Unit with project 2019-6-21-192, Türkiye.

Authors' Contribution

Conceptualization, G.Y. and T.T.; methodology, G.Y.; software, G.Y.; validation, G.Y., A. M. and T.T.; formal analysis, G.Y.; investigation, G.Y.; resources, G.Y.; data curation, G.Y., A.M. and M.Ö.; writing—original draft preparation, G.Y. and M.Ö.; writing—review and editing, G.Y. and M.Ö.; visualization, M.Ö. and A.M.; supervision, G.Y.; project administration, T.T.; funding acquisition, T.T. All authors have read and agreed to the published version of the manuscript.

The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by authors.

Artificial Intelligence Statement

No artificial intelligence tools were used while writing this article.

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