



Stabilization of durable tetragonal phase and barrier regions in y-123 ceramic systems with partial substitution mechanism

Gülnur Güdücü¹, Serap Safran², Sedat Kurnaz³, Elif Aşıkuzun Tokeser⁴, Turgay Seydioğlu⁵, Gürcan Yildirim^{6,*} , and Özgür Öztürk¹

¹ Department of Electrical and Electronics Engineering, Kastamonu University, 37210 Kastamonu, Türkiye

² Department of Physics, Ankara University, 06100 Ankara, Türkiye

³ Central Research Laboratory, Kastamonu University, 37210 Kastamonu, Türkiye

⁴ Department of Metallurgy and Materials Engineering, Kastamonu University, 37210 Kastamonu, Türkiye

⁵ Department of Electronics, Kastamonu Vocational School, Kastamonu University, 37210 Kastamonu, Türkiye

⁶ Department of Mechanical Engineering, Bolu Abant İzzet Baysal University, 14280 Bolu, Turkey

Received: 24 March 2024

Accepted: 15 June 2024

Published online:

4 July 2024

© The Author(s), 2024

ABSTRACT

This study examines the impact of Tb and Zn doping on the Y-123 superconducting system by analyzing crack propagation mechanisms through Vickers microhardness measurements. The measurements are conducted at various application forces ranging from 0.245 N to 2.940 N. The microhardness measurements are used to determine the role of impurity addition on Vickers hardness, modulus of elasticity, brittleness index, fracture toughness, and yield strengths. It is found that impurity ions serving as strong barrier regions improve the surface residual compressive stress sites and interactivity between the adjacent layers. Similarly, the sensitivity to the external forces reduce significantly with the substitution mechanism due to the induced new slip systems and ionic bond formations. Accordingly, all the mechanical performance properties are recorded to increase significantly with the impurity ions. Especially, the replacement of Zn by Cu ions in the Y-123 matrix exhibits higher resistance to failure, mechanical strength, and stabilization of the durable tetragonal phase. Accordingly, Zn/Cu substitution in Y-123 ceramics paves the way for the applications of ceramic compounds in the fields of heavy-industrial technology and industrial power systems. All the ceramic materials also exhibit indentation size effect feature based on the recovery mechanism. Additionally, load-independent microhardness parameters are semi-empirically modeled by Meyer's law, Hays-Kendall, indentation-induced cracking, elastic-plastic deformation, and proportional sample resistance model for the first time. According to the comparisons, the IIC model is identified as the most suitable for interpreting the real microhardness results of newly produced Y-123 ceramic matrices.

Address correspondence to E-mail: yildirim_g@ibu.edu.tr

1 Introduction

There are several significant benefits that YBCO superconductors offer in comparison to conventional superconducting materials; namely, the capacity to function at greater temperatures, higher thermodynamic stability, larger current carrying capability, reduced cooling requirements, larger resistance to strong magnetic fields, resistance to humidity, easy deforming/shaping/rolling for long cables, improved mechanical and electrical properties, and wide variety of applications in the industrial power systems and heavy-industrial technology fields [1–5]. To improve the capability of flux pinning and to reduce flux mobility, the superconducting crystal structure necessitates the incorporation of additional pinning centers, whether they naturally occur or are artificially created in the crystal system. Findings from research conducted on the effect of various additives/doping on the fundamental performance properties (electrical, superconducting, morphology, flux pinning, key mechanical design, etc.,) of YBCO composites provide useful information [6–13]. The critical current density (J_c), critical transition temperature (T_c), and applied critical magnetic field (H_c) are significantly influenced by the partial cationic/anionic substitution and chemical addition mechanism due to the re-modification of skeleton layers of YBCO [10]. In addition, the mechanical design performance properties and mechanical characteristics of high-temperature superconductors are just as significant as other characteristic properties such as T_c , H_c , and J_c , for heavy-industrial technology, advanced engineering, and energy-related sectors. This is because the superconducting wires, cables, and tapes are susceptible to mechanical stress when formed as coils. If subjected to mechanical stress, micro-cracks appear, causing a sudden reduction in both the critical magnetic field and the critical current density carrying capacity [12]. Hence, the examination of the mechanical characteristics of superconductors holds significance concerning actual implementations. In other words, there are strong relationship between the fundamental characteristic properties of superconducting ceramic compounds.

It is important to explain how materials deform (twist, compress, elongate) or fracture under different conditions; namely, load, temperature, and time to understand the key mechanical properties through experimentation. In the literature, Rockwell, Brinell, Knoop, and Vickers hardness tests are commonly

preferred to evaluate the basic mechanical performance features of a material. Especially, the Vickers hardness measurement method is preferred in the mechanical testing of superconductors due to the advantages of a small indentation mark on the specimen surface and applicability to small samples. The test results are obtained rapidly and easily with the diamond pyramid. A decrease in the calculated Vickers hardness (H_v) indicates softer materials and can serve as an indicator of porosity. The resistance of ceramic material to permanent and irreversible microscopic structural shape changes under applied test forces is known as the microhardness parameter. Various models including tensile strength, surface energy, chemical bond strength, and plastic flow ease are used to interpret and quantify measured hardness values. In polycrystalline samples, grain size is known to significantly impact the mechanical hardness behavior of a ceramic compound. Namely, the growth of smaller grain sizes in the main crystal structure results in the relative increment in the hardness due to grain boundaries impeding the propagation of voids, cracks, and dislocations caused by indentation test loads applied. Conversely, porosity influences microhardness properties considerably in ceramic superconducting samples with fewer cracks depending on the extension of the indented area over several grains [14].

Moreover, microhardness values determined enable us to describe the reliable relation between ion arrangements/distributions in the crystal system and plastic flow correlated with the lattice energy [15]. For ceramic materials, the covalent bonding shows more barrier to the formation of plastic flow as compared to the ionic bonding [16]. As per the theory of dislocation, complexes composed of aliovalent cations compensate lattice defects including both the elastic deformations and bond distortions within the crystal system. Hence, solid solution (involving aliovalent cation impurities) holds significant importance in numerous ceramic superconducting materials [17, 18]. Elastic modulus of ceramics either responds to applied stress for minor strains or correlates with the atomic bonding strength and also arrangement of identical or disparate ions within a crystal system. In the literature, there are several studies focusing on the improvement of the fundamental features of YBCO superconducting parents. To illustrate, in 2023, Slimani et. al. examined the role of PbO addition on the intragrain critical current density, $M(H)$ loops, thermal fluctuations induced excess conductivity, and flux pinning performances of the

$\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ superconducting materials prepared by solid-state reaction process. The experimental procedures including XRD, SEM, EDX, TEM, MH, and R-T measurements indicate that the presence of Pb in the main matrix led to the enhancement in the connections between grains, vortex pinning ability depending on the formation of additive stress or strain regions under an applied magnetic field strength, the average grain size, and yields. Besides, the grain boundaries and impurities were noted to diminish based on the PbO addition [1]. Moreover, Algarni et. al. tried to enhance the flux pinning ability by forming different effective defects with the use of the main properties such as concentration, electrical, and magnetic characteristics of Dy_2O_3 chemical addition in the crystal system [8]. It was observed that the dysprosium oxide added YBCO compounds were found to have higher connectivity between the grains, intragranular and intergranular superconducting critical parameters. Similarly, the existence of impurity was found to prevent the vortex motions and contribute to pinning ability. The similar improvements in the YBCO ceramics were obtained by the addition of optimum Ag₂O chemical in the main system [9]. Besides, in 2021 Erdem et al. indicated that the substitution of optimum erbium impurity for the yttrium sites in the YBCO superconductors led to the refinement of fundamental characteristic properties such as electrical, structural, physical, surface morphology, superconducting, and crystallinity features [10]. In all these kinds of studies, the main aim is to produce a new designed YBCO superconducting system with superior features to be used in much more application areas such as heavy-industrial technology, advanced engineering-related sectors, and large-scale applications. However, to the best of our understanding, in the features of Tb/Y or Zn/Cu partially replaced Y-123 superconductors fabricated through the sol-gel preparation route.

The powder XRD, R-T, SEM, EDS, and VSM measurements were used in our previous study to conduct an in-depth investigation into the magnetic, superconducting, morphological, electrical, and structural characteristics of Zn-doped and Tb-doped bulk samples [13]. The purpose of this investigation is to get information regarding the basic mechanical performance properties under various loads (0.245 N–2.940 N) and mechanical modeling of ceramic samples. Additionally, the original microhardness parameters obtained in the saturation limit areas are semi-empirically modeled by five available methods such as proportional

sample resistance, elastic/plastic deformation, Meyer's law, indentation-induced cracking, and Hays-Kendall models.

2 Experimental details

The current study is a continuation of the previous publication [13] being interested in the influence of divalent Zn/Cu and trivalent Tb/Y replacement on orbital hybridization, structural, pairing mechanism, stabilization, electrical, superconducting, and magnetization behaviors. The preparation procedure was thoroughly given in Ref. [13]. All the experimental methodological details as well as the experimental findings related to the energy dispersive X-ray spectrometry, powder X-ray diffraction, scanning electron microscopy, DC electrical resistivity, and DC magnetization VSM measurements can be seen in Ref. [13]. The XRD experimental results enable us to determine the roles of substitution mechanism on the phase volume fractions, lattice cell constants, crystallization symmetry, oxygen concentrations, O–T transition, crystallite size growth, grain alignment orientations, lattice strains, and grain distributions along the crystal system. Similarly, from the electrical resistivity measurements we determined the change in the onset/offset critical transition temperatures, localization of electronic state densities transition width, homogeneities of oxidation states, bipolarons formation, overlapping mechanism, mobile hole carriers, orbital hybridization mechanism, hole trap energy, and phase transition regions. Besides, the SEM images showcased the evolution of distribution of particles, surface morphology appearance, grain alignments, crystallinity problems, and grain boundaries of YBCO superconducting systems. Also, the EDS investigations indicated the successful substitution for the Y and Cu-sites of YBCO crystal systems. This study focuses sensitively on the evolution of the main mechanical performance properties of YBCO structure with the Zn/Cu and Tb/Y partial replacement in the main matrices using Vickers hardness measurements. The small sample bars are vertically placed in the tool. The experiments are measured from the different positions on the surfaces for 10 s using a digitally calibrated microscope (SHIMADZU HVM-2) at applied various forces. The microhardness measurements are repeated ten times to find the average indentation notch lengths with $\pm 0.1 \mu\text{m}$ accuracy. The Vickers microhardness quantities are

calculated by using the conventional equation. Experimental data are taken at normal ambient temperature. The hardness curves enable us to discuss the changes in the main mechanism. Moreover, the mechanical characteristic properties of substituted YBCO compounds are examined to determine the sensitivity to the external test forces. Additionally, the Vickers hardness parameters offer insights into various aspects of material behavior including resistance to permanent plastic deformation (elasticity of modulus), initiation of irreversible deformation (meaning the yield strength), the ratio between the tensile and compressive strengths (brittleness index), and resistivity to the propagation of flaws under applied stress (fracture toughness). Simultaneously, we explore Vickers experimental data within the saturation region using five mechanical modeling approaches.

3 Results and discussion

This study included two main parts: The first part gives short summaries of the scanning electron microscopy, powder X-ray diffraction, DC electrical resistivity, and DC magnetization VSM tests deduced from Ref. [13] to provide insight into relations between the key mechanical design and the other characteristic features. The second part focuses on the differentiation of the mechanical quantities, strength, durability, resistance to failure, and general mechanical characteristic features of YBCO ceramics with replacement mechanism. Additionally, we compare the load-independent Vickers microhardness findings semi-empirically obtained in the saturation regions to different mechanical model calculations to determine which model is the most adequate for the Zn-doped and Tb-doped crystal structure. In this respect, this paper aims to present a concise introduction to the structural and superconducting properties, followed by a detailed analysis of the key mechanical performance properties and semi-empirical mechanical modeling.

3.1 Structural, morphological, and superconducting properties

It was based on the XRD experiment results in Ref. [13] that each of the Zn-doped and Tb-doped materials produced exhibits crystallization in orthorhombic crystal structure but with slight deviation. Nevertheless, the basic crystal structure properties were noted

to diminish systematically due to the replacement mechanism. With the increase in the doping ratios, the intensities and of shifts (to larger/smaller angles) of diffraction lines were found to vary remarkably (especially for the Zn-replaced materials). Hence, impurity dopants seriously damage the crystallite size, lattice cell constants, oxygen concentration level, and orthorhombicity of system. Accordingly, the impurity ions (especially zinc particles) led to the enhancement of weak connections between superconductive layers, Cu-O₂ bond length, DOS localization, and microscopic structural faults as a result of the reduced crystallinity quality. Additionally, the foreign ions (notably zinc ions) led to a dramatic reduction in the modulation and pair wave function magnitude of the crystal structure. Correspondingly, the electron–phonon and electron–electron pairing mechanisms were found to diminish considerably. As a result, the significant diminish in the T_c^{onset} parameters of the Zn/Cu substituted ceramics was mostly due to a greater reduction in the uniformity of oxidation states, the order parameter belonging to super electrons, the mechanism of orbital hybridization, and the DOS localization.

The surface morphology of the YBCO superconductors was found to degrade regularly with increasing the impurity Tb and Zn ions in the main matrices. The grain orientations and distributions were observed to be randomly oriented through the sample surfaces. However, it was noted that the Tb-doped Y-123 ceramics exhibited better surface texture with a more homogenous appearance, lower porous structure, smoother surface, and better crystallinity quality and connection between well-linked cobblestone-like superconducting grains. Further, the electron dispersive X-ray (EDX) examination showed that all the Tb and Zn added Y-123 obtained different elemental composition distributions on the surface depending on the successful replacement mechanism.

Based on the VSM tests, it was seen that the magnetization behavior of the materials worsened as the dopant level (except for sample with 0.01 wt. % Tb doping) increased regularly. The sample prepared by 0.01 wt. % of Tb exhibited the greatest J_c value, measuring 21 kA/cm² at a magnetic field strength of 0.5 T and a temperature of 20 K. This is because the optimum terbium particles acted as nucleation centers to slow down the vortices and strengthen significantly coupling of adjacent layers. As a result, the ceramic compound demonstrated the highest level of resistance to both applied magnetic field strengths and

currents depending on the slower motion of vortices in the main system.

3.2 Key mechanical performance properties

The cuprate superconductors such as BSCCO and YBCO, typically found in hard ceramic form, are prone to brittleness due to numerous tiny cracks, dislocations, irregular grain orientation distributions, and boundary weak links between the adjacent stacked layers. Especially, foreign impurities introduced into the crystal structure can degrade or improve the problems mentioned above. Consequently, the critical stress threshold decreases or increases significantly, leading to a change in dislocation movement, void formation, and crack propagation along the system. In other words, introduction of new impurities into main matrix facilitates the straightforward propagations along the entire material. In essence, this means that the propagation of cracks and voids becomes uncontrollable, leading to immediate sample failure. However, sometimes dopants can mitigate inherent flaws in the crystal lattice, suppressing stress-amplified regions and crack initiation sites. This suppression results in a considerable diversion or slowdown of crack initiation and propagation. The variation of the main mechanism discussed above is totally determined by standard hardness tests which are one of the simplest and most common methods used to define basic mechanical performance properties. The response or resistance of a material against the applied force or load summarizes the mechanical behavior of that material. Three main factors enable us to determine the key mechanical performance properties of a material: (i) ability to form strong chemical bonds, (ii) strong crystal structure, and (iii) any imperfections present. Hardness is defined as a measure of the resistance of a material to a load applied to its surface or the resistance to indentation. The minimal damage to the material during the measurement is another important feature of hardness measurement. It is also very important for researchers due to the correlation between the hardness of the material and other mechanical properties. Microhardness, modulus of elasticity, tensile strength, fracture toughness, and flexibility used in the analysis of superconducting materials are examples of mechanical qualities. The key mechanical performance properties are as important as electrical, flux pinning, magnetic, and microstructural properties to determine the application

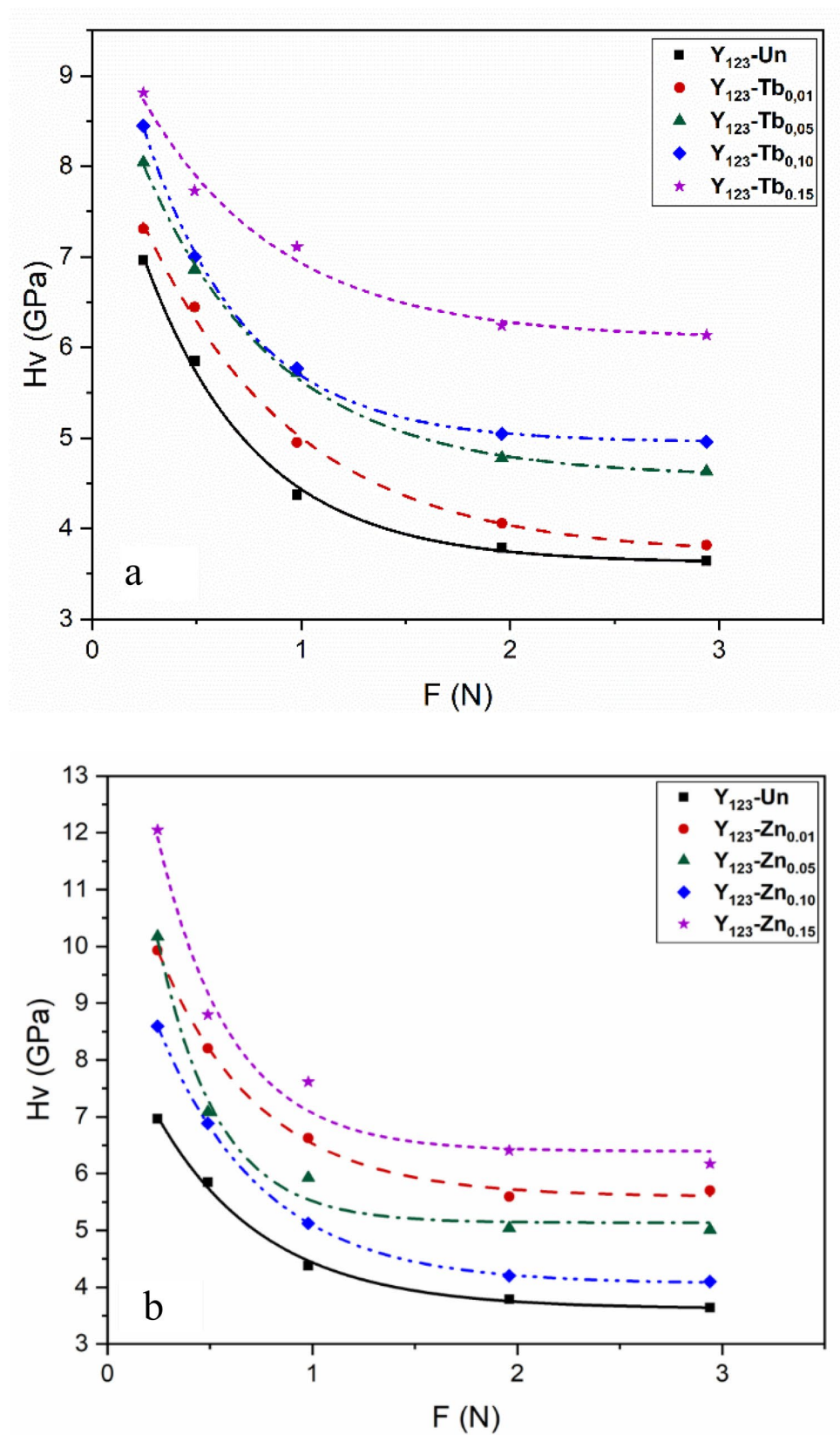
areas and service time of the superconducting materials. Additionally, since microhardness is affected by the structure, composition, and manufacturing method of materials as well as the hardness of the material and other mechanical qualities are related to one another, it is very important to know the numerical values of the microhardness parameter. In the current work, the Vickers microhardness test method was selected both to take more precise measurements and to describe basic mechanical performance properties of the Zn-replaced and Tb-replaced Y-123 ceramic structures. Microhardness experiments of the superconducting bulk compounds were found by a test load stemming from a conical notching tip immersed in the material at an angle of 136° . The samples were then measured for their response for 10 s under five distinct loads including $F = 0.245, 0.490, 0.980, 1.960$, and 2.940 N. To achieve very high levels of precision and to reduce the impact of sample surface imperfections, ten measurements were carried out for each load value, and an average value was recorded for every measurement. To determine the Vickers microhardness values, the load values and their corresponding d ($d = (d_1 + d_2) / 2$) (d_1 and d_2 are diagonal lengths of the trace left by the tip) values were calculated using Eq. 1 shown below;

$$H_v = 1854.4 \left(\frac{F}{d^2} \right) \quad (1)$$

The obtained Vickers microhardness values are used to find the other valuable mechanical performance features of a cuprate superconducting material. Additionally, the hardness curves enable the researchers to define the typical mechanical characteristic behavior: ISE (indentation size effect) and RISE (reverse indentation size effect) feature. The sign of surface energy enables us to decide the mechanical characteristic of a compound. Thirdly, the H_v experimental curves are used to model the real microhardness parameters using semi-empirical mechanical modeling methods to obtain the best theoretical approach for the Zn-doped and Tb-doped ceramic structures.

Figure 1 a-b displays the variations in microhardness values in un-doped, Zn-doped and Tb-doped Y-123 ceramics with the applied test loads. As seen from the curves, the hardness parameters reduce regularly as the applied test load increases. The decrement trend in the H_v parameters is due to the standard ISE phenomenon. As for the substitution effect, it is obtained that the microhardness values are observed

Fig. 1 Microhardness versus applied load graphs of **a** Tb-doped and **b** Zn-doped samples



to enhance systematically as the replacements of Tb^{3+} particles by Y^{3+} ions increase in the Y-123 crystal matrix. In fact, the substitution of Zn by Cu ions makes microhardness values augment considerably. In this respect, the foreign impurity ions serve as strong barrier regions depending on the reduction in stored internal strain energy and surface tensile stress to delay the propagation of the dislocation, cracks, and voids along the crystal system. That is to say, the control mechanisms regarding crack growth size and crack speed become easier due to the decrease in stored internal strain energy. The differentiation with the substitution mechanism clearly improves the durability phase. Moreover, with the increment in the substitution impurity amount new slip systems are induced in the crystal structure to change as much as possible the orientations of dislocation movement and crack propagation along the crystal structure so that entanglement of cracks and dislocations are prevented. Stress-augmented phase is suppressed. In this respect, the propagations are restricted as much as possible. Furthermore, presence of foreign impurity ions remarkably differs the deformation degree until the plateau limit regions (slight change of hardness values with the applied loads). Besides, at the atomic level the foreign (Tb and Zn) particles with different electronegativity support to formation of new chemical bonding (especially ionic bond formation based on the extension of bond directions through specific angles) between the host atoms. Considering all the explanations, the presence of impurity ions (especially Zn particles) stabilizes tetragonal phase. The similar result was seen in the Ho/Bi substituted Bi-2212 ceramic superconductors. In fact, Ulgen et al. displayed the considerable development in the mechanical strength of the superconducting system [19]. Besides, Mercan et al. demonstrated the positive effect of impurity ions on the operable slip systems and related mechanical performance properties [20]. Moreover, Asikuzun et al. examined the role of different zinc dopant ratios intervals 0%–20% on the fundamental characteristic properties of YBCO system. It was indicated that the microhardness values increased with the highest Zn impurity ions based on the penetration of Zn ions between intergranulars [21].

At the same time, according to the microhardness curves the cracks/dislocations prefer to move along transcrystalline rather than intergranular regions as a result of the induced new strong chemical bond formations and enhanced interactivity between the adjacent

stacked layers. Namely, the dislocations and cracks can propagate under much higher external forces because of the decrease of the failure and fracture. Correspondingly, the new modified crystal structures (especially decorated by Zn ions) are broken more hard depending on the decrease in the responsibility to the external test loads. The similar discussions can be seen in [19, 20].

In the case of greater values of the applied test load, the hardness-load curve exhibits a transition to a plateau depending on the saturation. The plateau values are believed to represent the Vickers hardness values that are not affected by the applied test loads, also known as the load-independent, real, true, or intrinsic microhardness values [22]. The values of the hardness saturation zones for the Zn-doped Y-123 ceramics are greater than those of Tb-doped samples for all substitution ratios; nonetheless, the values are quite near to one another (Fig. 2a–d). The increased load magnitudes on the Zn-doped samples lead to more decrease in the hardness values as compared to the Tb-doped ones. On this basis, the transition to the saturation area for the former materials occurs more suddenly as displayed in Fig. 2a–d. Specifically, doping significantly alters the extent of deformation until reaching the plateau limit zone. This, in turn, facilitates the control mechanisms for both crack development size and fracture velocity by reducing the stored internal strain energy. Namely, the response and sensitivity to the applied test loads are found to decrease remarkably with the substitution mechanism. To sum up, the Zn replaced materials with higher ISE behavior are more durable than the Tb-doped samples (more sensitive to the applied loads). Numerical values help to visualize and understand more easily. In this respect, the microhardness values deduced are utilized to find the key mechanical performance features including elasticity of modulus (E), brittleness index (Bi), fracture toughness (K_{IC}), and yield strength (Y). The elastic modulus quantifies the ability of a material to withstand elastic deformation when subjected to an external force. Elastic deformation refers to the temporary alteration in the shape of a material under an external force, and the material reverts to its original shape once the force is eliminated. Young's modulus of elasticity quantifies the extent of elastic deformation. A material possessing a high Young's modulus tends to exhibit hardness and brittleness due to its reduced ability to undergo elastic deformations with flexibility. The E value of a material is directly proportional to the value of the

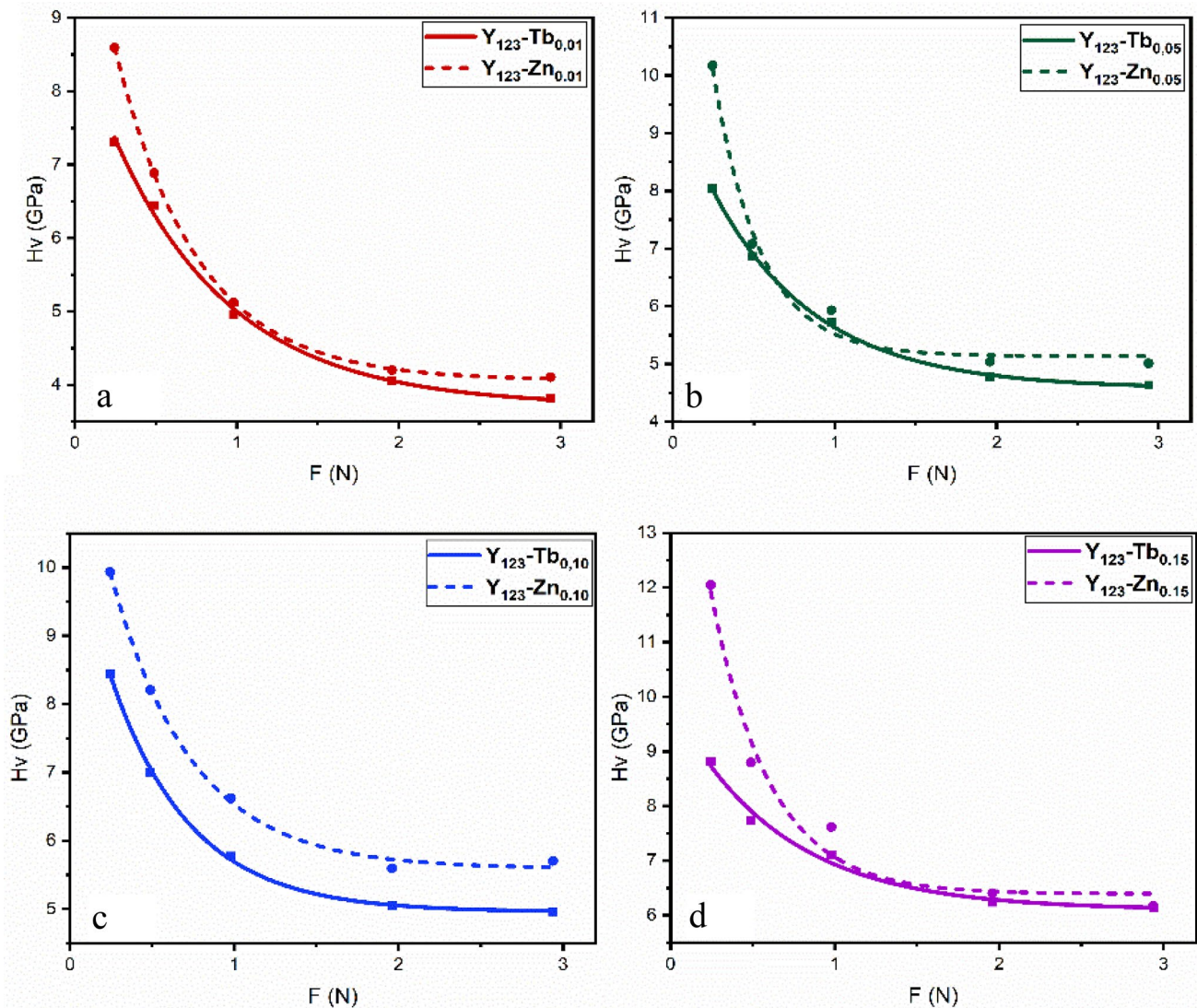


Fig. 2 Graphs comparing the microhardness of Y-123 samples with Zn and Tb doping at different molar ratios: **a** 0.01, **b** 0.05, **c** 0.10, and **d** 0.15 as a function of the applied loads

H_v parameter. This value is computed using Eq. 2 based on the measured H_v value. The value of the proportionality constant for the elastic modulus varies depending on the type of material being studied.

$$E = 81.9635H_v \quad (2)$$

K_{IC} is a quantification of the greatest possible amount of energy that a material can take before a crack forms. Thus, it can be described as the capacity of a specimen to undergo irreversible deformation. Linear K_{IC} is obtained by identifying the point at which cracks initiate in the material, as described by Eq. 3.

$$K_{IC} = \sqrt{2E\alpha} \quad (3)$$

Bi refers to the property of a material that makes it susceptible to persistent deformation, or plastic deformation, as described by Eq. 4.

$$B_i = H_v/K_{IC} \quad (4)$$

γ is the critical point at which a material transitions from reversible deformation to irreversible deformation, as defined by Eq. 5.

$$\gamma \approx H_v/3 \quad (5)$$

Table 1 Numerical values of H_v , E , Y , K_{IC} , and B_i values of Tb-doped, and Zn-doped Y-123 ceramic samples

Samples	F (N)	d (μm)	H_v (GPa)	E (GPa)	Y (GPa)	$K_{IC} \times 10^{-2}$ ($\text{Pa/m}^{1/2}$)	$B_i \times 10^{-2}$ ($\text{m}^{1/2}$)
$Y_{123}\text{-Un}$	0.245	8.08	6.964	570.738	2.321	472.155	1.475
	0.49	12.47	5.848	479.230	1.949	432.651	1.352
	0.98	20.38	4.374	358.494	1.458	374.203	1.169
	1.96	30.97	3.789	310.559	1.263	348.288	1.088
	2.94	38.68	3.643	298.587	1.214	341.508	1.067
$Y_{123}\text{-Tb}_{0.01}$	0.245	7.88	7.309	599.023	2.436	507.641	1.440
	0.49	11.87	6.445	528.228	2.148	476.701	1.352
	0.98	19.16	4.951	405.731	1.650	417.786	1.185
	1.96	29.94	4.056	332.364	1.352	378.131	1.073
	2.94	37.78	3.819	312.965	1.273	366.930	1.041
$Y_{123}\text{-Tb}_{0.05}$	0.245	7.52	8.040	658.918	2.680	506.670	1.587
	0.49	11.51	6.862	562.348	2.287	468.071	1.466
	0.98	17.83	5.716	468.484	1.905	427.225	1.338
	1.96	27.58	4.778	391.556	1.593	390.577	1.223
	2.94	34.32	4.630	379.446	1.543	384.490	1.204
$Y_{123}\text{-Tb}_{0.10}$	0.245	7.33	8.446	692.167	2.815	503.872	1.676
	0.49	11.39	7.001	573.758	2.334	458.753	1.526
	0.98	17.75	5.770	472.834	1.923	416.456	1.385
	1.96	26.83	5.048	413.699	1.683	389.544	1.296
	2.94	33.17	4.957	406.217	1.652	386.006	1.284
$Y_{123}\text{-Tb}_{0.15}$	0.245	7.18	8.813	722.251	2.938	461.276	1.911
	0.49	10.84	7.730	633.502	2.577	432.007	1.789
	0.98	15.99	7.111	582.797	2.370	414.357	1.716
	1.96	24.13	6.242	511.536	2.081	388.199	1.608
	2.94	29.81	6.137	502.968	2.046	384.934	1.594
$Y_{123}\text{-Zn}_{0.01}$	0.245	6.76	9.933	814.012	3.311	616.426	1.611
	0.49	10.52	8.205	672.447	2.735	560.266	1.465
	0.98	16.56	6.624	542.827	2.208	503.380	1.316
	1.96	25.49	5.593	458.361	1.864	462.561	1.209
	2.94	30.92	5.703	467.387	1.901	467.093	1.221
$Y_{123}\text{-Zn}_{0.05}$	0.245	6.68	10.175	833.869	3.392	603.242	1.687
	0.49	11.33	7.081	580.319	2.360	503.241	1.407
	0.98	17.51	5.930	486.008	1.977	460.537	1.288
	1.96	26.86	5.038	412.850	1.679	424.462	1.187
	2.94	32.99	5.010	410.626	1.670	423.317	1.184
$Y_{123}\text{-Zn}_{0.10}$	0.245	7.27	8.593	704.247	2.864	540.873	1.589
	0.49	11.49	6.886	564.348	2.295	484.180	1.422
	0.98	18.83	5.123	419.828	1.708	417.608	1.227
	1.96	29.42	4.200	344.237	1.400	378.148	1.111
	2.94	36.46	4.102	336.191	1.367	373.703	1.098
$Y_{123}\text{-Zn}_{0.15}$	0.245	6.14	12.048	987.386	4.016	686.857	1.754
	0.49	10.16	8.797	720.949	2.932	586.915	1.499
	0.98	15.45	7.616	624.136	2.539	546.088	1.395
	1.96	23.82	6.404	524.834	2.135	500.765	1.279
	2.94	29.72	6.173	505.874	2.058	491.637	1.256

Fig. 3 $\ln(F)-\ln(d)$ graphs of **a** Tb-doped and **b** Zn-doped Y-123 advanced ceramics

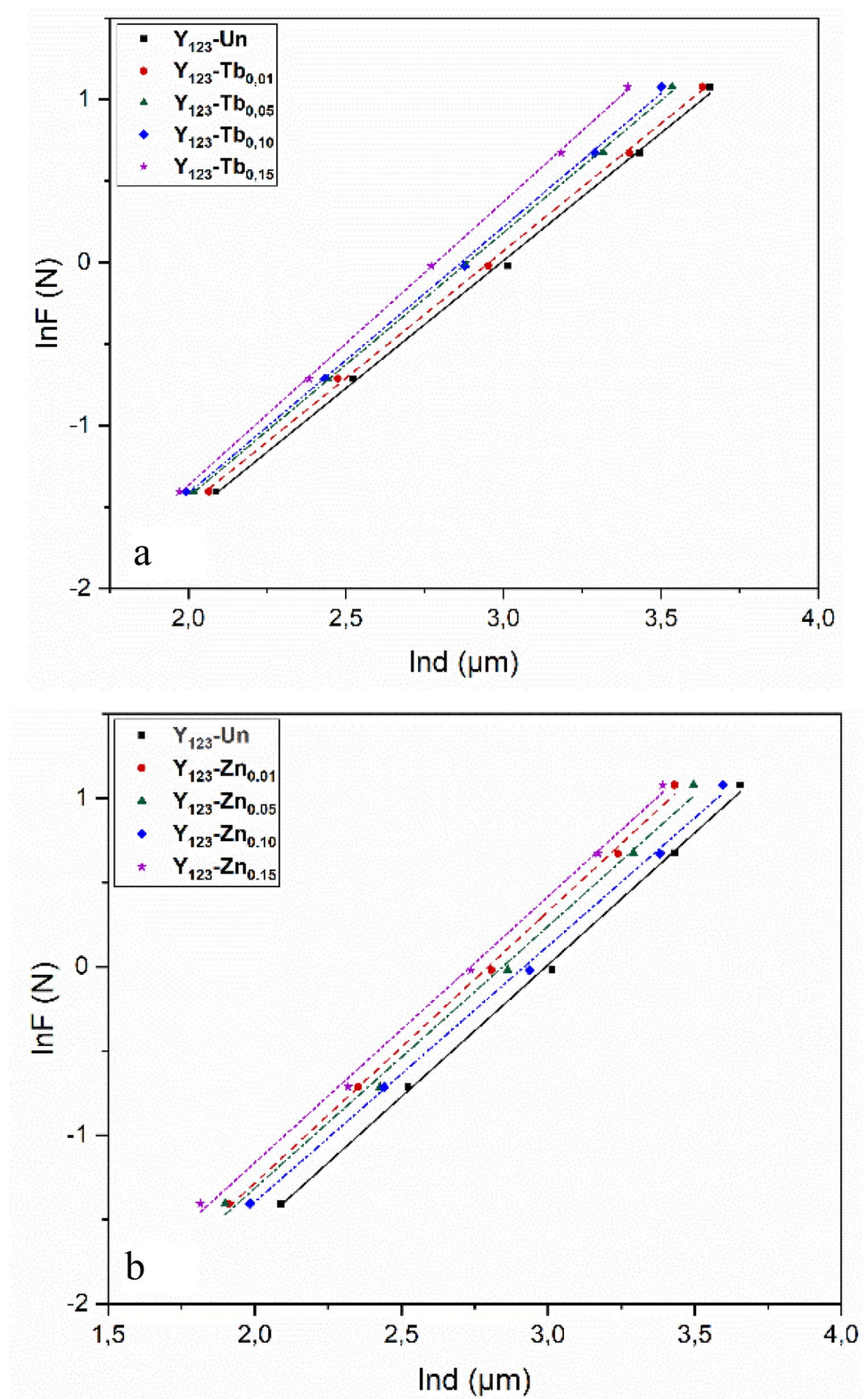


Table 2 n and $\ln(A)$ values of Tb/Y partially replaced Y-123 ceramic samples

Samples	Meyer model	
	n	$\ln(A)$ (in GPa unit)
Y ₁₂₃ -Un	1.566	- 4.687
Y ₁₂₃ -Tb _{0.01}	1.563	- 4.618
Y ₁₂₃ -Tb _{0.05}	1.622	- 4.682
Y ₁₂₃ -Tb _{0.10}	1.635	- 4.686
Y ₁₂₃ -Tb _{0.15}	1.740	- 4.848

Table 3 n and $\ln(A)$ values of Zn/Cu partially substituted Y-123 compounds

Ceramics	Meyer Model	
	n	$\ln A$ (GPa)
Y ₁₂₃ -Un	1.566	- 4.687
Y ₁₂₃ -Zn _{0.01}	1.611	- 4.506
Y ₁₂₃ -Zn _{0.05}	1.555	- 4.423
Y ₁₂₃ -Zn _{0.10}	1.519	- 4.435
Y ₁₂₃ -Zn _{0.15}	1.580	- 4.322

The E , Y , B_i , and K_{IC} values are computed and one can see all the calculations for the samples prepared in Table 1. Based on the table, it is observed that E and Y values exhibited a respective increase of 26% and 73% for materials prepared by 0.05 wt. Tb and 0.05 wt. Zn impurities in compared to the un-doped sample when subjected to a minimum applied force of 0.245 N. It is commonly accepted that the improvement in mechanical performance properties of a material can be inferred from an increase in both the E and Y parameters. When subjected to increased stress levels, the material becomes more rigid and can tolerate the applied test loads without incurring plastic deformation. Therefore, Table 1 indicates that Zn-doped samples prepared are harder than Tb-doped samples, and hence can handle more stress without permanently changing shape. Analogous behavior is also observed in both the B_i and K_{IC} parameters. The enhanced brittleness index parameter implies a greater tendency to break without substantial plastic deformation. This is especially noticeable in materials exhibiting low plasticity and a tendency to break abruptly. It can be interpreted that YBCO ceramics prepared by the Zn ions possess greater brittleness indices compared to those doped with the Tb impurities. In this respect, the zinc ions present much stronger barrier regions. The findings are similar to the change in the flux pinning ability depending on the artificial nucleation centers for the vortices deduced from the

previous study [13]. This discussion was also verified by in Ref. [19, 20].

3.3 Semi-empirical mechanical modeling

The load-independent Vickers hardness parameters are semi-empirically modeled by five available methods: (i) Meyer's law (ML), (ii) elastic/plastic deformation (EPD), (iii) proportional sample resistance (PSR), (iv) indentation-induced cracking (IIC), and (v) Hays-Kendall (HK) approach. The modeling results and related discussions are provided below.

3.3.1 Meyer's law model

ML is a hardness analysis technique that seeks to characterize the response of materials to external forces, specifically the characteristic ISE/RISE behavior [23]. The pertinent information can be found in Eq. 6.

$$F = Ad^n \quad (6)$$

whereas the constant n represents the Meyer number, used to explain ISE/RISE behavior, the constant A represents the conventional hardness constant. ISE feature is observed for the compound when n is less than two, as the hardness value rises with reducing applied load. According to Quinn et al. [24], the hardness value increases with increasing applied stress, and RISE behavior is observed when the value of n exceeds 2. Besides, if the value of the n coefficient changes from 1 to 1.6, the compound is hard; if $n > 1.6$, the sample is soft. When n equals 2, the microhardness is independent of the external forces applied, and this condition is called the Kick's law (Eq. 7).

$$F = A_{HK}d^2 \text{ (Kick's Law)} \quad (7)$$

The values of the Meyer index are determined by calculating the slope of the graph depicting the change in $\ln(F)$ as a function of $\ln(d)$ for new prepared Y-123 ceramics in Fig. 3.a-b. The values of the hardness constant are found by analyzing the points at which the graph encounters the vertical axis to determine the values. A linear regression analysis is performed on the values obtained from Fig. 3.a-b, and the results are presented in Tables 2, 3, respectively. It is visible that the values of the Meyer index for all the ceramic structures are found to be lower than 2. Therefore, the conclusion that the item demonstrates the standard ISE behavior is supported by this evidence. In addition,

Fig. 4 F - d^2 graphs of **a** Tb doped and **b** Zn doped Y-123 samples

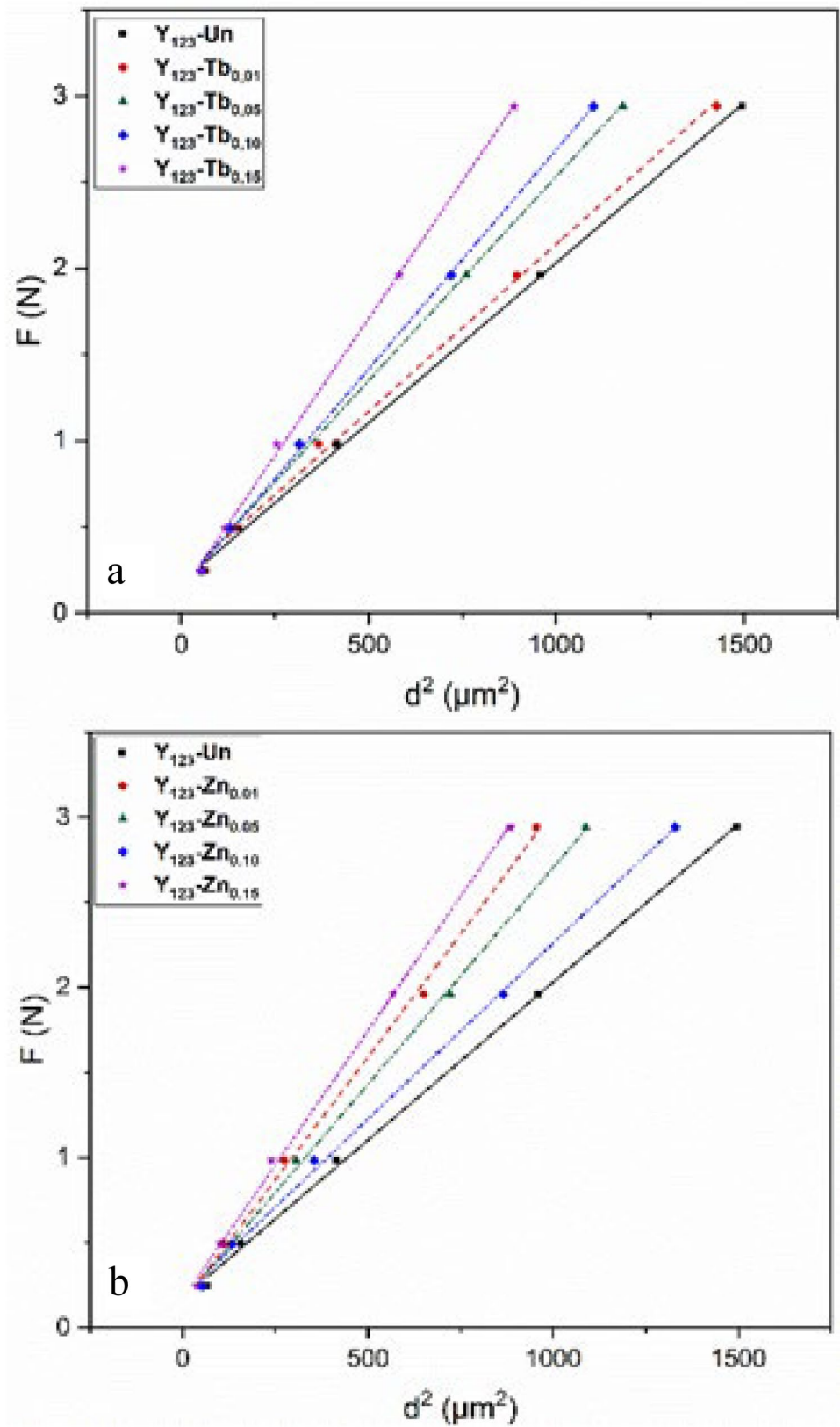


Table 4 A_{HK} and W_{HK} values of Tb/Y partially replaced Y-123 ceramics

Materials	HK approach			
	$A_{HK} \times 10^{-2}$ (GPa)	$W_{HK} \times 10^{-2}$ (N)	H_V (GPa)	H_{HK} (GPa)
Y ₁₂₃ -Un	0.186	17.544	4.374–3.643	3.442
Y ₁₂₃ -Tb _{0.01}	0.194	20.051	4.951–3.819	3.596
Y ₁₂₃ -Tb _{0.05}	0.237	16.631	5.716–4.630	4.386
Y ₁₂₃ -Tb _{0.10}	0.254	14.405	5.770–4.957	4.715
Y ₁₂₃ -Tb _{0.15}	0.319	11.527	7.111–6.137	5.908

Table 5 A_{HK} and W_{HK} parameters of Zn-doped Y-123 ceramics

Ceramics	HK approach			
	$A_{HK} \times 10^{-2}$ (GPa)	$W_{HK} \times 10^{-2}$ (N)	H_V (GPa)	H_{HK} (GPa)
Y ₁₂₃ -Un	0.186	14.509	4.374–3.643	3.442
Y ₁₂₃ -Zn _{0.01}	0.289	15.677	6.624–5.703	5.362
Y ₁₂₃ -Zn _{0.05}	0.255	19.235	5.930–5.010	4.724
Y ₁₂₃ -Zn _{0.10}	0.207	16.802	5.123–4.102	3.835
Y ₁₂₃ -Zn _{0.15}	0.315	17.544	7.616–6.173	5.851

n values of pure and 1% Tb-doped materials are calculated between 1 and 1.6 (hard ceramic samples). On the other hand, the 5% Tb-doped or more doping materials might be called soft because their n values are more than 1.6. Furthermore, in samples doped with Zn, the n value is somewhat greater than 1.6 for the sample with a 1% doping rate, and is about 1.6 in the other samples, but less than 1.6. Consequently, the materials reach the maximum level of microhardness. The similar results can be seen in Ref. [21].

3.3.2 Hays-Kendall model

In HK approach, the lowest load value (W_{HK}) has the potential to induce persistent deformation in a sample [25]. If the force applied is below the resistance threshold, no permanent deformation can occur, and only elastic deformation takes place in the following relation. Hays and Kendall approach introduces Eq. 8 to analyze behavior of the sample in terms of ISE/RISE behavior.

$$F - w_{HK} = A_{HK}d^2 \quad (8)$$

Equation 8 defines A_{HK} as the load-independent hardness constant determined using the HK method for a particular sample. The numerical W_{HK} and A_{HK} values are derived from the $F - d^2$ graphs (Fig. 4.a-b).

The load-independent hardness constant A_{HK} is determined by calculating the slopes of the graphs. The sample resistance pressure W_{HK} is also obtained by identifying the point where the graph meets the y-axis. The HK method is employed to calculate the load-independent microhardness using H_{HK} Eq. 9.

$$H_{HK} = 1854.4A_{HK} \quad (9)$$

The W_{HK} , A_{HK} , and H_{HK} values computed are listed in Tables 4, 5. It is seen from the tables that all W_{HK} values are greater than zero. Hence, the exerted force resulted in both elastic and plastic deformation (recovery mechanism) in the specimens [26]. Namely, all the materials exhibit the typical ISE behavior. The load-independent microhardness values obtained using the HK technique are found to be significantly different from the saturation zone values of the actual microhardness parameters. Thus, it can be concluded that the HK method is an inadequate model for explaining the microhardness properties of materials.

3.3.3 Elastic/plastic deformation semi-empiric model

Typically, the notch size is measured once the indenter tip takes off the surface of the sample in most tests. In such instances, the magnitude of the indentation surrounding the notch mark diminishes to a specific

Fig. 5 $F^{1/2}$ - d curves **a** Tb doped and **b** Zn doped Y-123 advanced ceramic structures

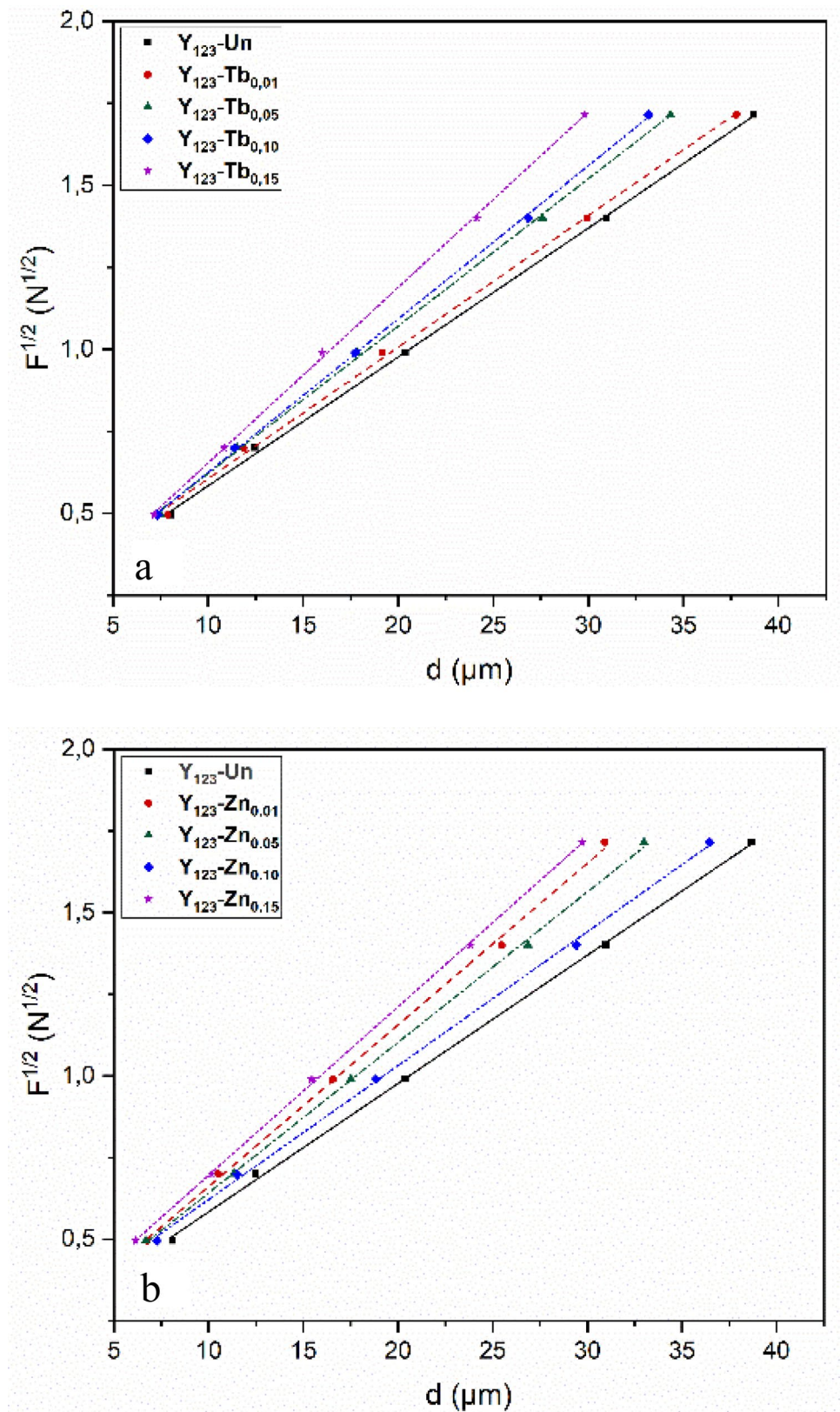


Table 6 A_{EPD} and d_0 values of Tb-doped Y-123 samples

Compounds	EPD Semi-empirical Model			
	$A_{EPD} \times 10^{-2}$ (GPa)	$d_0 \times 10^{-2}$ (μm)	H_V (GPa)	H_{EPD} (GPa)
Y ₁₂₃ -Un	0.154	19.103	4.374– 3.643	2.862
Y ₁₂₃ -Tb _{0.01}	0.161	20.469	4.951– 3.819	2.982
Y ₁₂₃ -Tb _{0.05}	0.202	17.323	5.716– 4.630	3.738
Y ₁₂₃ -Tb _{0.10}	0.218	15.854	5.770– 4.957	4.047
Y ₁₂₃ -Tb _{0.15}	0.286	11.886	7.111– 6.137	5.308

Table 7 A_{EPD} and d_0 values of Zn-doped Y-123 compounds

Materials	EPD Semi-empirical Model			
	$A_{EPD} \times 10^{-2}$ (GPa)	$d_0 \times 10^{-2}$ (μm)	H_V (GPa)	H_{EPD} (GPa)
Y ₁₂₃ -Un	0.154	19.103	4.374– 3.643	2.862
Y ₁₂₃ -Zn _{0.01}	0.245	16.688	6.624– 5.703	4.538
Y ₁₂₃ -Zn _{0.05}	0.212	18.153	5.930– 5.010	3.933
Y ₁₂₃ -Zn _{0.10}	0.168	21.137	5.123– 4.102	3.118
Y ₁₂₃ -Zn _{0.15}	0.266	18.050	7.616– 6.173	4.928

value. Incorporating the factor, an additional parameter is added to quantify the notch size in load-independent hardness calculations conducted using the EPD methodology [27–29]. According to the EPD model, Eq. 10 summarizes the relation between the external forces and sizes of notches.

$$F = A_2(d + d_0)^2 \quad (10)$$

In Eq. (10), A_2 represents a fixed value and d_0 denotes the adjustment performed to d . A_2 and d_0 are determined utilizing the d -dependent alteration graph of $F^{1/2}$. The value of d_0 is calculated at the y -intercept of the graph while A_2 is obtained by squaring the slope of the graph. Equation 11 is also utilized to compute the load-independent hardness values.

$$H_{EPD} = 1854.4A_2 \quad (11)$$

The correlation between the applied load and the notch size is illustrated in the $F^{1/2}$ - d graphs in Fig. 5a-b. The computed A_{EPD} , d_0 , and H_{EPD} values for Zn-added and Tb-added Y-123 superconductors are presented in Tables 6, 7. As encountered, all samples have positive d_0 values, indicating occurrence of reversible deformation in the materials [30]. Since the load-independent microhardness values (H_{EPD}) do not fall within the saturation zone range of the Vickers microhardness value, the EPD model is not an appropriate model for this particular study.

3.3.4 Proportional sample resistance model

The PSR model is a methodology employed to examine the ISE/RISE behavior of ceramic materials [31]. Based on the semi-empirical mechanical modeling approach, the resistance of the sample increases in direct proportion to the depth of the notch. The microhardness behavior in the PSR technique is determined by the equation of $F = \alpha d + \beta d^2$, where F represents the microhardness, d represents a variable, and α and β are coefficients. Equation 12 incorporates the parameter α , which determines how the Vickers microhardness is affected by the load, and the term αd , which represents the surface energy. The constants α and β are associated with the elastic and plastic characteristics of the material. The real Vickers hardness value in the PSR approach is determined using the H_{PSR} coefficient given in Eq. 12.

$$H_{PSR} = 1854.4\beta \quad (12)$$

The α constant in the PSR model is determined from the graphs indicated in Fig. 6a-b by intersecting the y -axes. Similarly, the β constant is calculated by analyzing the slopes of the graphs. The first constant belongs to elastic deformation while the second one relates to plastic deformation [31].

Tables 8, 9 demonstrate that α is consistently positive in all the ceramic samples. Hence, it may be asserted that materials exhibit both elastic and plastic deformation (recovery mechanism). In addition, the microhardness values computed according to the PSR model are below the real microhardness saturation regions, and hence the PSR semi-empirical method is not a suitable model for this investigation.

Fig. 6 F/d-d graphs of **a** Tb doped and **b** Zn doped Y-123 ceramics

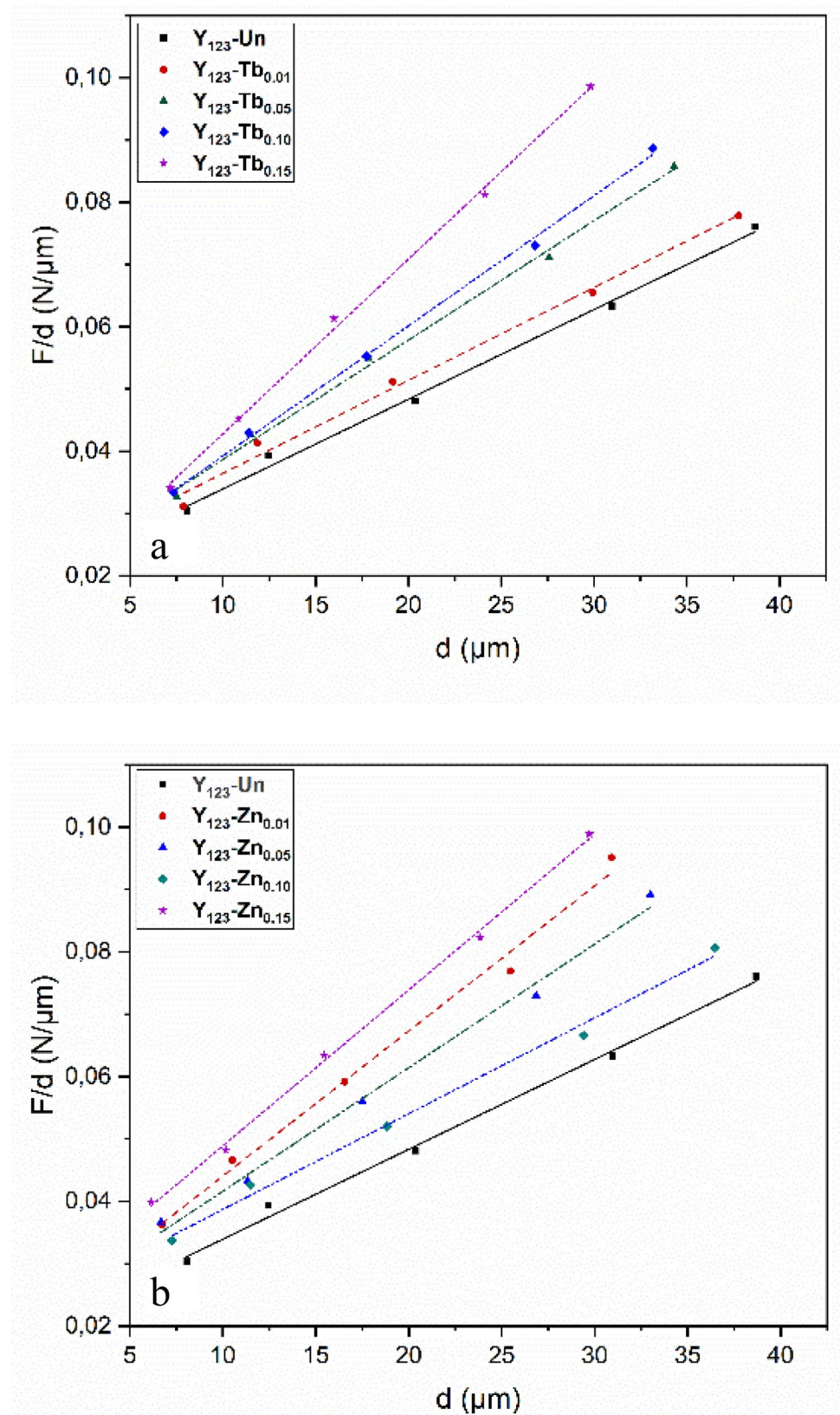


Table 8 α and β values of Tb-doped Y-123 ceramic structures

Materials	PSR model			
	$\alpha \times 10^{-2}$ (N)	$\beta \times 10^{-2}$ (N/ μm)	H_V (GPa)	H_{PSR} (GPa)
Y ₁₂₃ -Un	1.953	0.144	4.374– 3.643	2.672
Y ₁₂₃ -Tb _{0.01}	2.151	0.149	4.951– 3.819	2.769
Y ₁₂₃ -Tb _{0.05}	1.948	0.192	5.716– 4.630	3.558
Y ₁₂₃ -Tb _{0.10}	1.834	0.209	5.770– 4.957	3.876
Y ₁₂₃ -Tb _{0.15}	1.473	0.281	7.111– 6.137	5.205

Table 9 α and β values of Zn-doped Y-123 products

Materials	PSR model			
	$\alpha \times 10^{-2}$ (N)	$\beta \times 10^{-2}$ (N/ μm)	H_V (GPa)	H_{PSR} (GPa)
Y ₁₂₃ -Un	1.953	0.144	4.374– 3.643	2.672
Y ₁₂₃ -Zn _{0.01}	2.077	0.233	6.624– 5.703	4.316
Y ₁₂₃ -Zn _{0.05}	2.182	0.198	5.930– 5.010	3.673
Y ₁₂₃ -Zn _{0.10}	2.334	0.154	5.123– 4.102	2.849
Y ₁₂₃ -Zn _{0.15}	2.389	0.250	7.616– 6.173	4.637

3.3.5 Indentation-Induced cracking model

The Vickers hardness constants in the IIC model specified by Li and Bradt [32] are found using Eq. 13.

$$H_v = \lambda_1 K_1 \left(\frac{F}{d^2} \right) + K_2 \left(\frac{F^{5/3}}{d^3} \right) \quad (13)$$

In the equation, λ_1 , K_1 , and K_2 indicate constants. K_2 varies with the applied test load F whereas K_1 is a constant determined by the geometric structure of the notch. Equation 14 provides the hardness relation for a perfect plastic structure.

$$H_v = K_1 (F/d^2) \quad (14)$$

Equation 5.29 provides the hardness relation for an ideal brittle material when λ_1 equals zero.

$$H_v = K_2 (F^{5/3}/d^3) \quad (15)$$

Due to the high brittleness of the samples, the hardness values are calculated using Eq. 16, which was derived from Eq. 15.

$$H_v = K_2 \left(\frac{F^{5/3}}{d^3} \right)^m \quad (16)$$

m and K constants in Eq. 16 are found by examining the $\ln(H_v)$ and $\ln(F^{5/3}/d^3)$ curves. The m value characterizes the hardness features of the compound studied. The material exhibits ISE behavior when the m value is higher than 0.6. On the other hand, RISE behavior is observed in the sample when m is less than 0.6 [33, 34].

The IIC model utilizes constants K and m , which are derived from the logarithmic graphs of $\ln(H_v)$ and $\ln(F^{5/3}/d^3)$ in Fig. 7a-b. The m value is determined by calculating the slope of the graph while $\ln(K)$ is obtained by identifying the point of intersection between the graph and the vertical axis. Based on the data shown in Tables 10, 11, it can be observed that the value of m is more than 0.6 in all the replaced Y-123 superconducting materials. Consequently, the materials exhibit a hardness character that confirms the ISE behavior. Furthermore, upon comparing the saturation region of the Vickers microhardness values obtained for the doped structures with the H_{IIC} values evaluated from the IIC model, it is evident that the model computations align with the microhardness values in the saturation regions. Based on the data, it is determined that the IIC model is the best suitable for interpreting the microhardness values of Zn/Cu and Tb/Y partially substituted compounds.

In conclusion, the semi-empirical mechanical models preferred in the present study exhibit a successful trend both in inspecting the general mechanical characteristic behavior (ISE or RISE nature) and in explaining the effect of dopant type, substitution amount, and applied test loads on the microhardness parameters.

4 Conclusions

This research examines the role of Zn and Tb impurity on the ceramic structures by studying the mechanisms of crack propagation through experimental

Fig. 7 $\ln(H_V) - \ln(F^{5/3}/d^3)$ graphs **a** Tb doped and **b** Zn partially replaced Y-123 ceramic samples

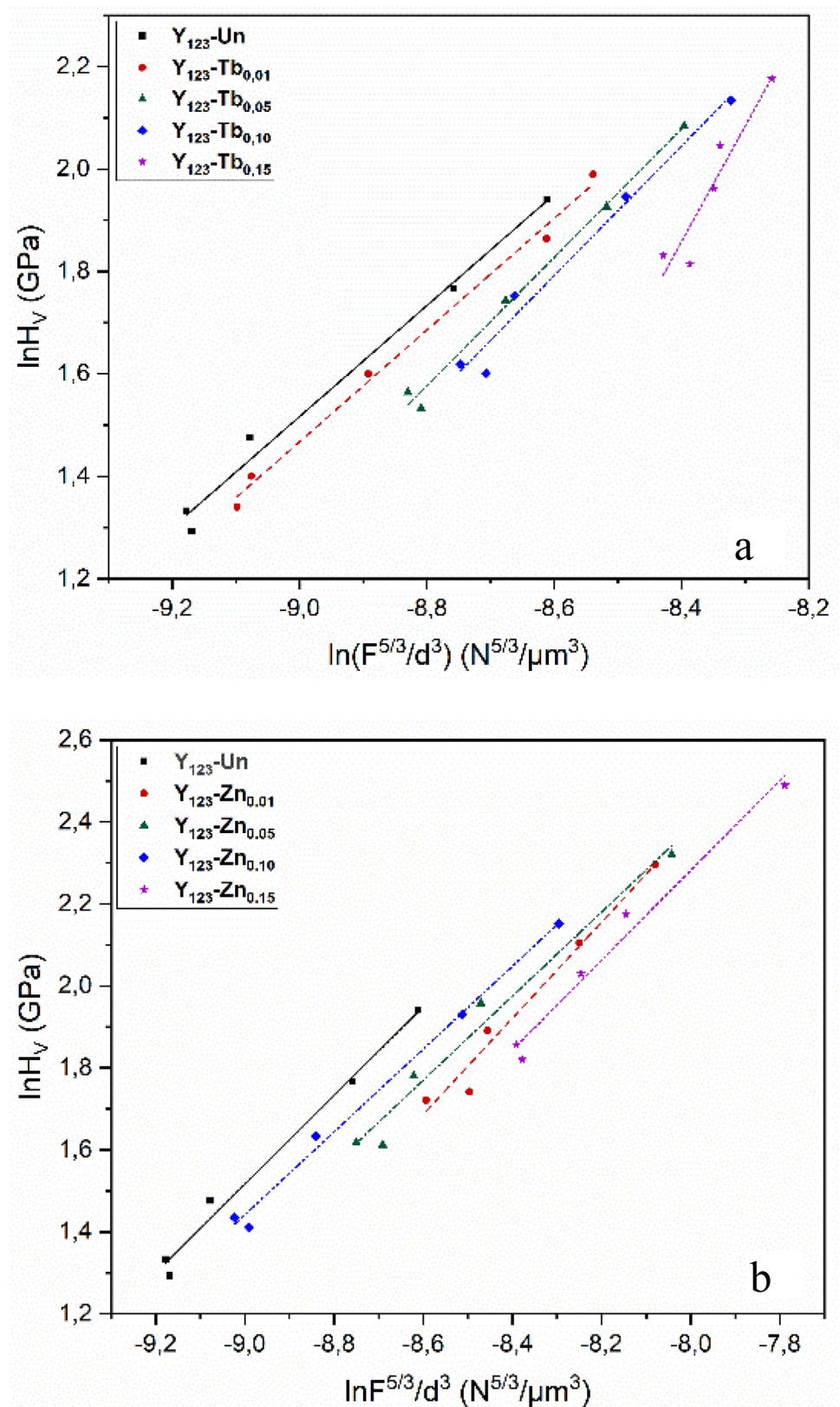


Table 10 $\ln(K)$ and m values of Tb/Y partially replaced Y-123 samples

Compounds	IIC approach			
	$\ln K$ ($N^{(3-5\ m)/3}/\mu m^{(2-3\ m)}$)	m	H_V (GPa)	H_{IIC} (GPa)
Y ₁₂₃ -Un	11.271	1.084	4.374–3.643	3.915
Y ₁₂₃ -Tb _{0.01}	11.291	1.092	4.951–3.819	4.257
Y ₁₂₃ -Tb _{0.05}	12.613	1.254	5.716–4.630	5.032
Y ₁₂₃ -Tb _{0.10}	12.676	1.266	5.770–4.957	5.255
Y ₁₂₃ -Tb _{0.15}	20.813	2.256	7.111–6.137	6.604

Table 11 $\ln(K)$ and m results of Zn/Cu partially substituted Y-123 ceramics

Compounds	IIC approach			
	$\ln K$ ($N^{(3-5\ m)/3}/\mu m^{(2-3\ m)}$)	m	H_V (GPa)	H_{IIC} (GPa)
Y ₁₂₃ -Un	1.084	1.084	4.374–3.643	3.915
Y ₁₂₃ -Zn _{0.01}	1.171	1.171	6.624–5.703	5.981
Y ₁₂₃ -Zn _{0.05}	1.025	1.025	5.930–5.010	5.376
Y ₁₂₃ -Zn _{0.10}	1.010	1.010	5.123–4.102	4.456
Y ₁₂₃ -Zn _{0.15}	1.096	1.096	7.616–6.173	6.781

Vickers microhardness measurements under different applied test loads. It is concluded that the load-dependent values of B_i , Y , E , and K_{IC} parameters for newly produced Y-123 ceramic matrices (especially prepared by the homovalent partial replacement of Zn^{2+} ions in Cu-sites in the Y-123 crystal matrix) are found to enhance remarkably with the substitution mechanism. This is because the impurities act as new strong barrier regions and thus the surface residual compressive stress sites and interactivity between the adjacent stacked layers are improved as much as possible. Additionally, the substitution mechanism leads to the formation of new slip systems and ionic bonding between the host ions. Consequently, the impurity ions decrease responsibility and sensitivity to the applied test forces depending on the increased ISE feature. To sum up, new matrices produced have higher deformation degrees, mechanical performance, strength, durability, resistance to failure, and general mechanical characteristic properties. Besides, the comparisons performed for the load-independent microhardness

parameters in the saturation limit regions show that the IIC model is the most appropriate of Zn/Cu and Tb/Y substituted ceramic superconductors.

Author contributions

GG, SK, and EAU conceived the idea for the project and designed the experiments. GG, SS, TS, GY, and ÖÖ performed methodology, project administration, investigation also performed materials production. SS, EAU, TS, and ÖÖ performed experimental measurement and resources, formal analysis, review & editing. GY, SS, and ÖÖ performed writing—original draft, writing—review & editing. All authors discussed the results and commented on the manuscript.

Funding

Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK). The authors have not disclosed any funding.

Data and code availability

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval There is no action that requires ethics committee approval.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made.

The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. S.R. Foltyn, L. Civale, J.L. MacManus-Driscoll, Q.X. Jia, B. Maiorov, H. Wang, M. Maley, Materials science challenges for high-temperature superconducting wire. *Nat. Mater.* **6**(9), 631–642 (2007)
2. F.N. Werfel, U. Floegel-Delor, R. Rothfeld, T. Riedel, B. Goebel, D. Wippich, P. Schirrmeister, Superconductor bearings, flywheels and transportation. *Supercond. Sci. Technol.* **25**(1), 014007 (2011)
3. L. Liang, Y. Wang, Z. Yan, W. Chen, Design and test of a multi capacity integrated HTS thin film reconfigurable current limiter. *Phys. C: Superconductivity Applications* **610**, 1354270 (2023)
4. B. Zhang, X. Zhang, Y.H. Zhou, Lightweight, highly tough and durable $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ superconductor. *Natl. Sci. Rev.* (2023). <https://doi.org/10.1093/nsr/nwad030>
5. C.C. Chow, M.D. Ainslie, K.T. Chau, High temperature superconducting rotating electrical machines: An overview. *Energy Rep.* **9**, 1124–1156 (2023)
6. X. Zhang, Y. Song, D. Zhou, T. Li, X. Wang, H. Huang, Z. Deng, *Cryogenics* **137**, 103774 (2024)
7. M.Z. Gaffoor, A.L.L. Jarvis, A. Swanson, Mechanical and structural properties of graphene oxide and reduced graphene oxide doped YBCO. *IEEE Trans. Appl. Supercond.* **33**(5), 1–9 (2023)
8. R.A. Algarni, Y. Slimani, E. Hannachi, M.A. Almessiere, T.M. Alqahtani, F. Ben Azzouz, Efficiency of dysprosium oxide nanoparticles on the intergranular coupling and intra-granular properties of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ ceramics. *J. Mater. Sci. Mater. Electron.* **34**(20), 1529 (2023)
9. A. Harabor, P. Rotaru, N.A. Harabor, P. Nozar, A. Rotaru, Structural, thermal and superconducting properties of Ag₂O-doped $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ composite materials. *Ceram. Int.* **49**(9), 14904–14916 (2023)
10. U. Erdem, M.B. Turkoz, G. Yildirim, Y. Zalaoglu, S. Nezir, Refinement of fundamental characteristic properties with homovalent Er/Y partial replacement of $\text{YBa}_2\text{Cu}_3\text{O}_{7-y}$ ceramic matrix. *J. Alloy. Compd.* **884**, 161131 (2021)
11. S. Safran, F. Bulut, A.R.A. Nefrow, H. Ada, O. Ozturk, Characterization of the $\text{CoFe}_2\text{O}_4/\text{Cu}$ displacement effect in the Y123 superconductor matrix on critical properties. *J. Mater. Sci. Mater. Electron.* **31**, 20578–20588 (2020)
12. B. Sahoo, K.L. Routray, G.C. Mirdha, S. Karmakar, A.K. Singh, D. Samal, D. Behera, Investigation of microhardness and superconducting parameters of CNTs blended YBCO superconductor. *Ceram. Int.* **45**(17), 22055–22066 (2019)
13. B. Sahoo, K.L. Routray, D. Samal, D. Behera, Effect of artificial pinning centers on YBCO high temperature superconductor through substitution of graphene nano-platelets. *Mater. Chem. Phys.* **223**, 784–788 (2019)
14. O. Ozturk, G. Guducu, S. Safran, G. Yildirim, Examination of pairing mechanism, orbital hybridization, stabilization and magnetization behavior of Tb/Y and Zn/Cu partially substituted Y-123 Superconductors. *J. Alloy. Compd.* **924**, 166362 (2022)
15. S.M. Khalil, A. Sedky, Annealing temperature effect on the properties of Bi:2212 superconducting system. *Physica B-Condensed Matter* **357**(3–4), 299–304 (2005)
16. M. Yilmazlar, H.A. Cetinkara, M. Nursoy, O. Ozturk, C. Terzioğlu, *Phys. C-Superconductivity Applications* **442**(2), 101–107 (2006)
17. A.K. Saxena, *High-temperature superconductors* (Springer, Berlin, 2010)
18. I. McColm, *Ceramic Hardness* (Springer, Berlin, 1990)
19. W.D. Callister, D.G. Retchwish, *Materials Science and Engineering an Introduction* (John Wiley&Sons Ltd., USA, 2007)
20. A.T. Ulgen, S. Cetin, Y. Zalaoglu, M.B. Turkoz, U. Erdem, G. Yildirim, Role of active slip systems induced with holmium impurity in Bi-2212 ceramics on mechanical design performance and morphological properties. *Ceram. Int.* **48**(18), 26361–26369 (2022)
21. A. Mercan, E. Kara, M.U. Dogan, S. Kaya, R. Terzioğlu, U. Erdem, G. Yildirim, C. Terzioğlu, Evolution of operable slip systems, lattice strain fields and morphological view of Bi-2223 ceramic system with optimum NiO addition. *Mater. Today Commun.* **35**, 106087 (2023)
22. E. Asikuzun, O. Ozturk, A.Y. Aydemir, A.T. Tasci, The effect of zinc on the structural, electrical, and mechanical properties of YBCO-123 superconducting nanoparticles prepared by an acetate-based sol-gel process. *J. Supercond. Novel Magn.Supercond. Novel Magn.* **32**, 3415–3423 (2019)
23. J.B. Quinn, G.D. Quinn, Indentation brittleness of ceramics: a fresh approach. *J. Mater. Sci.* **32**, 4331–4346 (1997)

24. K. Sangwal, B. Surowska, Study of indentation size effect and microhardness of SrLaAlO_4 and SrLaGaO_4 single crystals. *Mater. Res. Innovations* **7**(2), 91–104 (2003)
25. C. Hays, E.G. Kendall, An analysis of Knoop Hardness. *Metallography* **6**(4), 275–282 (1973)
26. R. Awad, A.I. Abou Aly, M. Kamal, M. Anas, Mechanical properties of $(\text{Cu}_{0.5}\text{Tl}_{0.5})$ -1223 substituted by Pr. *J. Supercond. Novel Magn.Supercond. Novel Magn.* **24**, 1947–1956 (2011)
27. S.J. Bull, T.F. Page, E.H. Yoffe, An explanation of the indentation size effect in ceramics. *Philos. Mag. Lett.* **59**(6), 281–288 (1989)
28. M.L. Tarkanian, J.P. Neumann, L. Raymond, Determination of the temperature dependence of 110 and 112 Slip in W From Knoop Hardness Measurements. *The Science of Hardness Testing and Its Research Applications*, ASM, Metals Park, Ohio. **1973**, 187–198 (1973)
29. G.P. Upit, S.A. Varchenya, Microhardness of alkali halide crystals. *Physica Status Solidi (b)* **17**(2), 831–835 (1966)
30. M.M. Barakat, Influence of $\text{Co}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ nanoparticles addition on vickers microhardness for $\text{Cu}_{0.5}\text{Tl}_{0.5}$ -1223 phase. *J. Supercond. Novel Magn.Supercond. Novel Magn.* **30**, 2945–2955 (2017)
31. M.M. Barakat, A.I. Abou-Aly, R. Awad, N.S. Aly, S. Ibrahim, Mechanical properties of $\text{Y}_{3-x}\text{Nd}_x\text{Ba}_{5-x}\text{Ca}_x\text{Cu}_8\text{O}_{18-6}$ samples. *J. Alloy. Compd.* **652**, 158–166 (2015)
32. H. Li, R.C. Bradt, The microhardness indentation load/size effect in rutile and cassiterite single crystals. *J. Mater. Sci.* **28**(4), 917–926 (1993)
33. K. Sangwal, On the reverse indentation size effect and microhardness measurement of solids. *Mater. Chem. Phys.* **63**(2), 145–152 (2000)
34. E.A. Tokeser, F. Bulut, A. Nefrow, T. Seydioglu, S. Kur-naz, The mechanical modelling of CoFe_2O_4 doped Y123 superconductor. *J. Adv. Appl. Sci.* **2**(1), 1–14 (2023)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.