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Key mechanical Design Performance Features and Mechanical Characterization of Poly-crystallized $Bi_{2.1}Sr_{2.0-x}Ti_xCa_{1.1}Cu_{2.0}O_y$ Superconducting Ceramic Cuprates

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Abstract

The primary scope of this study is to examine the variations of key mechanical design performance features and mechanical characterization of $Bi_{2.1}Sr_{2.0-x}Ti_xCa_{1.1}Cu_{2.0}O_y$ superconductors via Vickers hardness tests performed at different test loads between 0.245 N and 2.940 N. The materials are prepared within the molar ratios of $0 \leq x \leq 0.10$ by using the ceramic method in the atmospheric air. The measurement findings obtained indicate that the increment of Sr/Ti partial substitution level regresses remarkably the key design mechanical performances namely mechanical strength, stability, stiffness, critical stress, toughness, flexural strengths and mechanical durability. This means that the existence of Ti impurity matrix leads to the enhancement in the problematic defects, crack initiation sites and stress raisers based on the crack-producing omnipresent flaws. Accordingly, the propagation of the problematic defects accelerates considerably at lower indentation test loads applied, and the problematic defects locate easily in their critical propagation speed. All in all, the crystal defects are out of control, and the Sr/Ti partial substituted $Bi_{2.1}Sr_{2.0-x}Ti_xCa_{1.1}Cu_{2.0}O_y$ superconductions are much easier broken. Additionally, it is noted that every material produced show the typical indentation size effect but in diminish trend with enhancing Sr/Ti partial replacement level. The load-dependent mechanical parameters such as Young's modulus, yield strength, fracture toughness, brittleness index and elastic stiffness coefficients are also discussed in the text.

Keywords: $Bi_{2.1}Sr_{2.0-x}Ti_xCa_{1.1}Cu_{2.0}O_y$ cuprate, Mechanical performance, Mechanical characterization, Vickers hardness, Indentation size effect

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1. INTRODUCTION

In the Leiden University Heike Kamerlingh Onnes discovered the superconductivity phenomenon on 8th April in the year of 1911 when measuring the dc electrical resistivity over temperature of the mercury metal [1]. As well known that the superconductivity exerts in case of two main conditions. These are no electrical resistivity below such a low temperature called as critical transition temperature, and expulsion of magnetic flux fields above a critical applied magnetic field [2]. After the discovery of phenomenon, several scientists have extensively researched to find a new material exhibiting the superconductivity nature. As a matter of fact, the phenomenon has been observed in the following years for the materials such as organic compounds, elements (metals, metalloids, nonmetals: halogens and noble gases), dielectric materials, alloys, rutheno-cuprates, chalcogens, heavy fermions, silicon-based materials, pyrochlore oxides, rare-earth borocarbides, carbon-based compounds, A-15 materials, chevrel-phase compounds and cuprates (copper oxide layered samples) that drive the superconductivity nature [3]. Among all the compounds studied for a number of years, the cuprate-layered perovskite superconducting materials have widely attracted remarkable attention of academic researchers due to relatively larger critical temperatures higher than the liquid nitrogen temperature value [4–6]. Moreover, the other appealing characteristic features including much larger pinning ability, operating temperature, current and external magnetic field carrying capacity, smaller energy losses, heat dissipations and power consumptions enable the high temperature cuprate superconductors to use in the metallurgical and materials engineering, material science, energy sectors, particle accelerators, levitated trains, energy sectors, power transmission, sensitive process control, heavy-industrial technological and mechanical engineering-based applications such as generators, transformers and motor fields [7–14]. Besides, the cuprate materials with superior optical and electronic properties as well as much easier phase formation, lower material cost lighter weight/size, simpler availability of chemicals, harmless powder contents and especially environmental benefits can be much more encountered in the usages in the application fields of future refrigeration, innovative energy infrastructure, industrial, spintronics, medical diagnosis, sensitive process control and hydrogen society [15–18]. In the present work, we investigate the role of partial aliovalent replacement of Sr2+ impurities for the Ti4+ foreign additives in the Bi-2212 superconducting cuprate materials (from the parents of cuprate-layered perovskite superconducting materials) on the practicability and feasibility of Bi-2212 cuprates in the application fields by means of Vickers microhardness experimental measurement methods performed at the various applied test loads between the lowest value of 0.245 N and the highest value of 2.940. We also define the load-dependent key mechanical design performance and mechanical characteristic parameters as regards Young's modulus (E), yield strength (Y), fracture toughness (KIC), brittleness index (B) and elastic stiffness coefficient (C11) parameters throughout the full-text for the first time.

2. EXPERIMENTAL PREPARATION DETAILS AND MEASUREMENTS FOR BULK POLY-CRYSTALLIZED $Bi_{2.1}Sr_{2.0-x}Ti_xCa_{1.1}Cu_{2.0}O_y$ MATERIALS

This part of the paper can be dived into two main parts. The first part is about how we produce the pure and Sr/Ti partial substituted $Bi_{2.1}Sr_{2.0-x}Ti_xCa_{1.1}Cu_{2.0}O_y$ superconducting materials in the molar ratios of $0 \leq x \leq 0.10$ while the second part is interested in the variations of load-dependent key mechanical design performance and mechanical characteristic parameters of Bi-2212 cuprate-layered perovskite superconducting materials using Vickers hardness experimental measurement techniques. All the materials are prepared by using the solid-state reaction method. The chemicals of Bi_2O_3, $SrCO_3$, $CaCO_3$, CuO and TiO_2 within the high purity are purchased a distributor. For the first part, all the powder of chemicals is weighed with respect to the stoichiometric ratios (x= 0.00, 0.01, 0.03, 0.05, 0.07 and 0.10) with the assistant of the electronic scales and right after subjected to the milling process for six hours in medium of air conditions both to get more and more homogeneous powder and to minimalize the particle sizes of chemicals. The homogeneous powder of mixture is ground in the agate via the grinder for thirty minutes so that the formation of chemicals reaches to the desired particle sizes. After that, the homogeneous mixture is calcinated for the thirty-six hours at 800 °C in the porcelain crucibles with the 5 °C per min heating-cooling rates under medium of air. The powder mixture is re-milled again for nearly thirty minutes in the agate by means of grinder. The chemical powder in the blackish color is pelletized into volume of 1.5x0.5x0.2 mm^3 (rectangular bars) under 300 MPa load in the atmospheric air. The next process is annealing for the solidified powders at 850 °C for twenty-four hours. The bulk samples annealed are shown to be the pure or un-substituted, Ti-1, Ti-2, Ti-3, Ti-4 and Ti-5 in terms of mole-to-mole ratio changing of x= 0.00, 0.01, 0.03, 0.05, 0.07 and 0.10, respectively. As for the second part, the microhardness tests are conducted in the different load intervals of 0.245N-2.940N using *SHIMADZU HVM-2* tester in the atmospheric air conditions for 10 seconds within the accuracy of about ±0.1 μm. The indentation tracks in the diagonal forms are recorded with the calibrated microscope. The measurements (distances between two diagonals) are collected from the different locations on the smooth surfaces of materials both to prevent the hardening problem effects on the accurate values. Accordingly, we calculate the load-dependent key mechanical design performance and mechanical characteristic parameters including elastic modulus (abbreviated as E), fracture toughness (known as K_{IC}), yield strength (called as Y), brittleness index (abbreviated as B) and elastic stiffness coefficient (identified as C_{11}) parameters by the help of the experimental Vickers hardness data gathered. At the same time, the experimental curves enable us to discuss the differentiation of mechanical characterizations features (typical indentation size effect, *ISE* or reverse indentation size effect, *RISE* behavior) with the aliovalent Sr/Ti partial substitution level in the Bi-2212 crystal structure. The former is in the relation to the inverse dependence reduction of true Vickers microhardness parameters whereas *RISE* nature is related to the direct dependence augmentation in the original Vickers hardness values with increasing the external test load [19–21].

3. RESULTS AND DISCUSSION

3.1. Sr/Ti partial replacement effect on key design mechanical performances of $Bi_{2.1}Sr_{2.0-x}Ti_xCa_{1.1}Cu_{2.0}O_y$ superconducting materials

The role of Ti dopant on the main mechanical performances of bulk Bi-2212 ceramic materials is surveyed by the microhardness measurements conducted at various applied indentation loads between 0.245 N and 2.940 N. The microhardness experimental curves collected are displayed in Fig. 1.

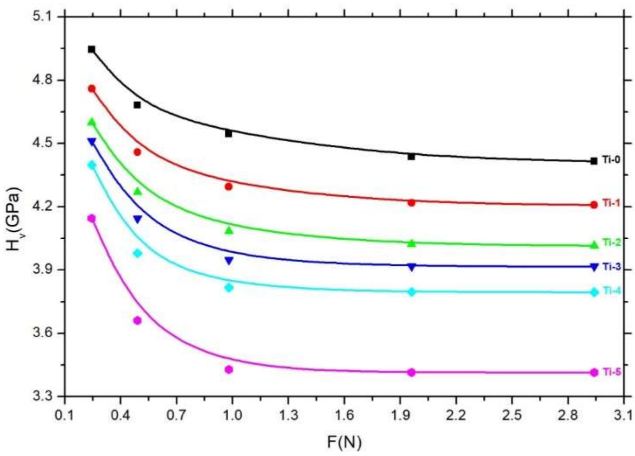

Figure 1. Differentiation of Vickers hardness parameters as a function of external indentation test loads.

It is shown that the key design mechanical performances are found to truncate remarkably with ascending the aliovalent Sr^{2+}/Ti^{4+} replacement level in the Bi-2212 superconducting system. This is because the presence of Ti impurity in the main matrix lead to increase harshly the permanent crystal structural problems, cracks, distortions, structural defects, porosity, disorders, voids, misorientations, lattice strains, inhomogeneity distributions, crack-producing omnipresent flaws, texturing, grain boundary couplings and strength quality of interaction between the superconducting grains in the active $Cu\text{-}O_2$ consecutively stacked layers of multi-layered perovskite Bi-2212 structure. In this regard, the experimental findings in the curves of Fig. 1 confirm that the existence of titanium atoms in the superconducting matrix damages seriously the tetragonal phase and especially critical stress value because of the rapid augmentation of crack initiation regions and stress raisers founded on the crack-producing omnipresent flaws in the distorted crystal lattice. In other words, the damage of aliovalent Sr/Ti partial substitution is explained that the propagation of the problematic defects such as the crack-initiating flaws, voids, cracks and dislocations accelerates significantly under such a relativistic low applied test load value. Thus, the problematic defects easily reach to their critical propagation speed. This is attributed to the fact that the defects are out of control, and the compounds are much easier broken in comparison with before. It is to be mentioned here that the microhardness values provided in Fig. 1 are determined from the following scientific relation:

$$H_V = 1854.4\left(\frac{F_{load}}{d^2}\right) \tag{1}$$

where the abbreviation of H_v shows the microhardness parameter (in the GPa unit) for the material studied in this work when F_{load} depicts the external indentation test loads. Also, d demonstrates the mean indentation track lengths in the diagonal forms. One can see all the calculations in the curves given in Fig. 1. Further, we numerically tabulate the values in Table 1. Based on the findings, for every material prepared in the current work the augmentation of Sr/Ti partial replacement level as well as the increase of test load results in the degradation of H_v parameters. The decrement trend in the H_v parameters with the load stems from the considerable reduction of active and independent slip systems founded on new-induced strain fields, stress concentrations and stress raisers in the Bi-2212 crystal lattice. On this basis, the highest value of H_v value is found to be about 4.94504 GPa at the test load of 0.245N for the pure sample while the value decreases towards to the smallest value of 4.14537 GPa at 2.940N. Moreover, the microhardness value is found to decrease to minimum value of 3.41318 GPa (for the poly-crystallized Ti-5 sample) at 2.940N applied load. It is very important to note that the penetration of titanium is ploughed to improve the general mechanical properties for the Bi-2212 cuprate materials. The mechanical curves in Fig. 1 also confirm that all the bulk poly-crystallized $Bi_{2.1}Sr_{2.0-x}Ti_xCa_{1.1}Cu_{2.0}O_y$ ceramic materials demonstrate typical indentation size effect (abbreviated as *ISE*) behavior. Namely, there is an inverse dependence (non-linear diminish) of real Vickers hardness values on the test loads. For example, the Ti-2 superconductor presents 0.245N, 4.59865 GPa, 4.26889 GPa, 4.08407 GPa, 4.421 GPa, 4.02184 GPa and 4.01588 GPa at the applied indentation test load of 0.49N, 0.98N, 1.96N and 2.94N, respectively (Table 1).

It is to be stressed here that the *ISE* feature-dependent seems to degrade with the dopant level. This means that the titanium impurity favors the formation of problematic defects in the Bi-2212 crystal structure [22–24]. At the same time, it is to be mentioned here that the main characteristics of the *ISE* nature is formation of reversible and irreversible deformations together in the Bi-2212 system. In this regard, in the poly-crystallized $Bi_{2.1}Sr_{2.0-x}Ti_xCa_{1.1}Cu_{2.0}O_y$ ceramic materials both the elastic and plastic deformations for immediately but in the decrement trend.

Moreover, there is a significant trick associated with the decrement trend on the microhardness curves as given in Fig. 1. Namely, the load-dependent microhardness values degrade dramatically with increasing indentation test loads until 2 N, after which the microhardness values nearly keep on the positions due the presence of saturation limit (or plateau) regions for all the ceramic superconducting materials. As well- known, even if the magnitude of test load increases, Vickers hardness values could not vary meaningfully. In the current study, the microhardness values for the bulk poly-crystallized Ti-6 cuprate ceramic compound reside in the plateau regions at relative lower applied test loads in comparison with those for the

Table 1. Change of original mechanical parameters as regards Young's modulus, yield strength, fracture toughness, brittleness index and elastic stiffness coefficients for the pure and Sr-site Ti partial replaced Bi-2212 cuprate ceramic compounds

Samples	*F (N)*	*H_v (GPa)*	*E (GPa)*	*Y (GPa)*	*K_{IC} ($MPam^{1/2}$)*	*C_{11} $(GPa)^{7/4}$*	*B ($m^{-1/2}$)*
	0.245	4.94504	405.313	1.648	9.609	16.398	514.633
	0.490	4.68095	383.667	1.560	9.349	14.897	500.703
Ti-0	0.980	4.54448	372.481	1.515	9.211	14.145	493.350
	1.960	4.43642	363.625	1.479	9.101	13.561	487.449
	2.940	4.41546	361.907	1.472	9.080	13.450	486.296
	0.245	4.75976	390.127	1.587	9.423	15.338	505.122
	0.490	4.45794	365.388	1.486	9.119	13.677	488.844
Ti-1	0.980	4.29511	352.042	1.432	8.951	12.815	479.834
	1.960	4.21798	345.720	1.406	8.871	12.415	475.506
	2.940	4.20866	344.957	1.403	8.861	12.367	474.980
	0.245	4.59865	376.921	1.533	9.475	14.441	485.327
	0.490	4.26889	349.893	1.423	9.129	12.678	467.602
Ti-2	0.980	4.08407	334.745	1.361	8.930	11.733	457.368
	1.960	4.02184	329.644	1.341	8.861	11.422	453.870
	2.940	4.01588	329.156	1.339	8.855	11.392	453.533
	0.245	4.51057	369.702	1.504	9.233	13.961	488.513
	0.490	4.14435	339.685	1.381	8.851	12.038	468.261
Ti-3	0.980	3.94718	323.525	1.316	8.637	11.054	456.987
	1.960	3.91775	321.113	1.306	8.605	10.910	455.280
	2.940	3.91663	321.021	1.305	8.604	10.904	455.215
	0.245	4.39828	360.498	1.466	8.962	13.358	490.765
	0.490	3.97946	326.170	1.326	8.525	11.212	466.814
Ti-4	0.980	3.81743	312.890	1.272	8.349	10.426	457.212
	1.960	3.79576	311.114	1.265	8.326	10.322	455.913
	2.940	3.79502	311.053	1.264	8.325	10.319	455.868
	0.245	4.14537	339.769	1.382	9.782	12.043	423.794
	0.490	3.66098	300.067	1.220	9.192	9.689	398.265
Ti-5	0.980	3.42855	281.016	1.143	8.896	8.639	385.415
	1.960	3.41504	279.909	1.138	8.878	8.579	384.655
	2.940	3.41448	279.863	1.137	8.877	8.577	384.623

Table 2. Fitting parameters for all the bulk poly-crystallized $Bi_{2.1}Sr_{2.0-x}Ti_xCa_{1.1}Cu_{2.0}O_y$ materials

Materials	***Fitting relations for the pure and Sr/Ti partial substituted Bi-2212 superconducting cuprates***
Pure	$y = 0.2001x^4 – 1.3028x^3 + 2.9015x^2 – 2.7073x + 5.4526$
Ti-1	$y = 0.2067x^4 – 1.3727x^3 + 3.1439x^2 – 3.0115x + 5.3283$
Ti-2	$y = 0.2111x^4 – 1.4200x^3 + 3.3098x^2 – 3.2286x + 5.2111$
Ti-3	$y = 0.2306x^4 - 1,5665x^3 + 3.6882x^2 – 3.5983x + 5.1930$
Ti-4	$y = 0.3303x^4 – 2.1853x^3 + 4.9298x^2 – 4.4875x + 5.2328$
Ti-5	$y = 0.3281x^4 – 2.2154x^3 + 5.1546x^2 – 4.9073x + 5.0696$

other superconducting materials prepared (Fig. 1). The rapid decrement in the H_v value at the test load of 0.245N is thought to be the other clue for the Ti-6 superconducts material. On the other hand, the variation of the H_v value at the test load of 0.245N is noted to be the least decrement as provide in Fig. 1. The different characteristic behavior can be explained by the rapid degradation in the mechanical strength, stability, stiffness, critical stress, toughness, flexural strengths and mechanical durability with the Ti dopant.

Additionally, we point out the negative influence of Sr/Ti substitution in main matrices of ceramic cuprates via the determination of fitting equations between F_{load} and H_v values. One can see the fitting parameters deduced in Table 2.

According to the parameters obtained, it can be summarized that the term of x^4 is calculated to increase systematically from the value of 0.2001 until 0.3281 with enhancing the Sr/Ti substitution level. The value is obviously related to the mechanical sensitivity to the applied test loads due to the increment in the problematic defects in the Bi-2212 cuprate-layered perovskite superconducting materials. Thus, it is derived on the findings that the value of 0.3281 belonging to the bulk Ti-6 superconducting material confirms the least resistant of the material to the applied test load. In other words, the propagation of the problematic defects appeared in the crystal matrix accelerates to locate in their critical propagation speed.

3.2. Role of *Sr/Ti* replacement on original mechanical performances of $Bi_{2.1}Sr_{2.0-x}Ti_xCa_{1.1}Cu_{2.0}O_y$ cuprate ceramic materials

By using some mathematical relations (arranged below), we determine the crucial variations in the load-dependent key design mechanical performances including the elastic modulus (abbreviated as E), fracture toughness (known as K_{IC}), yield strength (called as Y), brittleness index (abbreviated as B) and elastic stiffness coefficient (identified as C_{11}) parameters with the different Sr/Ti replacement level [2, 25, 26].

$$E = 81.9635 H_V \tag{2}$$

$$Y \approx \frac{H_V}{3} \tag{3}$$

$$K_{IC} = \sqrt{2E\alpha} \tag{4}$$

(α shows surface energy)

$$C_{11} = H_v^{7/4} \tag{5}$$

$$B = \frac{H_v}{K_{IC}} \tag{6}$$

One can encounter all the real mechanical performance parameters in Table 1, also. According to the table, it would be more precise to confirm that the parameters determined are noted to depend sensitively on both the indentation test loads and substitution mechanism. This is attributed to the rapid increment in the problematic defects in the superconducting crystal system. The increment causes to degrade remarkably in mechanical strength, stability, stiffness, critical stress, toughness, flexural strengths and mechanical durability. As for the numerical values for the elastic (Young's) modulus, the maximum value of 405.313 GPa is noted for the pristine material at the constant test load of 0.245N while the minimum value of 279.863 GPa ascribes to the bulk Ti-5 superconducting material at 2.940 N test load. The other values between 360.498 GPa-390.127 GPa are obtained for the moderate dopant levels at 0.245N. The reduction in the Young's modulus verifies the negative influence of titanium foreign additives on polycrystallized Bi-2212 main matrix. Similar results (decrease of Young's modulus with the augmentation of test loads applied) are obtained. On this basis, the smallest elastic modulus value related to the stiffness is observed to be about 279.863 GPa for the Ti-5 cuprate ceramic material at the applied indentation test load of 2.940 N. Likewise, the deepest value for the yield strength is calculated to be about 1.137 GPa for the bulk Ti-5 material at 2.940 N external indentation test load. Conversely, the maximum yield strength value of 1.648 GPa is observed for the pure sample when 0.245N indentation test load is applied to the sample. Namely, it is found that the Sr/Ti partial replacement in the Bi-2212 crystal lattice harms strongly on the yield strength parameters among the key mechanical design properties. As for the variation of fracture toughness parameters with the Sr/Ti partial substitution, the increse of both dopant level and applied test load leads to degrade the values. Accordingly, the maximum fracture toughness value of 9.609 GPa is noticed for the un-substituted superconducting material at 0.245N applied load while.877 GPa is determined to be the smallest value for the Ti-5 sample. The similar results are observed for the results of brittleness index and elastic stiffness coefficients. All the differentiations of key mechanical design properties discussed above show that the Sr/Ti partial replacement in the main matrix diminishes the mechanical strength, stability, stiffness, critical stress, toughness, flexural strengths and mechanical durability of Bi-2212 superconducting materials.

4. CONCLUSION

In the present work, we investigate the vital role of Sr/Ti partial substitution in the main matrix on the key mechanical design performance parameters and mechanical characterizations of poly-crystallized $Bi_{2.1}Sr_{2.0-x}Ti_xCa_{1.1}Cu_{2.0}O_y$ ceramic materials prepared within the molar ratios of $0 \leq x \leq 0.10$ by means of micro hardness tests conducted at the varied external loads between the value of 0.245 N and 2.940 N in the atmospheric air conditions. It is observed that the key design mechanical performances tend to degrade constantly with increasing the Sr/Ti partial replacement level in superconducting crystal due to the rapid augmentation of problematic defects, crack initiation sites and stress raisers based on the crack-producing omnipresent flaws. Moreover, the durable tetragonal phase and critical stress value are damaged significantly, and hence, the Sr/Ti partial substituted $Bi_{2.1}Sr_{2.0-x}Ti_xCa_{1.1}Cu_{2.0}O_y$ superconducting materials are much easier broken because of the increased problematic defects in the crystal lattice. Similarly, the Ti dopant level truncates dramatically the typical ISE feature. It is another valuable finding that the existence of excess Ti dopant in the crystal system makes the Bi-2212 material reach to the plateau regions at relative lower applied test loads.

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