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Mechanochemical synthesis and structural and phase characterization of composite inert matrices in the ZrO_2–Nb_2O_5 system

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A relationship was established between phase transformations, microstructural evolution, and the strengthening of $ZrO_2 - Nb_2O_5$ composite ceramics obtained by mechanochemical solid-state synthesis followed by annealing at $1500\,^{\circ}C$. The Nb_2O_5 content was varied from 0 to 50 wt.% in increments of 10 wt.%. Phase composition and structural changes were studied using X-ray diffraction and Raman spectroscopy, while grain morphology was examined by scanning electron microscopy. Mechanical properties were assessed using Vickers hardness and flexural strength measurements. The addition of Nb_2O_5 promoted the formation of the niobate phase $Nb_2Zr_6O_{17}$, accompanied by changes in grain morphology and relative grain refinement. At 20–30 wt.% Nb_2O_5, $Nb_2Zr_6O_{17}$ -rich ceramics with a relatively fine-grained microstructure exhibited the highest hardness and flexural strength values. At higher Nb_2O_5 contents, additional phases, including Nb_2O_5 and tetragonal ZrO_2, were detected, accompanied by morphological changes and reduced hardness and flexural strength. The observed strengthening correlates with phase composition and grain morphology; contributions from solid-solution effects, dispersion strengthening, and residual stresses remain possible but require independent verification.

Keywords: mechanochemical synthesis; zirconia ceramics; $ZrO_2 - Nb_2O_5$ system; phase transformations; microstructure; microhardness; flexural strength; dispersion strengthening.

1. Introduction

In the context of this study, inert matrices are defined as composite oxide ceramics that maintain phase and chemical stability under high-temperature treatment and mechanical loading and are considered as baseline materials for subsequent functional testing. In this context, zirconium dioxide (ZrO_2)-based ceramics are widely used in structural and functional systems operating under high thermal and mechanical loads due to their combination of high thermal resistance and phase stability [1], as well as their ability to undergo controlled polymorphic transformations, which are utilized to enhance strength and fracture toughness [2]. The performance characteristics of zirconia ceramics are largely determined by the phase ratio of the monoclinic (m-ZrO_2), tetragonal (t-ZrO_2), and cubic modifications [1], as well as by the defect structure and residual stresses formed during synthesis and subsequent heat treatment [3]. It has been established that variations in the phase composition and defect chemistry of ZrO_2 have a direct effect on the mechanical response of the material, including hardness and flexural strength [4]. More broadly, atomistic studies of functional materials highlight the importance of molecular-scale structural features and interactions in determining their functional properties [5].

One of the most effective approaches for controlling the phase stability and microstructure of ZrO_2 is doping with aliovalent components, which leads to the formation of oxygen vacancies and elastic distortions of the crystal lattice. Control over the concentration and distribution of defects is considered a universal tool for tuning the properties of oxide ceramics, including resistance to plastic deformation and fracture toughness [6]. It has been shown that even low concentrations of aliovalent dopants can significantly shift the equilibrium between the tetragonal and monoclinic phases of zirconia by altering the defect structure and thermodynamic stability of the phases [7].

In this context, niobium oxide (Nb_2O_5) is of particular interest as a dopant for ZrO_2. Nb^{5+} ions, when aliovalently substituting for Zr^{4+}, can modify the defect structure of the zirconia matrix and influence the kinetics of phase transformations and grain growth processes, as confirmed by experimental studies of Nb-doped zirconia ceramics [8]. At certain Nb_2O_5 concentrations and high-temperature treatment conditions, the $ZrO_2 - Nb_2O_5$ system becomes reactive, leading not only to the formation of a solid solution but also to the formation of complex niobate phases.

A key representative of such compounds is $Nb_2Zr_6O_{17}$ ($Zr_6Nb_2O_{17}$), which belongs to the class of $A_6B_2O_{17}$-type oxides. These phases are characterized by high structural complexity, a high defect concentration, and strong sensitivity of the phase state to synthesis and heat-treatment conditions [9]. Recent studies indicate that $A_6B_2O_{17}$-type compounds possess specific structural features and defect structures that influence their electrical and dielectric properties and suggest a potential impact of these phases on the mechanical behavior of composite zirconia ceramics [10, 11]. However, the role of the $Nb_2Zr_6O_{17}$ phase in the formation of the microstructure and mechanical properties of ZrO_2 ceramics has so far been insufficiently studied. Studies of other functional material systems,

including metal-organic frameworks such as ZIF-8, also highlight the importance of structural features in determining functional performance in electrochemical applications [12].

It is well known that microstructural parameters–such as grain size and shape, the distribution of secondary phases, and the nature of interphase boundaries–have a decisive influence on the mechanical properties of ceramic materials. Grain refinement and the formation of dispersed phases contribute to an increase in hardness and strength due to grain-boundary and dispersion strengthening, which can be described by Hall–Petch-type relationships [13, 14]. Experimental studies of zirconia ceramics confirm that grain size reduction and microstructure optimization lead to increased flexural strength and enhanced fracture resistance [4, 15]. In this regard, the analysis of phase composition, microstructure, and mechanical properties should be considered within a unified cause–effect framework.

The method of material preparation plays a crucial role in the formation of this chain. Mechanochemical activation of solid-state mixtures enables the intensification of diffusion processes, enhances the homogenization of components, and lowers the energy barriers for phase formation [16, 17]. When combined with subsequent high-temperature annealing, this approach provides favorable conditions for the controlled development of phase composition and microstructure in composite oxide ceramics, as demonstrated by recent studies on the mechanochemical synthesis of nanostructured and composite ceramic materials [18].

Despite a substantial body of work on Nb-doped zirconia ceramics and $A_6B_2O_{17}$-type oxides, the literature lacks a systematic analysis establishing a direct relationship between Nb_2O_5 content, the formation of the $Nb_2Zr_6O_{17}$ phase, the evolution of grain morphology, and the resulting changes in hardness and flexural strength under fixed high-temperature processing conditions. In particular, the optimal range of Nb_2O_5 concentrations that provides maximum strengthening, as well as the mechanisms leading to its degradation at higher dopant levels, remains unclear.

In this study, we hypothesize that the formation of $Nb_2Zr_6O_{17}$-rich compositions at intermediate Nb_2O_5 contents is associated with changes in grain morphology and improved mechanical properties, whereas higher Nb_2O_5 contents are accompanied by secondary phases and reduced hardness and flexural strength. The aim is to establish relationships among phase evolution, microstructure, and mechanical properties of $ZrO_2 - Nb_2O_5$ ceramics processed under fixed mechanochemical and annealing conditions ($1500\,^{\circ}C$), with initial Nb_2O_5 contents of 0–50 wt.%.

2. Materials and methods

Composite ceramics of the $ZrO_2 - Nb_2O_5$ system were produced by mechanochemical solid-state synthesis followed by high-temperature annealing. Zirconium dioxide (ZrO_2) and niobium pentoxide (Nb_2O_5) powders of high chemical pu-

rity (at least 99.95%, Sigma-Aldrich) were used as starting materials. The powders were mixed in different weight ratios, with the initial Nb_2O_5 content varying from 0 to 50 wt.% in increments of 10 wt.%. The total mass of each powder mixture was 20 g (for example, 14 g ZrO_2 and 6 g Nb_2O_5 for the 30 wt.% composition). Powders were weighed using a U.S. SOLID Precision Balance (USA) analytical balance with an accuracy of ± 0.0001 g. Mechanochemical activation was performed in a PULVERISETTE 6 planetary mill (Fritsch, Germany) using a tungsten carbide grinding jar and 10 mm tungsten carbide balls at a rotation speed of 250 rpm for 30 minutes. After milling, the powders were thermally annealed in a Nabertherm LE 4/11/R6 muffle furnace (Germany) at $1500 \pm 5\,^{\circ}\mathrm{C}$, with a heating rate of $15\,^{\circ}\mathrm{C}$/min and a holding time of 5 hours, followed by furnace cooling to room temperature over 20–25 hours. Identical milling and annealing conditions were used for all compositions to enable comparison of composition-dependent phase and microstructural changes; optimization of these processing parameters was not investigated. Phase composition was analyzed by X-ray diffraction using a D8 ADVANCE ECO diffractometer (Bruker, Germany) in Bragg–Brentano geometry with Cu $K\alpha$ radiation ($\lambda = 1.5406$ Å) over a 2θ range of 20–90° with a step size of 0.05°. Phase identification was performed using DIFFRAC.EVA v.4.2 software and the PDF-2 database (ICDD). Quantitative phase analysis was performed using the Rietveld refinement method based on the experimental X-ray diffraction patterns; relative weight fractions of the identified crystalline phases were determined from the refined profiles.Raman spectroscopy was performed at room temperature over the range 100–1000 cm^{-1} as a complementary probe of vibrational and local structural changes, rather than as an independent method for quantitative phase determination. The microstructure and grain morphology were examined by scanning electron microscopy using a Phenom ProX benchtop electron microscope (Thermo Fisher Scientific, Netherlands) equipped with an energy-dispersive X-ray (EDS) system at an accelerating voltage of 5–15 kV in secondary and backscattered electron modes. Images were acquired under comparable conditions; SEM observations were used for qualitative morphological comparisons, and no statistical grain-size distribution is claimed. Hardness was measured using a DUROLINE M1 microhardness tester (Metkon, Turkey) equipped with a Vickers pyramidal indenter. A constant load of approximately 100 N was applied for 15 s. At least 10 indentations were performed on each specimen to determine the Vickers hardness. The shape of each indentation was examined to evaluate the hardness values. The distance between successive indentations was at least 30 μm to minimize the influence of overlapping deformation zones on the hardness measurements. Flexural strength was determined by the three-point bending method using an LFM-L 10kH universal electromechanical testing machine (Walter + Bai AG, Switzerland). All ceramic samples were tested under identical experimental conditions to ensure the comparability of the obtained results.

3. Results and Discussion

The phase composition of $ZrO_2-Nb_2O_5$ ceramics depends strongly on the initial Nb_2O_5 content under the fixed thermal-treatment conditions used here (Figure 1). The undoped sample exhibits diffraction reflections of monoclinic ZrO_2 (m-ZrO_2), with no additional crystalline phases detected. At 10 wt.% Nb_2O_5, the diffraction patterns indicate the $Nb_2Zr_6O_{17}$ phase (PDF-00-009-0251) together with residual monoclinic ZrO_2. At 20 wt.% Nb_2O_5, $Nb_2Zr_6O_{17}$ is predominant, with a small residual contribution from m-ZrO_2. The Rietveld-derived estimate of this minor phase was reported as below 1 wt.%; however, this very low value should be interpreted cautiously until its uncertainty and quantification limit are established. At 30 wt.% Nb_2O_5, the recorded pattern was assigned predominantly to $Nb_2Zr_6O_{17}$, without additional crystalline reflections resolved under the measurement conditions. At 40 wt.% Nb_2O_5, reflections assigned to Nb_2O_5 (PDF-00-037-1468) are observed. At 50 wt.% Nb_2O_5, additional reflections assigned to tetragonal ZrO_2 are reported alongside Nb_2O_5. The possible role of defect chemistry in the stabilization of these phases requires further verification.

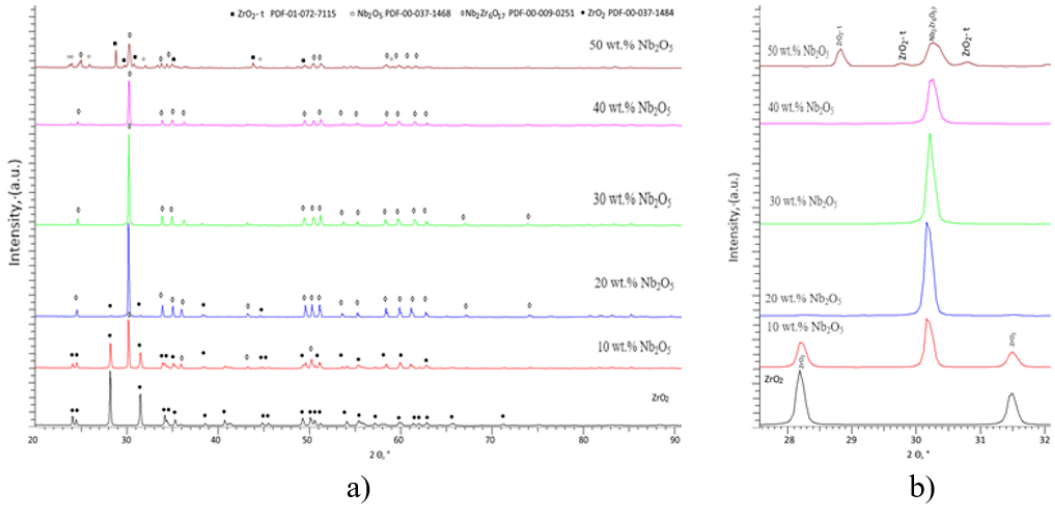


Figure 1. X-ray diffraction results of the studied $ZrO_2-Nb_2O_5$ composite ceramics with Nb_2O_5 contents ranging from 0 to 50 wt.%: a) general view of the diffraction patterns of the samples; b) detailed view of the main reflections of the samples.

Figure 2 shows the Raman spectra of $ZrO_2-Nb_2O_5$ composite ceramics annealed at 1500 °C. The spectra of the starting ZrO_2 exhibit peaks characteristic of the monoclinic phase of zirconium oxide, with 15 identifiable peaks corresponding to m-ZrO_2 at 178 (A_g), 190 (A_g), 221 (B_g), 305 (A_g), 333 (B_g), 346 (A_g), 381 (B_g), 452, 475 (A_g), 504 (B_g), 536 (B_g), 558 (A_g), 582, 615 (B_g), and 636 (A_g) cm^{-1} [19]. With the addition of 10 wt.% Nb_2O_5, broadening of the monoclinic ZrO_2 peaks is observed, which may be associated with the incorporation of Nb into the ZrO_2 lattice, as well as the formation of the $Nb_2Zr_6O_{17}$ phase, whose presence in the ceramics was confirmed by X-ray phase analysis.

At a concentration of 20 wt.% Nb_2O_5, the spectra show peaks at 141, 168, 189, 213, 282, 318, 348, 382, 399, 471, 515, 556, 589, 636, 658, and 775 cm^{-1}. The broad peak at 775 cm^{-1} may be associated with local ordering or the formation of defect clusters upon substitution of Zr by Nb in the $Nb_2Zr_6O_{17}$ phase. The shape

of this peak indicates the absence of long-range order, resulting from structural changes associated with defect formation in the phase [20]. The spectra also exhibit peaks at 141, 282, 318, 471, and 636 cm^{-1}, which may be attributed to the tetragonal ZrO_2 phase [21]; however, the formation of this phase, as confirmed by X-ray phase analysis, was observed only at higher Nb_2O_5 concentrations in the ceramics. The peak at 658 cm^{-1} may correspond to Nb–O vibrations [22]. At an Nb_2O_5 concentration of 40 wt.%, in addition to the main reflections, peaks at 134, 269, and 986 cm^{-1} also appear in the spectra, which may indicate the formation of the orthorhombic Nb_2O_5 phase. This phase is characterized by two narrow intense peaks at around 120 and 990 cm^{-1}, as well as two broader peaks at approximately 250 and 630 cm^{-1} [23]. At an Nb_2O_5 concentration of 50 wt.%, the most intense peaks in the spectra appear at 130, 179, 207, 242, 281, 409, and 924 cm^{-1}, which may be associated with the vibrational modes of Nb_2O_5 [24].

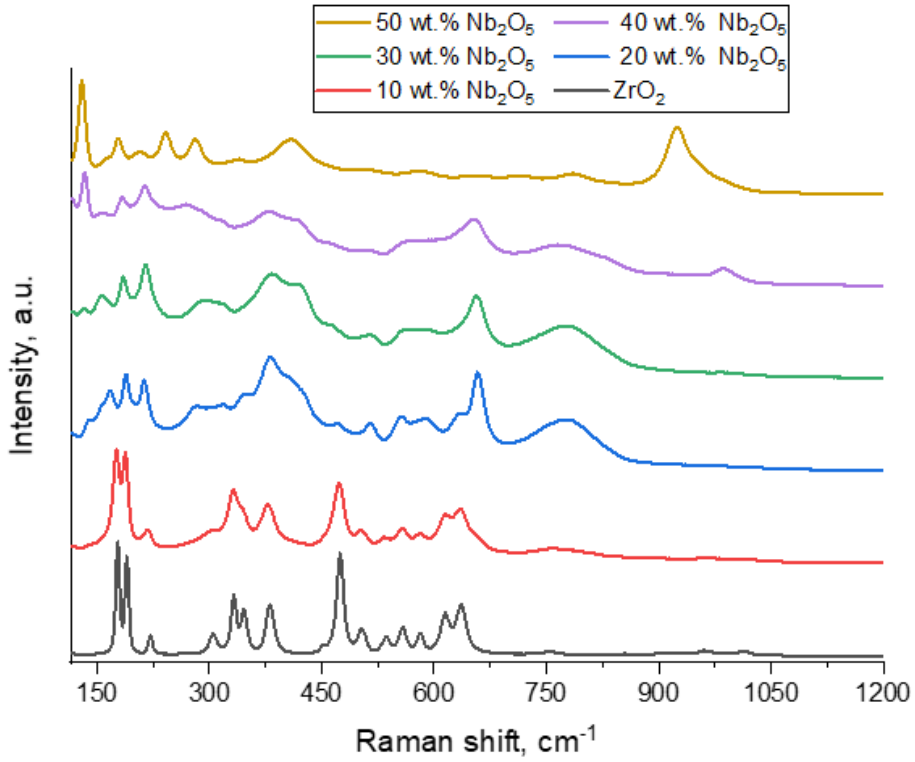


Figure 2. Raman spectra of $ZrO_2 - Nb_2O_5$ composite ceramics with varying component ratios.

Figure 3 presents SEM images of the $ZrO_2 - Nb_2O_5$ ceramics prepared with different initial component ratios. Images at comparable scales allow a qualitative comparison of grain morphology across the series. The micrographs suggest relative grain refinement in the intermediate-composition samples and changes in morphology at higher Nb_2O_5 contents. These observations are discussed in relation to the phase evolution identified by XRD. Because a statistical grain-size distribution was not established, the observed differences are described qualitatively rather than as measured changes in mean grain size.

Figure 4 shows a schematic representation of changes in grain size and shape during synthesis depending on the variation of component ratios in $ZrO_2 - Nb_2O_5$ ceramics. These changes are associated with phase transformations, as

well as the role of the formation of impurity inclusions in affecting grain size factors. According to the presented scheme, it can be seen that the formation of the $Nb_2Zr_6O_{17}$ phase in the ceramics initially may contribute to the initiation of grain growth suppression processes. This effect can be associated with the formation of a fine-dispersed $Nb_2Zr_6O_{17}$ fraction around the larger m-ZrO_2 grains. The presence of this fraction, together with an increase in its relative content, may contribute to the suppression of grain growth and the formation of large agglomerates. However, in the case where the ceramics contain inclusions of unreacted Nb_2O_5 (at dopant concentrations above 30 wt.%), the grain morphology is manifested in the form of the formation of plate-like elongated grains, followed by the development of large rhomboid grains with chipped edges. Moreover, phase transformations associated with the appearance of inclusions in the form of the tetragonal t-ZrO_2 phase lead to a pronounced coarsening of the rhomboid-shaped grains. Thus, analysis of the obtained data on changes in grain morphology and phase composition of the ceramics allows us to conclude that varying the component ratios in the ceramics not only enables control over the phase composition, but also indirectly regulates the grain crystallization processes, restraining grain growth through the formation of a fine-grained fraction within the microstructure.

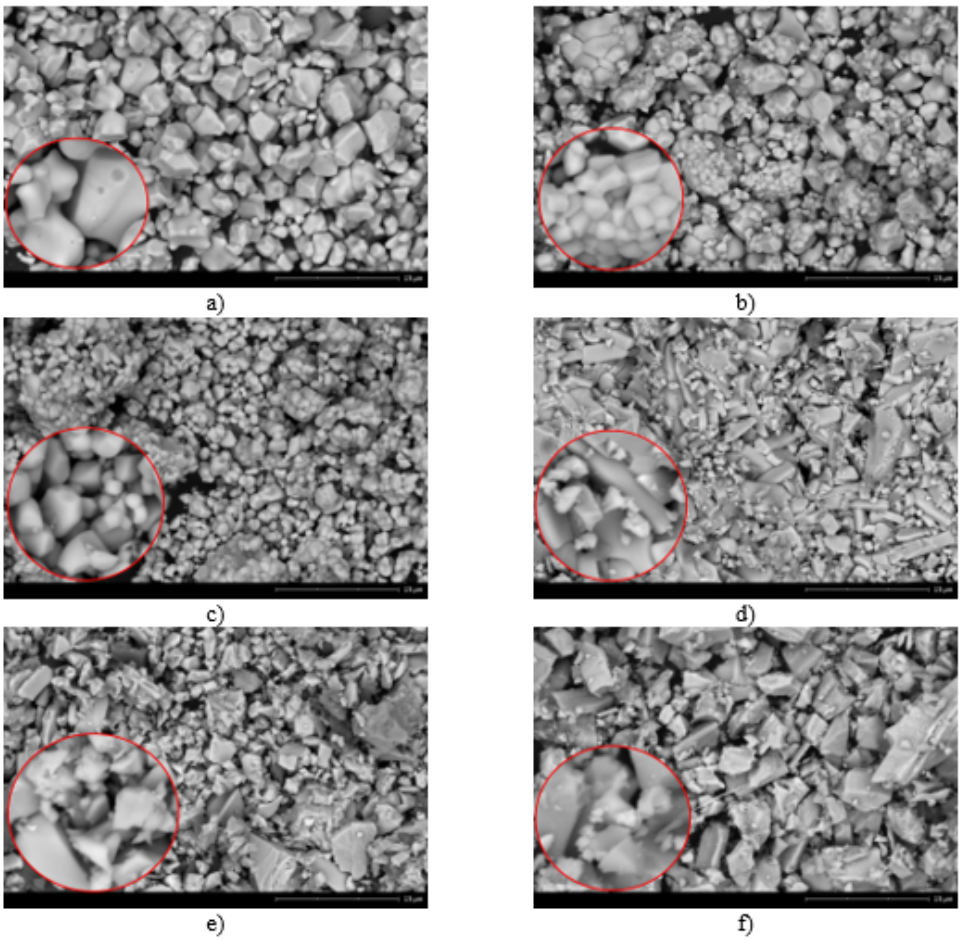


Figure 3. SEM images of the studied $ZrO_2 - Nb_2O_5$ ceramics with variation in the component ratios:(a) ZrO_2 ; (b) 10 wt.% Nb_2O_5 ; (c) 20 wt.% Nb_2O_5 ; (d) 30 wt.% Nb_2O_5 ; (e) 40 wt.% Nb_2O_5 ; (f) 50 wt.% Nb_2O_5 .

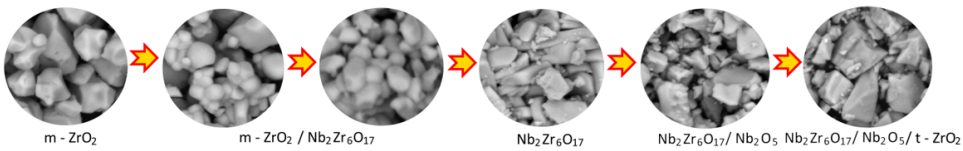


Figure 4. Schematic illustrating the relationship between changes in grain shape, size and the phase composition of the samples.

Figure 5 shows the changes in the mechanical properties of the investigated $ZrO_2 - Nb_2O_5$ ceramics as a function of the initial component ratios. In the absence of niobium additives (0 wt.%), the material consists primarily of monoclinic zirconium dioxide (m - ZrO_2) and exhibits the lowest hardness ($\sim$7.4–7.5 GPa) and flexural strength ($\sim$750 MPa) among the investigated compositions. The experimental results indicate that the increase in hardness and flexural strength following the addition of Nb_2O_5 is associated with changes in the phase composition and microstructural characteristics of the ceramics. The formation of the $Nb_2Zr_6O_{17}$ phase is accompanied by changes in grain morphology and relative grain refinement, which may contribute to the observed improvement in mechanical properties. The highest hardness and flexural strength values were observed at Nb_2O_5 concentrations of 20–30 wt.%, with both properties reaching their maximum values at 30 wt.% Nb_2O_5. This improvement correlates with the predominance of the $Nb_2Zr_6O_{17}$ phase and the development of a relatively fine-grained microstructure, as indicated by the XRD and SEM results.

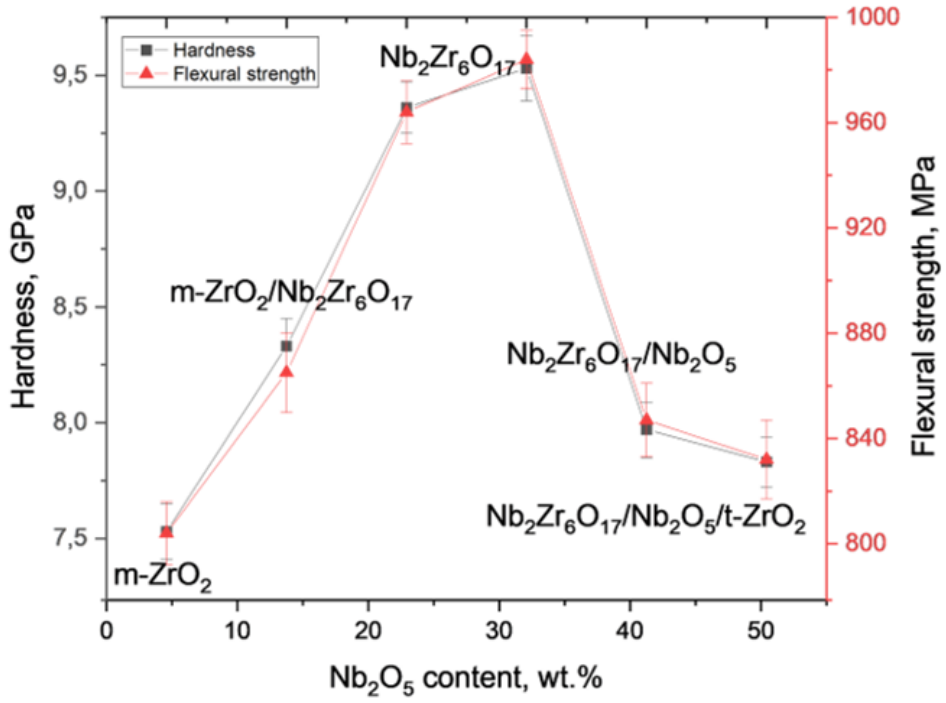


Figure 5. Dependence of hardness and flexural strength of $ZrO_2 - Nb_2O_5$ ceramics on Nb_2O_5 content (wt.%).

With a further increase in Nb_2O_5 content to 40–50 wt.%, free niobium oxide and additional zirconia phases, including tetragonal ZrO_2, appear in the material, accompanied by a decrease in both hardness and flexural strength. Although the resulting values remain higher than those of pure ZrO_2, they are noticeably

lower than the maximum values observed at 20–30 wt.% Nb_2O_5. The overall trend indicates a non-monotonic dependence of hardness and flexural strength on Nb_2O_5 content, with the highest mechanical properties achieved at intermediate concentrations. These findings suggest the existence of an optimal composition range within the investigated series, in which a favorable combination of phase composition and grain morphology is associated with improved mechanical performance.

Analysis of the experimental data allows us to identify several interrelated mechanisms that may contribute to the strengthening of zirconia-based composite ceramics upon the addition of niobium oxide.

First, phase transformations occurring in the $ZrO_2 - Nb_2O_5$ system during thermal annealing play an important role in determining the mechanical properties of the ceramics. When the Nb_2O_5 concentration increases to approximately 20–30 wt.%, the formation of the zirconium niobate phase $Nb_2Zr_6O_{17}$ becomes more pronounced. The presence of this phase coincides with a significant increase in hardness and flexural strength compared to the initial ZrO_2 ceramics. The distribution of $Nb_2Zr_6O_{17}$ within the ZrO_2-based microstructure may contribute to strengthening through the formation of additional interphase boundaries and changes in grain morphology. At higher Nb_2O_5 contents, unreacted Nb_2O_5 and other phase components appear in the structure, accompanied by a decrease in hardness and flexural strength compared to the optimal concentration range.

Second, the strengthening behavior may also be influenced by solid-solution effects. Partial incorporation of niobium ions into the zirconium dioxide crystal lattice could lead to local lattice distortions due to differences in ionic radii and valence states between Nb^{5+} and Zr^{4+}. Such structural distortions may modify local stress fields and defect distributions, thereby affecting the resistance of the material to deformation. This mechanism could contribute to the changes in hardness observed during the transition from undoped ZrO_2 to compositions containing low and intermediate amounts of Nb_2O_5.

Third, an additional strengthening contribution may arise from the formation of finely dispersed niobate phases, primarily $Nb_2Zr_6O_{17}$, within the ceramic microstructure. The presence of these secondary-phase inclusions and the associated interphase boundaries may restrict local deformation and influence the propagation of microcracks. The strengthening effect is expected to depend on the size, morphology, and spatial distribution of the phase inclusions. The relatively high hardness and flexural strength observed at Nb_2O_5 concentrations of approximately 20–30 wt.% may therefore be associated with a favorable combination of phase composition and microstructural characteristics.

An additional contribution to strengthening is associated with changes in the microstructure of the composites. The introduction of Nb_2O_5 affects phase formation and grain growth during thermal treatment, promoting the development of relatively fine-grained structures in certain compositions. Grain refinement increases the total area of grain and interphase boundaries, which may contribute to improved resistance to deformation and fracture. In addition, interfaces between the ZrO_2 matrix and niobate-phase inclusions may influence crack propagation by promoting crack deflection or branching. These effects provide a possible

explanation for the enhanced mechanical properties observed in compositions containing intermediate amounts of Nb_2O_5.

Finally, residual stresses may also contribute to the mechanical behavior of the ceramics. Such stresses can develop during cooling after thermal treatment because of differences in thermal expansion coefficients and elastic properties between the zirconia-based matrix and niobium-containing phases. Depending on their magnitude and distribution, residual stresses may influence the initiation and propagation of microcracks and, consequently, the flexural strength and fracture resistance of the ceramics.

Thus, the strengthening behavior of $ZrO_2 - Nb_2O_5$ composite ceramics can be interpreted in terms of the combined influence of phase transformations, possible solid-solution effects, secondary-phase formation, grain refinement, and residual stresses. The highest hardness and flexural strength are observed at intermediate Nb_2O_5 concentrations of approximately 20–30 wt.%, where a favorable combination of phase composition and grain morphology is achieved. These results demonstrate the importance of controlling the initial component ratios to optimize the structural and mechanical properties of zirconia-based composite ceramics.

4. Conclusion

In this study, a comprehensive investigation was carried out on the influence of niobium oxide content on the phase composition, microstructural evolution, and mechanical properties of $ZrO_2 - Nb_2O_5$ composite ceramics obtained by mechanochemical solid-phase synthesis followed by high-temperature annealing at $1500\,^{\circ}C$. Variation of the Nb_2O_5 concentration allowed the identification of relationships between phase formation, grain morphology, and the mechanical response of zirconia-based ceramics.

It was shown that increasing the Nb_2O_5 content leads to a gradual transformation of the phase composition from predominantly monoclinic zirconium dioxide to the formation of the zirconium niobate phase $Nb_2Zr_6O_{17}$. At Nb_2O_5 concentrations of 20–30 wt.%, the $Nb_2Zr_6O_{17}$ phase becomes dominant, with a small residual contribution from monoclinic ZrO_2 observed at 20 wt.%. At 30 wt.% Nb_2O_5, the phase composition is predominantly represented by $Nb_2Zr_6O_{17}$. Further increases in Nb_2O_5 content result in the appearance of unreacted niobium oxide and additional zirconia phases, including tetragonal ZrO_2. These results indicate that the phase composition of $ZrO_2 - Nb_2O_5$ ceramics can be controlled by varying the initial component ratios under fixed synthesis conditions.

It was found that the evolution of the phase composition is closely associated with changes in the microstructural characteristics of the ceramics. The formation of the $Nb_2Zr_6O_{17}$ phase is accompanied by the development of relatively fine-grained structures, suggesting that the presence of finely dispersed niobate phases may contribute to the suppression of grain growth and the formation of a more uniform microstructure. At higher Nb_2O_5 concentrations, the grain morphology changes, resulting in the formation of elongated and plate-like grains, as well

as the coarsening of grains associated with the appearance of secondary phase inclusions.

The analysis of mechanical properties revealed a non-monotonic dependence of hardness and flexural strength on the Nb_2O_5 concentration. The highest mechanical properties were observed at intermediate Nb_2O_5 concentrations of 20–30 wt.%, with the maximum values obtained for the composition containing 30 wt.% Nb_2O_5. This improvement correlates with the formation of a predominantly $Nb_2Zr_6O_{17}$ phase composition and a relatively fine-grained microstructure. Further increases in Nb_2O_5 content lead to a reduction in hardness and flexural strength, which may be associated with changes in phase composition and grain coarsening.

The observed strengthening behavior of $ZrO_2 - Nb_2O_5$ composite ceramics may be explained by the combined influence of several structural and phase-related factors, including the formation of the $Nb_2Zr_6O_{17}$ phase, possible solid-solution effects associated with niobium incorporation into the zirconia lattice, dispersion-related strengthening, grain refinement, and the development of residual stresses. The favorable combination of these factors at intermediate Nb_2O_5 concentrations may contribute to the observed improvement in mechanical properties.

The scientific novelty of this work lies in the systematic investigation of the relationship between Nb_2O_5 concentration, the formation of the $Nb_2Zr_6O_{17}$ phase, microstructural evolution, and changes in the mechanical properties of zirconia-based composite ceramics under fixed mechanochemical synthesis and high-temperature treatment conditions. The results demonstrate the existence of an optimal composition range within the investigated series, where the most favorable combination of phase composition, grain morphology, and mechanical properties is achieved.

The obtained results are of practical interest for the development of zirconia-based composite ceramics with improved mechanical properties, potentially suitable for structural and functional applications involving elevated temperatures and mechanical loads. The identified relationships between composition, phase formation, and mechanical behavior provide a basis for the targeted optimization of $ZrO_2 - Nb_2O_5$ ceramic materials. However, the radiation resistance and long-term thermal stability of the investigated ceramics were not evaluated in the present study; therefore, their applicability as inert matrices for nuclear applications requires further experimental verification.

Future studies should focus on evaluating the thermal cycling stability and radiation resistance of the obtained ceramics, as well as investigating the effects of synthesis parameters and Nb_2O_5 concentration on their structural and mechanical properties.

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