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MECHANICAL PROPERTIES OF ZrO_2-TOUGHENED Al_2O_3 CERAMICS: EFFECT OF ZrO_2 CONTENT

MEHANSKE LASTNOSTI KERAMIKE NA OSNOVI Al_2O_3 OJAČANE S ZrO_2: VPLIV VSEBNOSTI ZrO_2

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Alumina ceramics are important high-temperature materials with exceptional properties; however, their applications are limited by their low flexural strength and brittle nature. Adding a secondary phase effectively improves the toughness of alumina without compromising its hardness. In this study, as a cost-effective solution for the production of high-performance alumina composites, zirconia-toughened alumina (ZTA) composites with different ZrO_2 contents (3–20 %) were prepared using the vacuum hot-pressing sintering of micron-scale ZrO_2 and Al_2O_3 powders. Furthermore, the influence of the ZrO_2 content on the mechanical properties and fracture morphology of the composites was investigated. The density, hardness, fracture toughness and flexural strength of the zirconia/alumina composite ceramic increased with an increase in the ZrO_2 content from 3 % to 15 %. The ceramic exhibited the best comprehensive mechanical properties –a density of 98.15 %, a hardness of 887.3 HV and a bending strength of 326.28 MPa – at a ZrO_2 content of 15 %. This was attributed to the uniform distribution of the secondary phase at the fracture surface and toughening mechanisms of phase transformation and crack deflection. At ZrO_2 contents of ≥18 %, the agglomeration of the ZrO_2 particles caused stress concentration and other phenomena, which weakened the toughening mechanism. This study provided a feasible approach for the industrial-scale production and application of high-performance ZTA multiphase ceramics.

Keywords: vacuum hot-press sintering, zirconia-toughened alumina multiphase ceramics, toughening mechanism, mechanical properties

Keramika na osnovi aluminijevega oksida (Al_2O_3) je pomemben visokotemperaturni material z izjemnimi lastnostmi; vendar je njegova uporaba omejena zaradi nizke upogibne trdnosti in krhkosti. Dodajanje sekundarne faze lahko učinkovito izboljša žilavost aluminijevega oksida, ne da bi se pri tem ogrozilo njegovo trdoto. V tem članku avtorji opisujejo študijo stroškovno učinkovite rešitve za proizvodnjo visokozmogljivih kompozitov iz aluminijevega oksida z dodatkom cirkonijevega oksida (ZTA; angl.: zirconia-toughened alumina). Avtorji so Al_2O_3 dodajali različno vsebnost ZrO_2 (od 3 % do 20 %) in kompozite zgoščevali s postopkom vakuumskega vročega stiskanja in istočasnega sintranja mikronskih prahov ZrO_2 in Al_2O_3. Po zgoščevanju so avtorji ugotavljali vpliv vsebnosti ZrO_2 na mehanske lastnosti in morfologijo loma kompozitov. Gostota, trdota, lomna žilavost in upogibna trdnost kompozitne keramike iz Al_2O_3 in ZrO_2 so se povečevale s povečevanjem vsebnosti ZrO_2 s 3 % na 15 %. Kompozitna keramika je pokazala najboljše fizikalne in mehanske lastnosti (gostoto: 98,15 %, trdoto: 887,3 HV in upogibno trdnost: 326,28 MPa) pri 15 %-ni vsebnosti ZrO_2. To so avtorji pripisali enakomerni porazdelitvi sekundarne faze na površini loma ter mehanizmom utrjevanja fazne transformacije in nastalim oviram za napredovanje rapok. Pri vsebnosti ZrO_2 nad 18 % je aglomeracija delcev ZrO_2 že povzročila koncentracije napetosti in druge pojave, ki so oslabili mehanizme utrjevanja. S to študijo so avtorji omogočili razvoj novega materiala za industrijsko proizvodnjo in uporabo visokozmogljive večfazne ZTA keramike.

Ključne besede: sintranje z vakuumskim vročim stiskanjem, večfazna keramika na osnovi aluminijevega oksida, utrjevanje s cirkonijem oksidom, mehanizem utrjevanja, mehanske lastnosti

1 INTRODUCTION

Alumina (Al_2O_3) ceramics are important in the field of materials science because of their high hardness, high-temperature resistance, corrosion resistance, wear resistance and low cost.[1–6] However, their low flexural strength and fracture toughness are the factors limiting their broad applications.[7–11] Currently, research on toughening alumina has primarily focused on three approaches: introducing high-strength ceramic whiskers or fibres to enhance toughness;[12–14] incorporating nano- or micro-scale particles to improve toughness via pinning effects and crack deflection[15,16] and achieving synergistic toughening by combining multiple mechanisms, such as phase transformation, whisker reinforcement and particle toughening.[17] In this study, zirconia (ZrO_2) particles are incorporated into alumina.[18,19] The transformation of the tetragonal phase (t-ZrO_2) to the monoclinic phase (m-ZrO_2) induces volume expansion and shear strain, which effectively absorbs the energy released during crack propagation, thereby enhancing the material's toughness. Zirconia (ZrO_2) is an important ceramic with exceptional properties, including high toughness, high wear resistance and good thermal stability.[20–22] To over-

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come the limitations of alumina and expand its application scope, toughened alumina composite ceramics have been developed by adding some amounts of zirconia, SiC, Si_3N_4 and TiC powders/fibres. Through the synergistic effect of different toughening mechanisms, including stress-induced phase transformation, microcracks and surface strengthening, the fracture toughness of the composites is improved while retaining the desirable mechanical properties of alumina. This improves the service life and reliability of alumina ceramic materials.[23–26] Cui et al.[27] examined the effect of the nano-ZrO_2 content on the microstructure and mechanical properties of nano-ZrO_2-toughened Al_2O_3 composite ceramics. However, the high cost of nano-scale raw materials, combined with the lack of standardisation in process parameters such as the sintering temperature and second-phase ZrO_2 content, limits the cost-effectiveness of equipment and renders large-scale batch production impractical. In this context, this study explored the use of micron-scale ZrO_2 particles, simple equipment (vacuum hot-press sintering furnace) and optimised processes (ball milling duration and sintering pressure) to reduce production costs while maintaining performance, thereby offering a practical solution for the industrial production and application of high-performance zirconia-toughened alumina (ZTA) multiphase ceramics.

To this end, ZTA composite ceramics with different mass fractions of ZrO_2 (3–20 %) were prepared to investigate the effect of varying mass fractions on the mechanical properties, such as the density, hardness, and flexural strength, of the ceramics. Additionally, the toughening mechanism of their fracture morphology was analysed.

2 EXPERIMENTAL DETAILS

2.1 Materials and methods

Zirconia and alumina powders with a particle size of 75 μm and purity of 99.99 % were used as the raw materials. The mass fractions of different samples are listed in **Table 1**. The powders (according to the proportions in **Table 1**) were mixed in a planetary ball mill (XQM-4-KL, Dandong Tongda) for 5 h and then placed in a dryer (101-0A, Beijing Kewei Yongxing Instrument) at 80 °C for 3 h. The mixed powders were sintered via vacuum hot-press sintering (ZR50B-8T, China) at 1300 °C and 20 MPa to obtain ZTA composite ceramic materials.

Table 1: Mass fractions of the zirconia-toughened alumina composite samples

ZrO_2		Al_2O_3		Total mass, g
Mass fraction, %	Mass, g	Mass fraction, %	Mass, g	
3	2.4	97	77.6	80.0
9	7.2	93	72.8	80.0
15	12.0	85	68.0	80.0
20	16.0	80	64.0	80.0

2.2 Performance characterizations and testings

The structure of the ZTA composite ceramic material was characterised by X-ray diffraction (XRD; TD-3500, Dandong Tongda). The density of the composite was measured based on Archimedes' principle using a direct-reading electronic densitometer (DH-300, Shanghai Taiming), and relative density was calculated as the ratio of the measured bulk density to the theoretical density predicted by the rule of mixtures. The Vickers hardness was evaluated using a digital microhardness tester (HXD-1000, LaiZhou Huayin), and the flexural strength and fracture toughness were measured using a universal testing machine (WDW-2.0, Shen Zhen Wance). A JSM-6510LV scanning electron microscope (JEOL) was used to observe the micromorphology of the fracture surface. In this study, at least five replicate specimens were fabricated for each composition, and mechanical and physical properties were reported as mean ± standard deviation.

3 RESULTS AND DISCUSSION

3.1 Structure

Figure 1 shows the XRD patterns of the ZTA composites with different ZrO_2 contents. The peaks corresponding to α-Al_2O_3 (2 = 57°) and t-ZrO_2 (2θ = 35° and 50°) are observed in the XRD patterns of the composites; however, no peak attributed to the monoclinic phase of ZrO_2 is detected. The intensity of the ZrO_2 peak gradually increases with an increasing ZrO_2 content. Furthermore, all composites exhibit sharp and well-defined diffraction peaks with narrow half-widths and clear profiles, indicating high crystallinity. The test results confirm that the prepared samples exhibit typical crystal structure characteristics, with well-developed alumina grains.

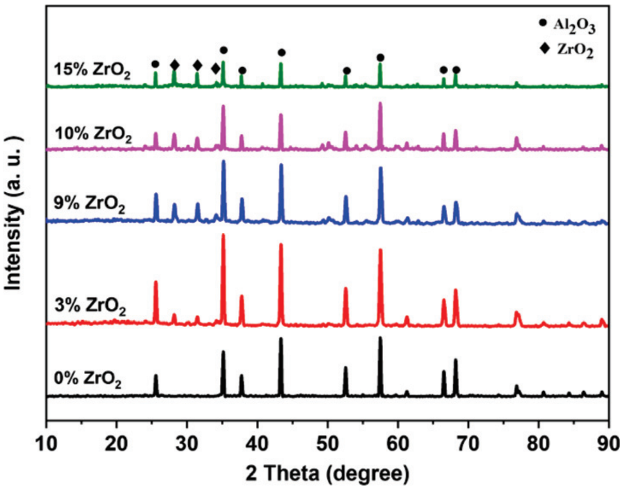

Figure 1: X-ray diffraction patterns of the zirconia-toughened alumina composites with different ZrO_2 contents

3.2 Density

Table 2 lists the theoretical, actual, and relative densities of the ZrO_2-toughened Al_2O_3 multiphase ceramics with different ZrO_2 contents, and **Figure 2** shows a density histogram. The density of the multiphase ceramics increases with an increasing ZrO_2 content, and the ratio of the actual to the theoretical density first increases and then decreases, reaching a maximum value of 98.15 % at 15 % ZrO_2. At low ZrO_2 contents, the density continues to increase because of an increase in the sintering driving force of the material caused by the ZrO_2 particles. With an increase in the ZrO_2 content, the contact area between the alumina matrix and secondary phase increases. Owing to the different valence electrons in zirconium and aluminium ions, vacancies are easily formed in the matrix and the lattice constant changes, which is favourable for increasing the density of the ZTA multiphase ceramics. However, at high ZrO_2 contents, the excess ZrO_2 agglomerates, weakening the pinning effect. The phase transformation of the ZrO_2 agglomerates causes the accumulation of microcracks, resulting in the formation of crystal defects and cracking of the crystal interface, thereby reducing the density of the multiphase ceramic composites.

Table 2: Density analysis of the zirconia-toughened alumina composites

Sample	0 % ZrO_2	3 % ZrO_2	9 % ZrO_2	15 % ZrO_2	20 % ZrO_2
Actual density (g/cm^3)	3.31	3.44	3.61	3.76	3.78
Theoretical density (g/cm^3)	3.60	3.64	3.73	3.83	3.92
Relative density (%)	91.89	94.45	96.86	98.15	96.30

3.3 Microhardness

Figure 3 shows the hardness values of the ZTA multiphase ceramics with different ZrO_2 contents. The hardness of pure alumina is the lowest (5.72 GPa), and that of the ZTA composite ceramics first increases, reaching a maximum value of 8.75 GPa at 15 % ZrO_2, and then decreases with an increasing ZrO_2 content. The dispersion of the ZrO_2 particles in the alumina matrix hinders the movement of dislocations and strengthens the second phase, thereby increasing the composite hardness. With a further increase in the ZrO_2 content (20 %), the excess ZrO_2 particles cause lattice defects in the matrix, which act as stress concentrators, thereby reducing the hardness of the multiphase ceramics.

3.4 Fracture toughness

Figure 4 shows the fracture toughness of the composite ceramics with different ZrO_2 contents. The fracture toughness of the single-phase Al_2O_3 ceramics is 4.3 $MPa{\cdot}m^{1/2}$. With the ZrO_2 addition, the fracture toughness of the Al_2O_3/ZrO_2 composite first increases and then decreases; however, it is always higher than that of pure Al_2O_3 ceramics. This strengthening is due to the synergistic effects of the stress-induced and microcrack toughening mechanisms. When the ZrO_2 content is 9 %, the fracture toughness of the composite ceramics is the highest (4.91 $MPa{\cdot}m^{1/2}$). This is because the tetragonal zirconia particles undergo martensitic transformation under the action of the stress field at the crack tip.[28] During phase transformation, volume expansion offsets a part of the stress, thereby reducing the fracture energy.[29] On increasing the ZrO_2 content, the lattice defects increase significantly and the toughening effect gradually weakens.

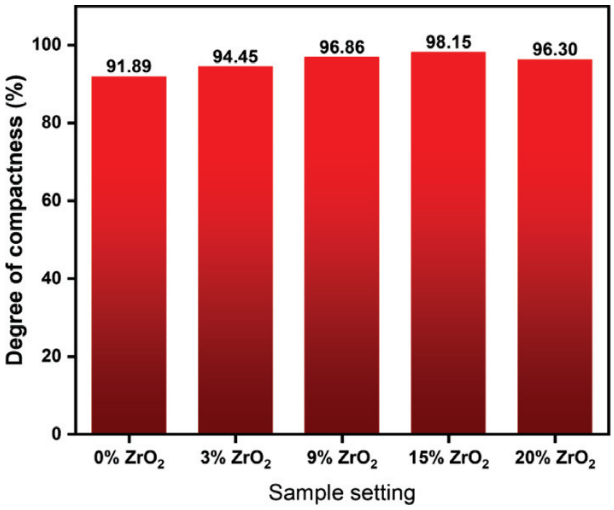

Figure 2: Bar graph of the densities of the zirconia-toughened alumina composites

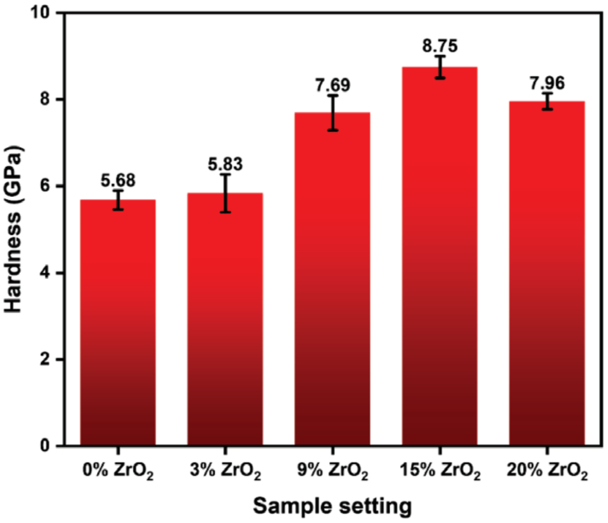

Figure 3: Hardness of the zirconia-toughened alumina composite ceramics with different ZrO_2 contents

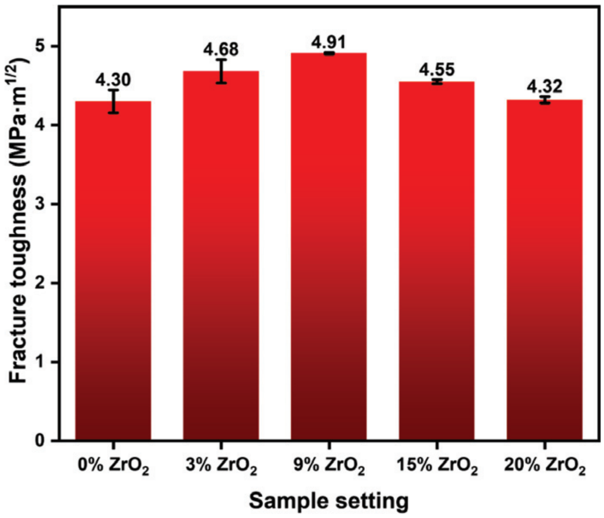

Figure 4: Fracture toughness of the zirconia-toughened alumina composite ceramics with different zirconia contents

3.5 Bending strength

Figure 5 shows the bending strengths of the ZTA multiphase ceramics with different ZrO_2 contents. The bending strength of the ZTA composite ceramics first increases and then decreases with an increasing ZrO_2 content. The maximum bending strength of 326.28 MPa is achieved when the ZrO_2 content is 15 %. At ZrO_2 contents of < 15 %, alumina has a stabilising effect on the metastable tetragonal zirconia crystals. The application of an external stress promotes the transformation of the tetragonal zirconia crystals into monoclinic zirconia. This phase transformation process is accompanied by a volume change of 5–8 %. This volume change produced by the phase transformation inevitably causes microcracks inside the ceramic sample, thereby dispersing and reducing the energy of the main crack. This reduces the stress concentration and improves the bending strength of the ceramic material via microcrack toughening. When the ZrO_2 content is 20 %, the bending strength decreases because of the increase in the secondary phase content, attributed to agglomeration at high ZrO_2 contents. In the presence of an external stress, more microcracks are formed around the agglomerates; the accumulation of these microcracks causes matrix cracking and decreases the bending strength.

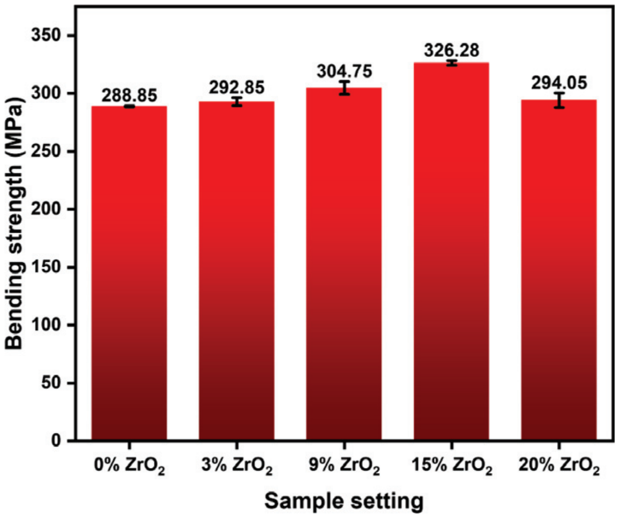

Figure 5: Bending strength of the zirconia-toughened alumina composite ceramics with different zirconia contents

3.6 Fracture morphology

Figure 6 shows the fracture morphologies of the ZTA multiphase ceramics with different zirconia contents. The fracture observed in the ZTA multiphase ceramic with 15 % ZrO_2 content is relatively flat and shows typical transgranular fracture characteristics. Several fine dimples are observed on the fracture surface, indicating that the material undergoes significant plastic deformation during the fracture process. For pure alumina, the fracture surface exhibits predominantly intergranular fracture characteristics and demonstrates significantly higher brittleness. At ZrO_2 contents of 3 % and 9 %, the zirconia particles are relatively sparse, and the cracks propagate mainly along the intergranular or transgranular alumina grains. In this case, the dimples are evenly distributed and plastic deformation is more significant. As the ZrO_2 content is increased to 20 %, particle agglomeration becomes prominent, and the crack propagation path becomes more tortuous. This indicates that ZrO_2 particle agglomeration significantly hinders the crack propagation, causing stress concentration and other phenomena, thereby weakening the toughening mechanism. When the ZrO_2 content is 15 %, the microcracks in the material are evenly distributed, effectively hindering crack propagation and toughening the material. Thus, 15 % ZrO_2 content is the optimum amount for enhancing the comprehensive mechanical properties of a ZTA composite material.

In this study, the resulting balance of high hardness (8.75 GPa) and markedly improved fracture toughness ($K_IC \approx 5$ MPa·$m^{1/2}$) was achieved without compromising process simplicity or cost-effectiveness – underscoring the material's strong potential for real-world engineering applications. This synergistic property profile makes it especially promising for cost-sensitive, wear- and corrosion-prone structural components – including valve seats, slurry pump liners, and cutting tool substrates – where reliability, manufacturability, and lifecycle economics are paramount. Looking ahead, targeted enhancements – such as a judicious addition of trace sintering aids or controlled nanostructuring of the ZrO_2 phase – could further elevate mechanical performance while preserving the core advantages of scalability and affordability, thereby bridging the gap toward more demanding service environments.

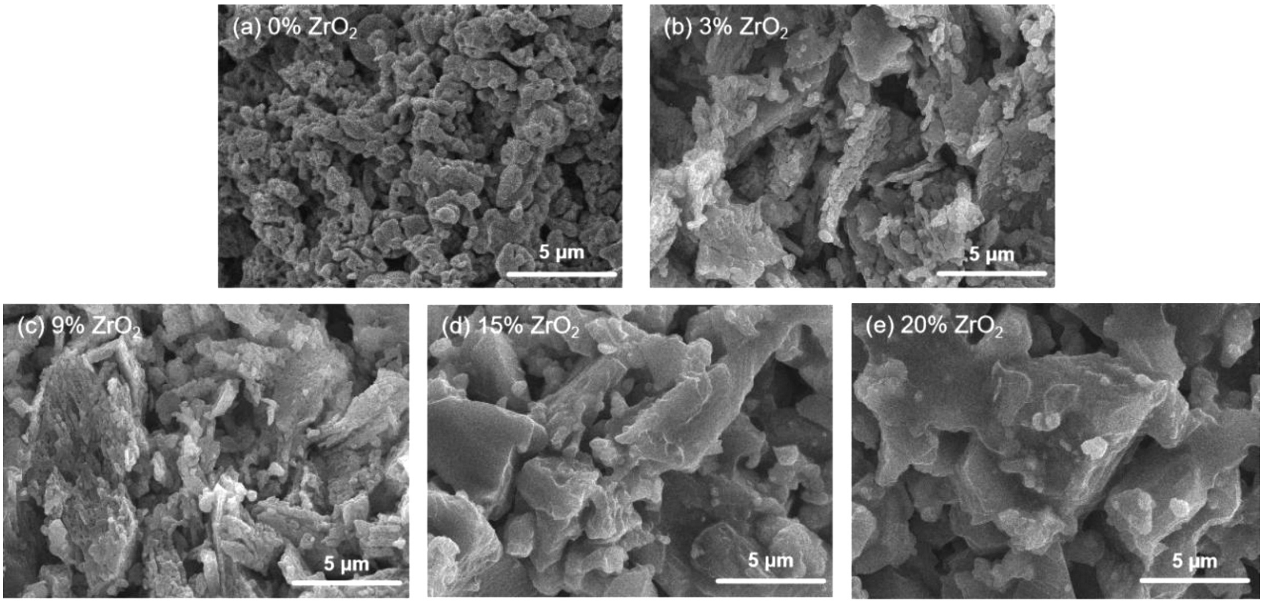

Figure 6: Scanning electron microscopy images of the fracture morphologies of the zirconia-toughened alumina composite ceramics with different ZrO_2 contents

4 CONCLUSIONS

The effects of different mass fractions of micron-scale ZrO_2 on the mechanical properties of the ZTA multiphase ceramics were investigated. The following conclusions are drawn from this study.

The zirconia/alumina multiphase ceramics with good crystallinity were successfully prepared using the vacuum hot-press sintering method.

The densities of the ZTA multiphase ceramics first increased and then decreased with an increase in the ZrO_2 content. The highest ceramic density of 98.15 % was observed at a ZrO_2 content of 15 %.

The Vickers hardness and flexural strength of the ZTA composites were significantly higher than those of pure Al_2O_3 ceramics, reaching maximum values of 8.75 GPa and 326.28 MPa, respectively.

The fracture toughness of the composite ceramics reached a maximum of 4.91 $MPa \cdot m^{1/2}$ when the mass fraction of ZrO_2 was 9 %. This is mainly attributed to the combined influence of the t→m phase transformation and microcrack toughening mechanisms. However, the toughening effect gradually weakened at higher ZrO_2 contents owing to the significant increase in the lattice defects.

The main toughening mechanisms of the ZTA composite ceramics are the phase-transformation-induced volume change and microcrack toughening.

When the mass fraction of the ZrO_2 second-phase added was 15 %, the comprehensive mechanical properties of the ZTA multiphase materials prepared from micron-scale raw materials reached their optimal values, and the phase transformation toughening and microcrack toughening effects were also maximised. This research result provides a solid theoretical foundation and valuable technical reserve for the industrial application of ZTA multiphase ceramic materials.

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5 REFERENCES

[1] D. Z. Liu, J. F. Hu, G. Y. Zhang, G. Wang, K. X. Gui, M. Wang, W. B. Han, D. Y. Zhang, Effect of synthesizing temperature of alumina powder with rose-like structure on the microstructure and mechanical property of alumina ceramic, J. Mater. Res. Technol., 28 (**2024**), 1907–1914, doi:10.1016/j.jmrt.2023.12.104

[2] Y. F. Jiang, R. Y. Xu, R. Jiang, F. Yang, H. F. Liu, X. Sun, High-temperature mechanical properties and thermal shock resistance of an alumina-fiber-reinforced alumina ceramic matrix composite, Ceram. Int., 51 (**2025**) 4, 5459–5469, doi:10.1016/j.ceramint.2024.11.502

[3] X. F. Zhai, J. J. Chen, Y. R. Wang, R. Y. Su, X. Gao, X. Q. Zhang, H. Jin, R. J. He, Fabrication of Al_2O_3 ceramic cores with high porosity and high strength by vat photopolymerization 3D printing and sacrificial templating, Ceram. Int., 49 (**2023**) 19, 32096–32103, doi:10.1016/j.ceramint.2023.07.177

[4] S. Tang, L. Fu, H. Gu, A. Huang, S. Yang, R. Lv, Improved mechanical properties of alumina ceramics using plasma-assisted milling technique, Materials, 16 (**2023**) 3, 1128, doi:10.3390/ma16031128

[5] A. Ikesue, Y. L. Aung, Anisotropic alumina ceramics with isotropic optical properties, J. Adv. Ceram., 12 (**2023**) 1, 72–81, doi:10.26599/JAC.2023.9220667

[6] M. T. Dang, X. Z. Yue, G. H. Zhou, S. Hu, Influence of resin composition on rheology and polymerization kinetics of alumina ceramic suspensions for digital light processing (DLP) additive manufacturing, Ceram. Int., 49 (**2023**) 12, 20456–20464, doi:10.1016/j.ceramint.2023.03.175

[7] Z. Wu, Q. Gao, Q. Wang, Y. Wang, Z. Zhang, Y. Zhang, Effect of hollow beads content in aluminum oxide hollow beads reinforced epoxy composites on mechanical and energy absorption properties of

the composites, Materialwissenschaft und Werkstofftechnik, 55 (**2024**) 12, 1640–1651, doi:10.1002/mawe.202400163

[8] J. Keyte, K. Pancholi, J. Njuguna, Recent developments in graphene oxide/epoxy carbon fiber-reinforced composites, Front. Mater., 6 (**2019**) 224, doi:10.3389/fmats.2019.00224

[9] E. Altuncu, S. Irıc, Evaluation of fracture toughness and crack propagation of aluminum alloy 7075–T651 with chromium oxide coating, Acta Phys. Pol. A, 135 (**2019**) 5, 877–880, doi:10.12693/APhysPolA.135.877

[10] C. Kaykılarlı, H. A. Yeprem, D. Uzunsoy, Mechanical and tribological characterization of graphene nanoplatelets/Al_2O_3 reinforced epoxy hybrid composites, Fullerenes Nanotubes Carbon Nanostruct., 31 (**2023**) 5, 435–447, doi:10.1080/1536383X.2023.2173740

[11] J. Wang, D. Lu, W. Xuan, Y. Ji, R. Chen, S. Li, W. Li, W. Chen, S. Tang, G. Zheng, F. Long, Boron nitride microribbons strengthened and toughened alumina composite ceramics with excellent mechanical, dielectric, and thermal conductivity properties, J. Adv. Ceram., 13 (**2024**) 4, 496–506, doi:10.26599/JAC.2024.9220872

[12] Y. Tamura, B. M. Moshtaghioun, D. Gomez-Garcia, A. D. Rodriguez, Spark plasma sintering of fine-grained alumina ceramics reinforced with alumina whiskers, Ceram. Int., 43 (**2017**) 1, 658–663, doi:10.1016/j.ceramint.2016.09.210

[13] Y. Fang, N. Chen, G. Du, M. Zhang, X. Zhao, J. Wu, Effect of Y_2O_3-stabilized ZrO_2 whiskers on the microstructure, mechanical and wear resistance properties of Al_2O_3 based ceramic composites, Ceram. Int., 45 (**2019**) 13, 16504–16511, doi:10.1016/j.ceramint.2019.05.184

[14] L. D'Andrea, T. Yang, M. Dao, P. Vena, Nature-inspired orientation-dependent toughening mechanism for TPMS ceramic architectures, MRS Bull., 50 (**2025**) 4, 374–383, doi:10.1557/s43577-024-00831-5

[15] H. Xing, B. Zou, X. Wang, Y. Hu, C. Huang, K. Xue, Fabrication and characterization of SiC whiskers toughened Al_2O_3 paste for stereolithography 3D printing applications, J. Alloys Compd., 828 (**2020**), 154347, doi:10.1016/j.jallcom.2020.154347

[16] U. Betke, M. Scheunemann, M. Scheffler, Refitting of zirconia toughening into open-cellular alumina foams by infiltration with zirconyl nitrate, Materials, 12 (**2019**) 12, 1886, doi:10.3390/ma12121886

[17] S. Y. Zhang, Q. S. Ma, L. M. Yu, J. W. Zhang, H. J. Li, Q. Z. Qiu, Effect of pre-aging on microstructure and properties of cold-rolled alumina-forming austenitic steel, Acta Metall. Sin., 61 (**2024**) 1, 177–190, doi:10.11900/0412.1961.2024.00236

[18] W. J. Ma, X. Lai, W. T. Yao, Recent advances in synthesis and electrochemical energy storage applications of porous carbon materials, Adv. Sustain. Syst., 8 (**2024**) 12, 2400312, doi:10.1002/adsu.202400312

[19] O. S. Taskin, I. I. A. Yayla, N. Yuca, Interpenetrating and cross-linking effects of commercial and biopolymer binders on silicon anode performance in lithium-ion batteries, Mater. Chem. Phys., 339 (**2025**), 130723, doi:10.1016/j.matchemphys.2025.130723

[20] Y. P. Zhao, Y. Hu, Y. Yang, Y. W. Wang, X. Y. Wang, W. Li, Y. X. Shao, W. W. Sun, H. J. Zhao, Y. D. Ma, Microstructure and properties of plasma sprayed NbC-Al_2O_3 composite coatings, Ceram. Int., 50 (**2024**) 24, 54955–54965, doi:10.1016/j.ceramint.2024.10.344

[21] Z. Y. Chen, H. X. Yan, Q. Lyu, S. Niu, C. Tang, Ternary hybrid nanoparticles of reduced graphene oxide/graphene-like MoS_2/zirconia as lubricant additives for bismaleimide composites with improved mechanical and tribological properties, Compos. Part A Appl. Sci. Manuf., 101 (**2017**), 98–107, doi:10.1016/j.compositesa.2017.06.008

[22] Y. Y. Che, Z. L. Sun, R. R. Zhan, S. Z. Wang, S. F. Zhou, J. Huang, Effects of graphene oxide sheets-zirconia spheres nanohybrids on mechanical, thermal and tribological performances of epoxy composites, Ceram. Int., 44 (**2018**) 15, 18067–18077, doi:10.1016/j.ceramint.2018.07.010

[23] J. D. Han, B. Göksel, S. Mohajernia, M. S. Killian, J. Vleugels, A. Braem, S. Castagne, Ultrashort pulsed laser ablation of zirconia toughened alumina: Material removal mechanism and surface characteristics, Appl. Surf. Sci., 615 (**2023**), 156407, doi:10.1016/j.apsusc.2023.156407

[24] K. Ravikumar, D. Sarkar, B. Basu, ZrO_2-toughened Al_2O_3 composites with better fracture and wear resistance properties, J. Biomater. Appl., 32 (**2018**) 9, 1174–1186, doi:10.1177/0885328217750820

[25] K. L. Meena, S. Mozammil, Influence of MgO/MWCNTs incorporation on the physical, mechanical characteristics, and microstructural response of ZTA composite, J. Alloys Compd., 1018 (**2025**), 179095, doi:10.1016/j.jallcom.2025.179095

[26] R. Vemoori, S. Bejugama, A. K. Khanra, Fabrication and characterization of alumina and zirconia-toughened alumina porous structures, Ceram. Int., 49 (**2023**) 13, 21708–21715, doi:10.1016/j.ceramint.2023.03.310

[27] E. Cui, J. Zhao, X. Wang, Effects of nano-ZrO_2 content on microstructure and mechanical properties of GNPs/nano-ZrO_2 reinforced Al_2O_3/Ti (C, N) composite ceramics, J. Eur. Ceram. Soc., 40 (**2020**) 4, 1532–153, doi:10.1016/j.jeurceramsoc.2019.11.039

[28] X. Y. Zhu, Y. J. Pan, H. Zhang, D. Q. Ke, Effect of Ni content on the microstructure and properties of WCoB-TiC cermets, Int. J. Refract. Met. Hard Mater., 117 (**2023**) 9, doi:10.1016/j.ijrmhm.2023.106381

[29] Y. Abe, D. Fukui, R. Nagashima, N. Nakada, K. Shibanuma, Fracture mechanics analysis of anisotropic cleavage fracture caused by transformation-induced microscopic internal stresses in lath martensite, Mater. Charact., 223 (**2025**), 114905, doi:10.1016/j.matchar.2025.114905