

Ceramic and Glass Material Coatings: Advances in Raw Materials, Processing, Functional Performance, and Sustainability

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1. Introduction

Ceramic and glass material coatings have become essential components in numerous industrial sectors, including aerospace, energy production, transportation, construction, electronics, and advanced manufacturing. Their unique combination of thermal stability, chemical resistance, mechanical durability, optical functionality, and environmental compatibility has enabled their widespread use in applications ranging from thermal barrier systems and protective coatings to energy-efficient building materials and multifunctional engineered surfaces [1–4].

Recent decades have witnessed significant progress in ceramic and glass coating technologies, driven by advances in materials science, surface engineering, computational modeling, and characterization techniques. Simultaneously, global concerns regarding resource depletion, carbon emissions, and sustainable manufacturing have encouraged the development of coatings based on recycled materials, waste valorization strategies, and circular economy principles [5–7]. These developments have expanded the traditional role of ceramic and glass coatings beyond protection and durability, transforming them into active functional systems capable of contributing to energy efficiency, environmental sustainability, and enhanced operational performance.

Despite these advances, several scientific and technological challenges remain unresolved. The long-term durability of coatings under extreme environments, the incorporation of secondary raw materials without compromising performance, the development of multifunctional coating systems, and the integration of predictive computational approaches continue to represent major research priorities. Addressing these challenges requires interdisciplinary collaboration among materials scientists, chemists, mineralogists, physicists, and engineers.

This Special Issue, Ceramic and Glass Material Coatings, was conceived to contribute to these ongoing efforts by bringing together research addressing raw materials, processing technologies, functional performance, thermal stability, sustainability, and analytical methodologies. The nine papers published in this collection provide valuable insights into several of the most relevant challenges currently facing the field.

2. Current Challenges and Knowledge Gaps in Ceramic and Glass Material Coatings

2.1. Sustainability and Circular Economy

The transition toward sustainable manufacturing represents one of the most significant challenges facing ceramic and glass industries. Although recycled materials and industrial by-products offer considerable environmental benefits, their incorporation into ceramic



Received: 14 July 2026

Accepted: 16 July 2026

Published: 20 July 2026

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systems often introduces variability in composition, impurities, and processing behavior that can affect final performance [5,8].

Further research is needed to better understand the relationships between secondary raw material characteristics, processing parameters, microstructural evolution, and long-term durability. In addition, comprehensive life-cycle assessments and resource-efficiency analyses remain necessary to quantify the true environmental benefits of emerging recycling strategies.

2.2. High-Temperature Performance and Environmental Degradation

Thermal barrier coatings (TBCs) remain among the most technologically important ceramic coating systems due to their critical role in gas turbines, aero-engines, and advanced energy systems [2,9]. However, increasing operating temperatures continue to expose limitations associated with phase instability, thermomechanical stresses, oxidation processes, and degradation induced by calcium–magnesium–aluminum–silicate (CMAS) deposits [10].

While significant advances have been achieved in understanding degradation mechanisms, important knowledge gaps persist regarding long-term performance prediction, environmental interactions, and the development of next-generation ceramic compositions capable of maintaining stability under increasingly severe operating conditions.

2.3. Multifunctional and Smart Coatings

Modern industrial applications increasingly demand coatings that provide multiple functionalities simultaneously. In addition to mechanical protection, coatings are expected to deliver thermal management, optical control, self-cleaning behavior, photocatalytic activity, wear resistance, corrosion protection, and energy-saving capabilities [11].

Achieving such multifunctionality often requires precise control of composition and microstructure across multiple length scales. The design of coatings capable of maintaining several functional properties under real service conditions remains a major scientific challenge.

2.4. Characterization and Digital Materials Design

Advanced characterization methods have become indispensable for understanding complex ceramic systems. Simultaneously, computational materials science, artificial intelligence, and machine learning are emerging as powerful tools for accelerating materials discovery and optimization [12,13].

Nevertheless, reliable experimental datasets and standardized characterization methodologies remain essential prerequisites for the successful implementation of data-driven approaches. The integration of experimental characterization with predictive modeling represents one of the most promising directions for future ceramic materials research.

3. Contributions of This Special Issue

The papers published in this Special Issue contribute to several of the challenges identified above and collectively illustrate the diversity of current research in ceramic and glass material coatings.

Within the context of sustainability and resource efficiency, studies addressing coal gangue valorization and recycled glass utilization demonstrate the growing interest in circular economy approaches for ceramic production [14,15]. These contributions show how waste-derived materials can be transformed into valuable resources through appropriate processing strategies while maintaining satisfactory performance characteristics.

A significant portion of this Special Issue is devoted to thermal barrier coating systems and high-temperature ceramic materials [16]. These studies investigate topics including

novel ceramic compositions, phase stability, thermomechanical behavior, crack propagation, and resistance to aggressive CMAS environments. Together, they provide valuable insights into the mechanisms governing coating durability and offer potential pathways toward the development of more robust high-temperature protective systems.

This Special Issue also highlights advances in functional surface engineering through contributions focused on reflective thermal insulation coatings and low-friction tribological coatings [17,18]. These studies demonstrate how microstructural control and process optimization can be employed to tailor surface properties and enhance functional performance for specific applications.

Finally, advances in analytical methodologies are represented through the development of a semi-quantitative ATR-FTIR approach for mineralogical characterization of ceramic coatings and raw materials [10]. Such methodologies contribute to improving materials characterization capabilities and support more efficient process control and quality assurance procedures.

Collectively, these contributions illustrate the increasingly interdisciplinary nature of ceramic and glass coating research, where experimental studies, computational approaches, process engineering, and advanced characterization techniques converge to address complex technological challenges.

4. Future Research Directions

The papers included in this Special Issue, together with broader developments in the field, suggest several promising directions for future research.

4.1. Circular Manufacturing and Sustainable Raw Materials

Future ceramic industries will likely depend increasingly on secondary resources, industrial by-products, and recycled feedstocks. Research efforts should focus on improving beneficiation technologies, reducing variability in waste-derived materials, and establishing standardized methodologies for evaluating environmental performance and resource efficiency.

4.2. Next-Generation Thermal Barrier Coatings

The demand for higher operating temperatures in energy and aerospace systems will continue to drive the development of advanced ceramic compositions. Particular attention should be directed toward rare-earth zirconates, high-entropy ceramics, environmental barrier coatings, and CMAS-resistant materials. Improved understanding of degradation mechanisms under realistic service conditions will remain essential.

4.3. Multifunctional Coating Systems

Future coatings will increasingly integrate multiple functionalities within a single material system. Opportunities exist in the development of coatings capable of combining thermal insulation, optical regulation, photocatalytic activity, wear resistance, corrosion protection, and energy management. Such multifunctionality will require sophisticated microstructural engineering and advanced manufacturing strategies.

4.4. Artificial Intelligence and Digital Materials Design

Machine learning and artificial intelligence are expected to play an increasingly important role in ceramic materials research. The combination of experimental databases, computational simulations, and predictive algorithms offers opportunities to accelerate materials discovery and optimize processing conditions. The development of digital twins for coating performance prediction may become particularly relevant for industrial applications.

4.5. Advanced Characterization and In Situ Analysis

The continued development of in situ and operand characterization techniques will improve understanding of microstructural evolution during processing and service. Combining spectroscopy, microscopy, diffraction methods, and computational analysis will provide increasingly detailed insights into structure–property relationships and degradation phenomena.

5. Conclusions

The field of ceramic and glass material coatings continues to evolve rapidly in response to growing technological demands and sustainability challenges. Current research increasingly emphasizes circular economy strategies, multifunctional performance, advanced characterization, and predictive materials design. The contributions collected in this Special Issue reflect these trends and provide valuable advances in areas ranging from resource valorization and thermal barrier coatings to functional surfaces and analytical methodologies.

Although important challenges remain, particularly regarding long-term durability, sustainable manufacturing, and multifunctional performance, the studies presented in this Special Issue demonstrate the considerable progress being achieved across the field. Future advances will likely emerge from the integration of experimental research, computational modeling, advanced characterization, and data-driven design approaches, further strengthening the role of ceramic and glass coatings in addressing the technological and environmental challenges of the coming decades.

As Guest Editors, we sincerely thank all authors for their valuable contributions and the reviewers for their time, expertise, and constructive comments, which have ensured the high scientific quality of the published papers. We are also grateful to the editorial staff of *Coatings* for their continuous support throughout the preparation and management of this Special Issue.

We hope that the articles collected in this volume will serve not only as a record of current achievements but also as a source of inspiration for future investigations. The challenges facing ceramic and glass material coatings are substantial, but so too are the opportunities for innovation. Continued advances in materials design, characterization, processing, and sustainability will undoubtedly strengthen the role of ceramic and glass coatings in addressing the technological and environmental demands of the coming decades.

The contributions presented in this Special Issue clearly demonstrate that ceramic and glass material coatings remain a vibrant and rapidly evolving area of research. By linking fundamental understanding with practical applications, these studies provide valuable foundations for future developments and reinforce the importance of interdisciplinary collaboration in advancing the science and engineering of ceramic materials.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Padture, N.P.; Gell, M.; Jordan, E.H. Thermal Barrier Coatings for Gas-Turbine Engine Applications. *Science* **2002**, *296*, 280–284. [[CrossRef](#)]
2. Clarke, D.R.; Levi, C.G. Materials Design for the Next Generation Thermal Barrier Coatings. *Annu. Rev. Mater. Res.* **2003**, *33*, 383–417. [[CrossRef](#)]
3. Evans, A.G.; Mumm, D.R.; Hutchinson, J.W.; Meier, G.H.; Pettit, F.S. Mechanisms Controlling the Durability of Thermal Barrier Coatings. *Prog. Mater. Sci.* **2001**, *46*, 505–553. [[CrossRef](#)]
4. Vaßen, R.; Jarligo, M.O.; Steinke, T.; Mack, D.E.; Stöver, D. Overview on Advanced Thermal Barrier Coatings. *Surf. Coat. Technol.* **2010**, *205*, 938–942. [[CrossRef](#)]

5. Bernardo, E.; Cedro, R.; Florean, M.; Hreglich, S. Reutilization and Stabilization of Waste by the Production of Glass Foams. *Ceram. Int.* **2007**, *33*, 963–968. [[CrossRef](#)]
6. Colombo, P. Engineering Porosity in Polymer-Derived Ceramics. *J. Eur. Ceram. Soc.* **2008**, *28*, 1389–1395. [[CrossRef](#)]
7. Baines, F.; Hamzehlou, S.; Kargozar, S. Bioactive Glasses: Where Are We and Where Are We Going? *J. Funct. Biomater.* **2018**, *9*, 25. [[CrossRef](#)]
8. Yan, Z.; Guo, L.; Li, Z.; Yu, Y.; He, Q. Effects of Laser Glazing on CMAS Corrosion Behavior of Y₂O₃-Stabilized ZrO₂ Thermal Barrier Coatings. *Corros. Sci.* **2019**, *157*, 450–461. [[CrossRef](#)]
9. Lookman, T.; Balachandran, P.V.; Xue, D.; Yuan, R. Active Learning in Materials Science with Emphasis on Adaptive Sampling Using Uncertainties for Targeted Design. *npj Comput. Mater.* **2019**, *5*, 21. [[CrossRef](#)]
10. Jordán Vidal, M.M.; Almendro-Candel, M.B. Semi-Quantitative Mineralogical Analysis of Ceramic Coatings and Their Raw Materials Using ATR-FTIR Spectroscopy. *Coatings* **2026**, *16*, 530. [[CrossRef](#)]
11. Mao, R.; Huang, S.; Dou, Y.; Mo, X.; Liang, T. Effect of Gd₂O₃ Addition on the Growth Behavior of the Dense Reaction Layer at the Interface Between Al₂O₃ Ceramic and CMAS at 1300 °C. *Coatings* **2026**, *16*, 327. [[CrossRef](#)]
12. Kan, S.; Zeng, X.; Xie, X.; Wang, R.-Z.; Cheng, X. Preparation and Investigation of Nano-TiO₂-Modified Silicone-Based Reflective Thermal Insulation Coatings. *Coatings* **2026**, *16*, 319. [[CrossRef](#)]
13. Zhang, L.; Dou, R.; Liu, N.; Sun, J.; Liu, X.; Wen, Z. Coupled Thermo-Mechanical Modeling of Crack-Induced Stress Fields in Thermal Barrier Coatings with Varying Crack Geometries. *Coatings* **2025**, *15*, 785. [[CrossRef](#)]
14. Epure, C.; Munteanu, C.; Istrate, B.; Harja, M.; Lupu, F.C.; Luca, D. Innovation in the Use of Recycled and Heat-Treated Glass in Various Applications. *Coatings* **2025**, *15*, 651. [[CrossRef](#)]
15. Lv, K.; Sun, S.; Yuan, B.; Guo, X.; Song, W.; Boiko, A.A. First-Principles Analysis of Phase Stability and Transformation Suppression for Hydrogen-Doped Alumina. *Coatings* **2025**, *15*, 545. [[CrossRef](#)]
16. Li, R.; Gu, S.; Guo, Y.; Xue, B.; Zhou, Q.; Yuan, R.; Cong, L.; Zhang, Y. Microstructure and Thermal Analysis Kinetics of Y₂Hf₂O₇/Y₃Al₅O₁₂ Composites Prepared by Solution Combustion Synthesis. *Coatings* **2025**, *15*, 470. [[CrossRef](#)]
17. Hou, X.; Ji, W.; Li, H.; Fan, X.; Wang, Y. Study on the Effect of Coal Gangue Particle Size Distribution for the Preparation of Kaolin by Shaking Table Separation. *Coatings* **2025**, *15*, 430. [[CrossRef](#)]
18. Qiao, H.; Liu, M.; Xiang, Y.; Xu, X.; Wang, Z.; Wu, W.; Wang, Y. Low-Friction Coatings Grown on Cemented Carbides by Modulating the Sputtering Process Parameters of TiN Targets. *Coatings* **2025**, *15*, 329. [[CrossRef](#)]

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