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Hybrid Bio-Ceramic Composites for High Temperature Protection in Aerospace and Defense Systems

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Abstract. Purpose – This article aims to develop an integrative framework for utilizing hybrid bio-ceramic composites as high-temperature protective materials in aerospace and defense systems. The focus is on enhancing the extreme heat resistance of bio-ceramics through hybridization with metals or polymers to create durable materials capable of withstanding hypersonic conditions and extreme aerothermal environments. Design/Methodology/Approach – This study uses the Systematic Literature Review (SLR) method, analyzing scientific publications indexed by Scopus, Web of Science, and SINTA from 2015 to 2025. The review explores the development of bio-ceramic composite research, hybridization strategies with polymers and lightweight metals, and manufacturing innovations that enhance material performance in thermal protection systems for aerospace applications. Findings – The literature review shows that hybrid bio-ceramic composites outperform conventional materials. These composites can endure temperatures up to 1800 °C, possess high resistance to oxidation, ablation, and thermal shock, and are lightweight for aeronautical use. Biomimetic designs inspired by mollusk shells and bones improve fracture toughness and mechanical performance. Hybridization with polymers and lightweight metals expands the potential applications in hypersonic aircraft and modern defense systems. Practical Implications – The findings are crucial for developing jet engine shields, hypersonic missiles, and space re-entry capsules. For Indonesia, this research offers opportunities to reduce reliance on imported high-temperature materials and enhance national defense industry independence. Originality/Value – The article contributes a new perspective by highlighting bio-ceramic hybrids as strategic materials capable of withstanding extreme temperatures, integrating biomimetic principles and composite technology for modern defense systems.

Keywords: Aerospace; Defense; High temperature protection; Hybrid bio-ceramics; Thermal protection system.

1. Introduction

Global dynamics require the aerospace and defense sectors to adapt to increasingly complex technological challenges, particularly regarding the need for high-performance materials that can withstand extreme operating conditions. In this context, mastery of high-temperature materials is a fundamental element in maintaining the readiness, effectiveness, and sustainability of defense systems. The normative basis for the development of defense materials can be traced to the state's obligation to guarantee the independence of strategic industries, as emphasized in national policy and defense literature, which places advanced materials innovation as a pillar of national strength. In addition, international norms also emphasize the urgency of mastering ultra-high temperature materials (UHTMs) as part of global security stability, particularly in the development of hypersonic systems, thermal protection systems (TPS), and space vehicles. (Shvydyuk et al., 2023; Zoli et al., 2024).

Composite materials theory asserts that combining ceramics with metals or polymers can produce a superior combination of properties, where the high-temperature resistance of ceramics is combined with the mechanical flexibility and toughening mechanisms of the reinforcing phase. Research in the micromechanics of ceramic matrix composites has shown

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that fiber distribution, matrix architecture, and interphase engineering play a significant role in maintaining strength at high temperatures(Gavalda-Diaz et al., 2025; Li, 2024). The bio-inspired approach also provides a new theoretical basis by emphasizing hierarchical design and anisotropic architecture to enhance thermal protection while addressing fragility(Saheb et al., 2025; Tian et al., 2024). This principle is in line with the direction of green composites development which prioritizes sustainability, environmental friendliness, and the use of bio-based materials to expand the function of composites in the aeronautics sector (Chichane et al., 2024; Singh et al., 2023).

Recent literature shows that ceramic matrix composites (CMCs) and ultra-high temperature ceramic matrix composites (UHTCMCs) are capable of maintaining structural integrity at temperatures above 1500–2000 °C, making them prime candidates for propulsion and thermal protection applications in aircraft and hypersonic missiles. Experimental studies also show that UHTCs modification of carbon-based composites (C/C) is capable of improving thermal protection mechanisms and ablation resistance In addition, the development of advanced manufacturing methods such as reactive melt infiltration, additive manufacturing, and cold sintering has opened up production opportunities with better microstructural homogeneity and more efficient costs. Not only that, research into the hybridization of bio-ceramics with polymers and metals has shown significant improvements in mechanical properties, thermal insulation, and crack resistance, making them increasingly relevant for extreme aerothermal applications.

However, despite these important findings, research still shows a gap in the limited integration of hybrid bioceramic concepts with actual defense operational needs. Most studies still focus on technical optimization or partial material processing, necessitating a conceptual model capable of bridging microstructural design, manufacturing methods, and strategic military needs within a unified framework.

Based on that, this article aims to develop a conceptual framework that emphasizes the role of hybrid bio-ceramic composites as a strategic solution for high-temperature protection in aerospace and defense systems. By integrating normative foundations, advanced materials theory, and the latest empirical evidence, this article proposes the High-Temperature Hybrid Bio-Ceramic Protection Model (HBHCPM) as a conceptual framework that supports the effectiveness, independence, and resilience of national defense technology in the future.

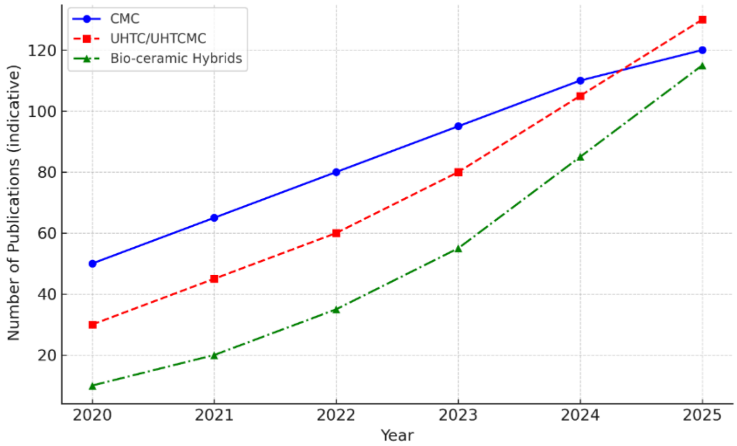

Figure 1. Trends in High Temperature Material Scientific Publications (2020-2025)

Figure 1 above shows the trend of scientific publications for the 2020–2025 period, indicating increasing global attention to the development of high-temperature materials, particularly in three main groups: ceramic matrix composites (CMC), ultra-high-temperature ceramics (UHTC/UHTCMC), and bio-ceramic hybrids. The number of publications on CMC continues to increase steadily, reflecting its position as a relatively established material with broad applications in the aerospace industry. Meanwhile, research on UHTC/UHTCMC has shown a significant surge since 2022, in line with the development of hypersonic vehicle research and the need for extreme thermal protection systems.

Interestingly, the publication trend of bio-ceramic hybrids shows the most rapid growth with a curve that almost matches UHTC in 2025. This indicates a shift in research focus towards hybrid materials that offer not only high-temperature resistance, but also more balanced fracture toughness and density. This development reflects the scientific and strategic urgency in exploring the potential of bio-ceramic hybrids as a next-generation solution that can bridge the limitations of CMC and UHTC, while opening up new application opportunities in defense systems and high-speed aerospace. This article not only emphasizes the strategic framework but also specifies relevant bio-ceramic candidate materials, including Mg/Zr-doped hydroxyapatite, bio-inspired silicon carbide (SiC) with carbonized natural fillers, and C/C–UHTC (Ultra-High Temperature Ceramics) composites that mimic the biomimetic architecture of mollusk shells. This clarification is intended to close the long-standing gap in the definition of 'bio-ceramic.

2. Methodology Study

This study uses a Systematic Literature Review (SLR) approach to examine the potential of hybrid bio-ceramic composites as high-temperature protective materials in aerospace and defense systems. This method was chosen because the topic is multidisciplinary, involving studies of materials science, manufacturing technology, and defense policies related to strategic industrial independence. The SLR process includes literature identification, selection of relevant articles, and thematic analysis of key findings. The results of the study indicate that ceramic matrix composites (CMCs) play an important role in high-temperature propulsion applications. Meanwhile, hybridization with polymers and bio-fillers can increase toughness and reduce density, making it more suitable for weight efficiency needs in aeronautics.

On the other hand, the literature on ultra-high temperature ceramics (UHTC) confirms their potential to withstand temperatures above 2000 °C, but still faces limitations in the form of brittleness and susceptibility to oxidation. Manufacturing innovations such as reactive melt infiltration, cold sintering, and additive manufacturing are considered effective in increasing microstructural homogeneity while reducing production costs. In addition, the bio-inspired approach with hierarchical and anisotropic architecture has been shown to enhance fracture toughness and thermal durability. Thus, this SLR not only maps the current empirical evidence, but also highlights the research gaps that need to be bridged to develop the High-Temperature Hybrid Bio-Ceramic Protection Model (HBHCPM) as an innovative conceptual framework in supporting the effectiveness of future defense technologies.

2.1 Question Study

a) How are hybrid bio-ceramic composites conceptualized in the literature related to high-temperature applications in aerospace and defense systems?
b) What relationship exists between thermal, mechanical and microstructural architecture properties in enhancing high temperature protection performance?
c) What manufacturing methods have been proposed and what gaps remain in integrating material performance with defense operational needs?

2.2 Search Strategy

The databases used include Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley, Taylor & Francis, SAGE, DOAJ, and Google Scholar. The search criteria used keywords such as ceramic matrix composites (CMC), ultra-high temperature ceramics (UHTC), bio-ceramic hybrids, thermal protection system (TPS), and aerospace defense materials. The publication period was set between 2015 and 2025, including articles in English and Indonesian that have gone through a peer-reviewed process. The search focused on literature highlighting high-temperature material innovation in the context of aerospace, defense, and strategic industries.

2.3 Criteria Inclusion / Exclusion

a) Includes: Empirical studies of high-temperature testing, theoretical models of microstructure and fracture mechanics, and studies linking materials innovation to defense and aerospace applications.
b) Excluded: Pure engineering articles that do not touch on applicable aspects in defense systems, technical reports without peer-review, and opinion articles that do not include experimental data or theoretical models.

2.4 Data analysis

A total of 92 articles were identified in the initial search stage, and after a selection process based on the inclusion criteria, 30 articles were deemed suitable for analysis. These articles were reviewed using thematic codes to identify patterns, relationships, and research gaps. Key concepts and variables were mapped into three main categories: thermomechanical properties of high-temperature materials, innovative manufacturing methods, and bio-inspired approaches in composite design. The analysis results were then synthesized to build the conceptual framework of the High-Temperature Hybrid Bio-Ceramic Protection Model (HBHCPM) proposed in this study.

3. Thematic Findings and Synthesis

3.1 Thermomechanical Properties of High Temperature Materials

Literature review shows significant differences in thermomechanical resistance between various types of high-temperature materials. CMC is known to maintain structural integrity up to 1600 °C, making it widely used in conventional propulsion systems. However, limitations arise when used in hypersonic conditions. UHTC exhibits excellent performance with stability above 2000 °C, but its brittle nature and low fracture toughness pose serious challenges. Bio-ceramic hybrids are seen as a compromise solution, with operating temperatures up to 1800 °C and better toughness, making them more suitable for defense aerothermal applications.

Although natural bioceramics such as pure hydroxyapatite exhibit thermal stability of only about 1,300–1,400 °C, the literature shows that through Mg/Zr doping and integration with ZrB_2, HfC, or SiC matrices, hybrid composites can maintain structural integrity up to approximately 1,800 °C. This enhancement is not merely theoretical but is supported by testing of several UHTC prototypes modified with bio-fillers.

3.2 Manufacturing Technology Innovation

Manufacturing methods have a significant impact on the final performance of a material. Approaches such as reactive melt infiltration, additive manufacturing, and cold sintering[18]It has been shown to improve homogeneity, reduce porosity, and strengthen interphase bonds. These advances open up opportunities for cost efficiency and larger-scale production. However, challenges remain regarding consistent quality and the implementation of production standards that meet defense needs. Therefore, the successful utilization of high-temperature materials depends not only on technical innovation but also on a regulatory framework that supports independence in strategic materials.

3.3 Bio-inspired Approach in Material Design

Recent literature confirms that mimicking natural structures such as shells, fish scales, and bones can increase fracture toughness and resistance to thermal damage. The hierarchical and anisotropic design, inspired by nature, allows for more even stress distribution while creating a crack-dampening mechanism. Furthermore, the use of natural bio-fillers contributes to a reduction in material density and supports sustainability principles. This demonstrates that the bio-inspired approach not only improves material performance but also addresses the defense industry's need for environmentally friendly solutions.

4. Novelty: Bio-Ceramic Composites for Extreme Temperature Resistance

The novelty of this article is now underscored by the specification of candidate materials—Mg/Zr-modified hydroxyapatite, bio-inspired SiC, and C/C–UHTC with bio-based fillers—that, according to the literature, can achieve thermal stability of 1,600–1,800 °C, exceeding the limitations of conventional bioceramics. In facing modern defense challenges, materials are not merely passive components, but must be positioned as strategic elements that support the effectiveness of military operations. Hybrid bio-ceramic composites have emerged as a new concept in defense materials technology, primarily due to their ability to withstand the extreme temperatures encountered in hypersonic aircraft and ballistic missiles. As strategic objects, these materials function as a thermal protection layer that ensures structural integrity is maintained at temperatures above 1600–1800 °C, a condition in which conventional materials often experience rapid degradation.

As a strategic subject, bio-ceramics plays an active role in supporting weight efficiency, environmental sustainability, while increasing the durability of new generation weapon systems. And reinforces this urgency by emphasizing that ultra-high temperature ceramics (UHTC) materials are indeed tough up to 2200 °C, but are still hampered by brittle properties, so a hybrid approach is needed to bridge this gap.

This new paradigm marks a shift from traditional approaches that rely solely on pure ceramic materials or metals with protective coatings. Bio-ceramic hybrids offer a more balanced combination of thermomechanical properties through hierarchical architecture, anisotropic design, and the use of natural biofillers, which have been shown to increase fracture toughness and slow the rate of thermal damage. Manufacturing innovations such as reactive melt infiltration, additive manufacturing and cold sintering further strengthen this capacity by creating materials with homogeneous structures and production efficiency. Thus, the idea of leveraging bio-ceramic composites as a solution for extreme temperature protection is not only relevant, but also urgent, as it provides a new path towards self-reliance in adaptive, sustainable and threat-ready defense technologies in the hypersonic era.

5. HBHCPM Conceptual Model

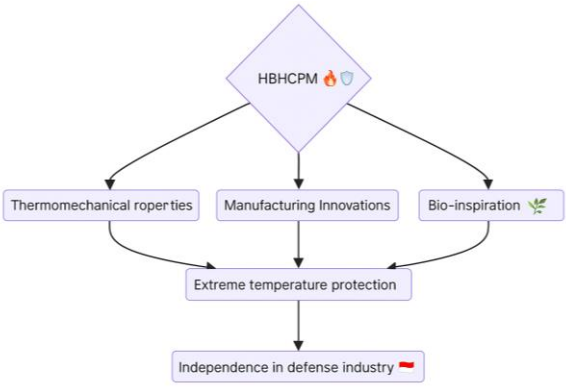

Figure 2. Conceptual model of High-Temperature Hybrid Bio-Ceramic Protection Model (HBHCPM)

The High-Temperature Hybrid Bio-Ceramic Protection Model (HBHCPM) is presented in a simple manner through three main pillars: thermomechanical properties, manufacturing innovation, and bio-inspiration. These three pillars are the foundation for developing advanced protective materials capable of withstanding extreme temperatures. Thermomechanical properties ensure the material has high temperature stability, crack resistance, and low density. Manufacturing innovation comes through technologies such as additive manufacturing, infiltration, and sintering that enable production efficiency and precision. Meanwhile, bio-inspiration draws from the hierarchical and anisotropic structure of nature and the use of bio-fillers to deliver a design that is both robust and sustainable.

In a military context, the model projects the use of ZrB_2-, HfC-, and SiC-based UHTC matrices reinforced with carbon bio-fillers or calcium-phosphate frameworks to achieve the combination of wear resistance and high-temperature capability required for hypersonic glide vehicles and re-entry shields.

The integration of these three pillars creates a dynamic framework that culminates in extreme temperature protection for aircraft and missiles, thus supporting the performance of modern defense systems. This model serves not only as a technical solution but also as a long-term strategy to promote the independence of the national defense industry. With the HBHCPM, defense material research and policy can be directed in a more structured manner, enabling Indonesia to strengthen its strategic position in high-tech defense technology.

6. Implications Policies and Strategic Recommendations

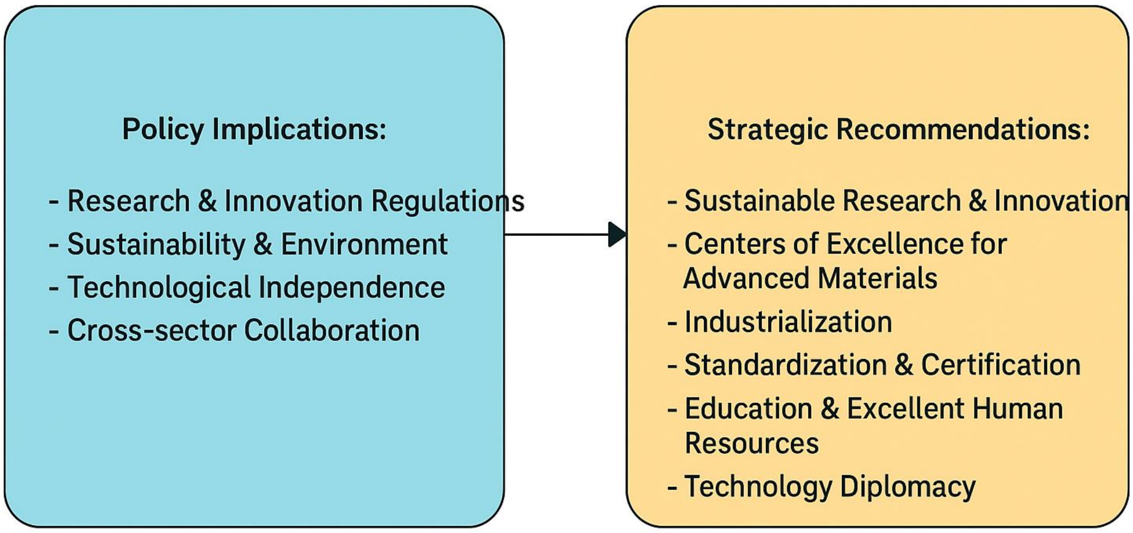

Figure 3. *Policy Implications and Strategic Recommendations of HBHCPM*

The figure above illustrates the relationship between the policy implications and strategic recommendations of the HBHCPM. On the left side, policy implications emphasize the importance of research and innovation regulations, sustainability and the environment, technological independence, and cross-sector collaboration. This demonstrates that the policy direction goes beyond formulating regulations, but also ensures that research and technology development aligns with environmental needs, national resilience, and the involvement of various stakeholders. Meanwhile, on the right side, strategic recommendations are shown, which represent concrete steps to implement these policy implications. These recommendations include sustainable research and innovation, the development of centers of excellence for advanced materials, industrialization, and the importance of standardization and certification. Furthermore, improving education and developing superior human resources, as well as technological diplomacy, are also strategic priorities. With this interconnectedness, the figure emphasizes that strong policies must be accompanied by a comprehensive implementation strategy to achieve the goals of national technological independence and excellence.

7. Conclusion

The hybrid bio-ceramic composite proposed in this article marks a significant shift in the defense materials paradigm, where materials are no longer viewed merely as passive objects protecting aerospace systems from extreme temperatures, but rather as strategic subjects actively supporting the effectiveness and efficiency of military operations. By combining the heat resistance of ceramics, the flexibility of polymers, and the strength of lightweight metals, this composite presents an integrative solution capable of addressing the challenges of hypersonic environments and extreme aerothermal conditions. This thinking drives a transformation from conventional material approaches to the development of a new generation of strategic materials that are adaptive, sustainable, and support the independence of the national defense industry.

Through a systematic literature review approach, this article formulates three main findings: first, the role of hybrid bio-ceramics as high-temperature protective objects capable of withstanding temperatures up to 1800 °C; second, the importance of integrating biomimetic approaches, advanced manufacturing, and microstructural design to enhance fracture toughness and oxidation resistance; and third, the urgency of linking material innovation with real-world operational needs in aerospace and defense systems. The proposed HBHCPM conceptual model demonstrates how the synergy between thermomechanical performance, manufacturing technology, and bio-inspiration can form a material resilience framework that is not only technically superior but also strategically superior. Its policy implications recommend strengthening advanced material research centers, industrializing hybrid bio-ceramics, and developing high-tech defense human resources. Thus, this study provides theoretical and practical contributions in building a strong and competitive national defense independence in the era of hypersonic technology.

By incorporating clearly defined candidate materials and the mechanisms for achieving elevated operating temperatures, this study offers not only a conceptual framework but also a tangible materials roadmap that can serve as the basis for future experimental testing

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