Advances in high-performance ceramic materials for aerospace and defence applications: A state-of-the-art review

Alfredo Aguilar-Elguezabal [1], Armando Reyes-Rojas [1], Hilda Esperanza Esparza-Ponce [1], Daniel Lardizábal-Gutiérrez [1] and Miguel Humberto Bocanegra-Bernal[1]*

1 Centro de Investigación en Materiales Avanzados, CIMAV S.C., Miguel de Cervantes # 120, Complejo Industrial Chihuahua, Chihuahua 31136, Mexico

S1. Fracture toughness vs maximum service temperature

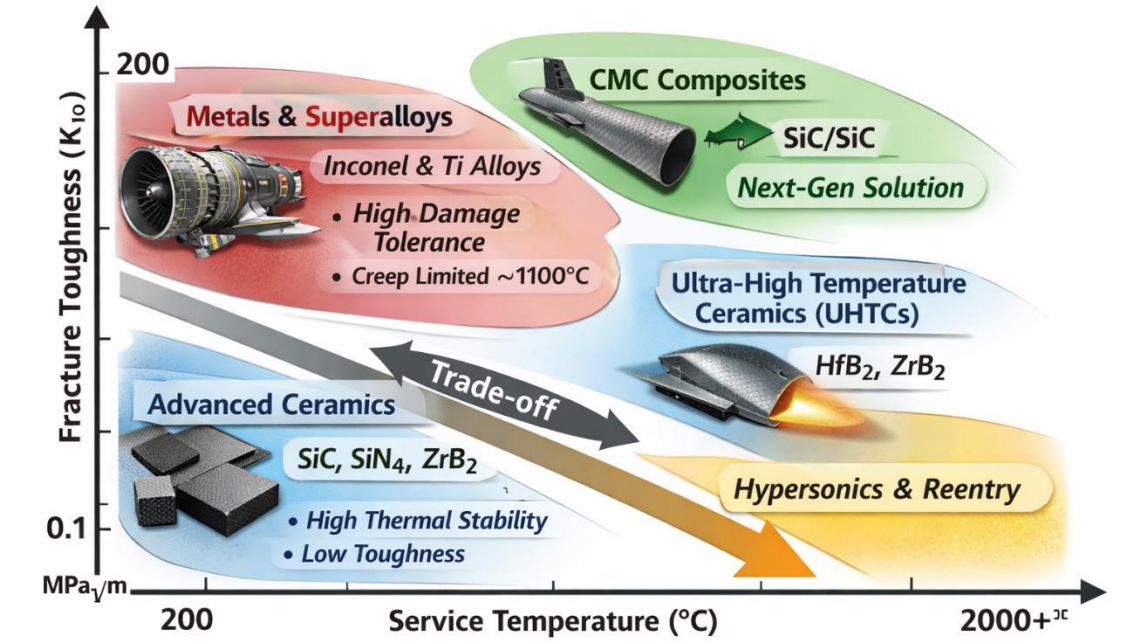


Figure S1. Conceptual Ashby-type map correlating fracture toughness (K_{IC}) and maximum service temperature for structural materials used in aerospace and defense systems. The diagram contrasts metals and nickel-based superalloys, advanced monolithic ceramics, ultra-high-temperature ceramics (UHTCs), and ceramic matrix composites (CMCs). Metals exhibit high intrinsic fracture toughness governed by dislocation-mediated plasticity but are thermally limited by creep and microstructural instability above ~1000–1100 °C. In contrast, covalent/ionic ceramics provide superior thermal stability yet display low intrinsic toughness due to limited crack-tip plasticity. UHTCs extend service capability beyond 1800 °C but remain damage-sensitive. CMCs partially overcome this trade-off through extrinsic toughening mechanisms such as crack deflection, fiber bridging, and pull-out. The map is conceptually inspired by materials selection methodologies proposed by Ashby [1].

S2. Fundamental Failure Processes in Advanced Ceramics and Ceramic Matrix Composites (CMCs)

Advanced ceramics and ceramic matrix composites (CMCs) are increasingly deployed in aerospace, defense, energy, and high-temperature propulsion systems due to their exceptional thermal stability, oxidation resistance, and low density. Despite these advantages, their structural reliability is fundamentally governed by complex

failure processes associated with brittle fracture behavior, flaw sensitivity, and limited intrinsic plasticity. In monolithic ceramics, failure is typically initiated at microstructural defects that trigger rapid crack propagation once the critical stress intensity is reached. In contrast, CMCs exhibit more intricate, multiscale damage evolution involving matrix cracking, fiber–matrix debonding, crack deflection, fiber bridging, and pull-out, thereby enabling progressive and non-catastrophic failure.

Modern toughening strategies emerged from advances in fracture mechanics in the 1960s [1], followed by the development of transformation toughening in zirconia [2] and the subsequent evolution of ceramic matrix composites (CMCs) [3]. Microstructural design, through tailoring of grain size, secondary phases, fibers, whiskers, and interfacial properties, activates extrinsic toughening mechanisms such as crack deflection, bridging, branching, pull-out, and related energy-dissipating processes [4]. These mechanisms are particularly effective in anisotropic or laminated architectures that promote tortuous crack paths and multiscale energy dissipation. In zirconia, stress-induced tetragonal-to-monoclinic transformation generates compressive stresses around cracks, increasing fracture toughness to ~15 $MPa \cdot m^{1/2}$ [3, 4]. In alumina, silicon carbide, and silicon nitride, toughening arises from grain bridging and intergranular fracture mechanisms [5]. The integration of graphene-based reinforcements into ceramics has further enhanced mechanical performance; for example, Al_2O_3/rGO and Si_3N_4/rGO systems demonstrated toughness increases of 53% and 135%, respectively, when uniform dispersion was achieved [6, 7].

Because multiple mechanisms often operate simultaneously, isolating their individual contributions remains challenging [8]. Systems such as magnesia-partially stabilized zirconia (Mg-PSZ) exhibit concurrent transformation toughening, microcracking, and crack deflection (See Fig. S2). Studies demonstrated that rod-like inclusions can increase toughness up to fourfold, depending on aspect ratio [4]. Contemporary SiC–SiC CMCs exemplify extrinsic toughening through engineered weak interfaces (e.g., BN), enabling pseudo-ductile behaviour suitable for turbine engines and nuclear systems [9, 10]. Research has expanded into ultra-high-temperature ceramics (UHTCs), including borides, carbides, and nitrides of group IVB and VB transition metals, and high-entropy ceramic systems inspired by metallurgical compositional complexity [11, 12].

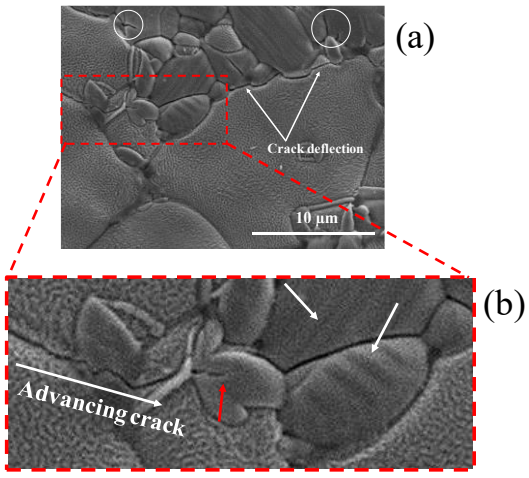


Figure S2. Scanning electron microscopy (SEM) characterization of ZrO_2 with 9.25 mol% ultrafine as-received MgO powder, sintered at 1600 °C for 3 hours in air. (a) SEM image showing transformed zones with visible crack deflection, as well as a few microcracks and instances of debonding (highlighted with white circles) at the surface of the transformed region. (b) Magnified view of the marked rectangle in (a), illustrating a crack advancing into a tetragonal grain, which transforms into a monoclinic grain, arresting the crack (indicated by the red arrow). Transformed zirconia grains can be identified by their twin-like appearance and distinct grey contrast; some are marked with white arrows in (b). Source: Author's own work.

Phase Transformation Toughening (TT)

Transformation toughening in ZrO_2 is one of the most successful ceramic toughening strategies. First reported in 1975 [2], stress-induced martensitic transformation (t→m) produces a 3–5% volume expansion and 1–10% shear strain, generating compressive stresses that shield crack tips. Proper stabilization with Y_2O_3, MgO, or CeO_2 enables metastable tetragonal phases at room temperature, forming materials such as PSZ, Y-TZP, and ZTA [13]. 3Y-TZP, characterized by ultrafine grains (<200 nm), achieves high toughness and reliability, particularly in biomedical applications [14]. TT produces R-curve behaviour, where toughness increases with crack extension [15]. However, low-temperature degradation (LTD) in moist environments (30–300 °C) can induce spontaneous transformation and microcracking, compromising durability [16]. Recent developments include ZrO_2-reinforced alumina and silicon nitride composites [17], ZrO_2-WC systems with thermochemical stability up to ~1400 °C, and investigations into superelastic and shape-memory effects in stabilized zirconia [16].

Crack Bridging

Crack bridging is central to toughness enhancement in advanced ceramics, particularly CMCs used in extreme aerospace and defence environments [8, 18]. Fibres, whiskers, or unbroken grains span crack surfaces, reducing stress intensity and delaying failure. Observed in alumina, silicon nitride, PSZ, ZTA (See Fig. S3a and Fig. S3b), respectively, and multiphase ceramics, bridging significantly increases energy dissipation through pull-out and interfacial friction [19]. Continuous fibre systems offer superior flaw tolerance and delayed failure [20]. Metallic inclusions can also serve as ductile bridges [21]. Carbon nanostructures, including CNTs and graphene, have shown potential for enhanced bridging [22], though dispersion challenges and agglomeration can reduce effectiveness [23]. In well-designed systems, CNTs synergistically complement transformation toughening by promoting crack deflection, bridging, and residual compressive stresses, particularly under high-temperature conditions relevant to aerospace and defence.

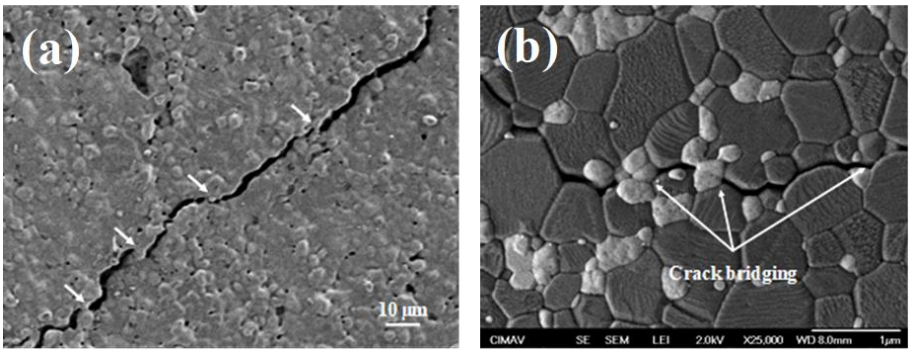


Figure S3. SEM micrographs illustrating the crack bridging toughening mechanism in (a) high-temperature sintered 9.25 mol% Mg-PSZ ceramic, and (b) Multi wall carbon nanotube (MWCNT)-reinforced ZTA sintered at 1520 °C for 1 hour. Arrows indicate regions where crack bridging occurs, highlighting the contribution of microstructural features to toughening in each material. Source: Author's own work.

Crack Deflection

Crack deflection increases fracture energy by forcing cracks along tortuous paths through microstructural obstacles [21]. Interfaces, second-phase particles, fibres, and laminated architectures are engineered to promote deflection [24] (See Fig. S4). In CMCs, weak fibre–matrix interphases (e.g., BN or PyC) enable multiple deflections and sliding, improving R-curve behaviour and damage tolerance. Graphene nanoplatelets (GNP) and rGO enhance deflection at platelet interfaces, increasing K_{IC} by up to ~50% depending on dispersion and morphology [5]. Laminated and multilayer ceramics further exploit interlayer deflection to enhance thermal shock resistance [25]. Theoretical frameworks by He and Hutchinson [26], Faber formalized criteria governing crack deflection versus penetration. Even polycrystalline ceramics exhibit intrinsic grain-boundary deflection due to irregular grain morphologies [27, 28].

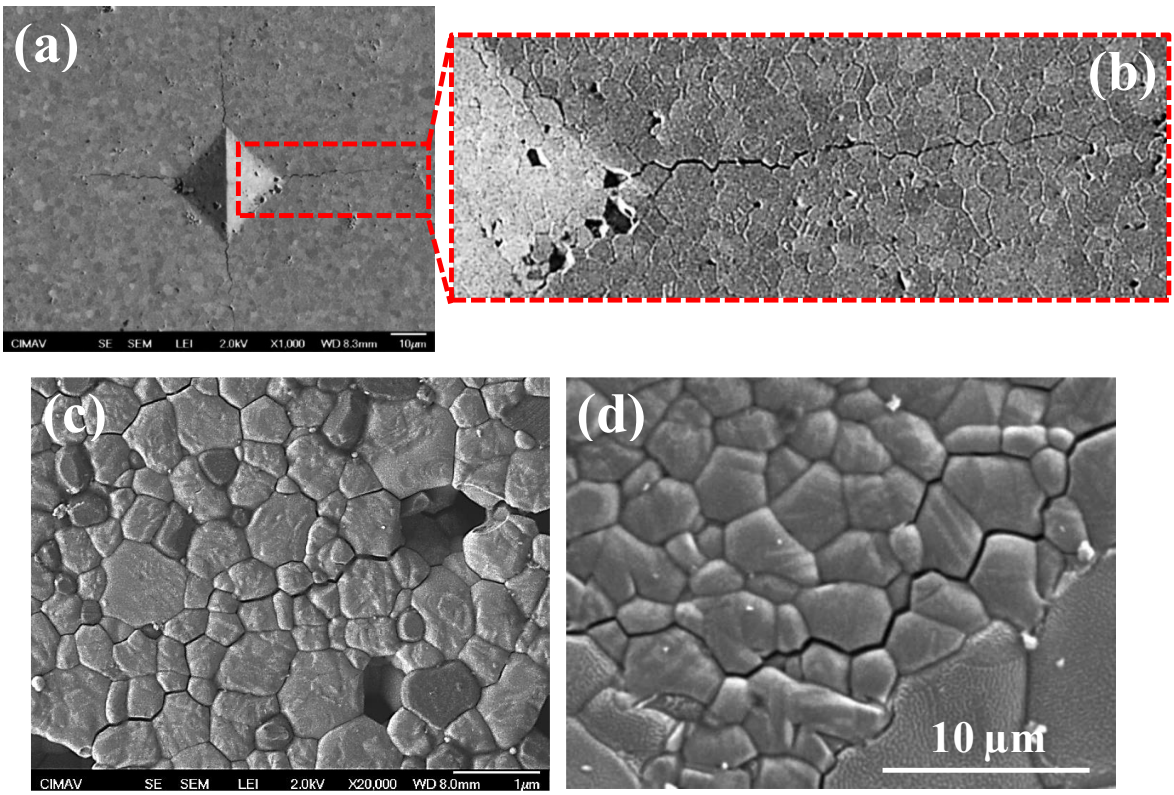


Figure S4. SEM micrographs showing crack deflection paths in various ceramics: (a) Sintered Al_2O_3 at 1520 °C for 2 h, indented with a 9.8 N load for 15 s; (b) higher magnification of the crack arm marked by the rectangle in (a); (c) ZTA reinforced with 0.1 wt% MWCNTs, sintered at 1500 °C for 2 h; and (d) 14.5 mol% Mg-PSZ sintered at 1600 °C in air for 3 h. Source: Author's own work.

Addition of Ductile Phases and Reinforcements

Incorporating ductile phases or reinforcements addresses ceramic brittleness, enhancing fracture toughness, impact resistance, and energy absorption [22]. This strategy is critical in armour systems, turbine engines, and thermal protection systems (TPS). CMCs, one of the three primary composite classes alongside PMCs and MMCs [29], were developed specifically to overcome monolithic ceramic brittleness [30]. Reinforcement may be continuous (fibres) or discontinuous (particles, whiskers), with continuous fibres being most effective through bridging and pull-out mechanisms. SiC-based CMCs dominate high-temperature structural applications due to their thermal resistance and low density [24, 30], though oxidation and notch sensitivity remain challenges. Toughness improvements rely on fibre optimization, interphase engineering, nano-reinforcements, laminated structures, and even self-healing additives such as WC [131].

Ultra-high-temperature ceramic matrix composites (UHTCMCs), reinforced with continuous SiC or carbon fibres, extend performance into hypersonic, propulsion, and nuclear environments [29]. These systems outperform monolithic oxides and non-oxides by combining tailored microstructures with controlled crack propagation [32]. Advanced microstructural strategies include elongated grains in Si_3N_4 formed via $\alpha \rightarrow \beta$ transformation [33], metallic additions in alumina to promote crack deflection [34], and nanoscale reinforcements such as CNTs and graphene for hybrid toughening architectures [22, 31]. Despite high production costs and reliability challenges [35], CMCs and UHTCMCs remain strategic materials for extreme-environment engineering systems [5, 21, 23, 25].

Matrix Cracking

Matrix cracking is the initial damage mechanism in CMCs under tensile or flexural loading, originating at defects due to the low strain-to-failure of ceramic matrices. In optimized systems, cracks distribute rather than propagate catastrophically, arresting at fibre interfaces and activating toughening mechanisms such as crack deflection and fibre bridging. Crack spacing stabilizes at a saturation density controlled by fibre volume fraction, interfacial shear strength, and matrix modulus, although excessive cracking can reduce stiffness, thermal conductivity, and environmental resistance [1, 22].

Fibre Fracture

Fibre fracture is the dominant load-limiting failure mechanism in CMCs. After matrix cracking and interfacial debonding, load is redistributed to intact fibres bridging the crack. As applied stress increases, fibres progressively fail according to their strength distribution (Weibull statistics). Therefore, unlike monolithic ceramics, failure in CMCs is gradual: i) Matrix cracking, ii) Fiber bridging and sliding, iii) Progressive fiber breakage, and iv) Final composite failure. Fibre strength degradation due to oxidation, creep, or irradiation can significantly accelerate failure, particularly in high-temperature environments (>1000 °C) [36, 37].

Environmental Degradation and Oxidation-Induced Failure

High-temperature oxidation is one of the most critical degradation mechanisms in non-oxide CMCs (e.g., SiC/SiC or C/SiC). Oxygen ingress through matrix cracks can oxidize fibers, degrade BN or PyC interphases, reduce fiber strength, and increase interfacial bonding (loss of debonding capability). This leads to a transition from pseudo-ductile to brittle behaviour. Environmental Barrier Coatings (EBCs) are often applied to mitigate oxidation and moisture attack. However, coating spallation or cracking can expose the composite to rapid degradation [38-41].

The hallmark of CMC behaviour is non-catastrophic, damage-tolerant failure. Unlike monolithic ceramics, which fail immediately upon critical crack growth, CMCs exhibit: i) mmultiple matrix cracking, ii) rrising R-curve behavior, iii) ggradual stiffness degradation, iv) ssignificant work-of-fracture. However, environmental degradation, poor interfacial design, or extreme loading can suppress extrinsic toughening mechanisms, reverting the composite to brittle behaviour. CMCs are preferred in turbine and hypersonic applications due to their higher damage tolerance and reduced catastrophic failure under complex loading. Monolithic ceramics are better suited for extreme compression, armour, and ultra-high-temperature regions with low tensile stress. Material selection depends on stress conditions, environment, and reliability demands, highlighting the importance of understanding failure mechanisms for advanced high-temperature systems. A comparative failure mechanisms and damage tolerance of monolithic ceramics and ceramic matrix composites (CMCs) for high-temperature structural applications, is illustrated in Table S1.

Table S1. Comparative failure characteristics of monolithic ceramics and ceramic matrix composites (CMCs)

Feature	**Monolithic Ceramics (e.g., SiC, Al_2O_3, ZrB_2)**	**Ceramic Matrix Composites (e.g., SiC/SiC, C/SiC, Oxide/Oxide)**
Primary Load-Bearing Phase	Single-phase ceramic	Fibres + ceramic matrix
Fracture Behaviour	Catastrophic, brittle	Progressive, pseudo-ductile
Crack Propagation	Straight, unstable crack growth	Crack deflection at interfaces
Toughening Mechanisms	Limited (grain bridging, transformation toughening in some systems)	Fibre bridging, interfacial debonding, fibres pull-out
Fracture Toughness (K_{IC})	Low–moderate (typically 2–6 $MPa \cdot m^{½}$)	Moderate–high (can exceed 15–25 $MPa \cdot m^{½}$ depending on architecture)

Damage Tolerance	Low	High (damage accumulation before failure)
Failure Sequence	Crack initiation → unstable propagation → sudden fracture	Matrix cracking → interfacial debonding → fibre pull-out → fibre fracture
Thermal Shock Resistance	Limited (controlled by strength and thermal expansion)	Improved due to crack deflection and strain tolerance
Creep Resistance	Excellent intrinsic resistance (grain boundary controlled)	Dependent on fibre stability and interface integrity
Oxidation Sensitivity	Surface-controlled degradation	Fibre/interphase oxidation may severely reduce toughness
Impact Resistance	Fragmentation and comminution	Energy dissipation via progressive cracking and fibre pull-out
Design Philosophy	Strength-based design	Damage-tolerant design

References.

[1] Ashby, M.F. *Materials Selection in Mechanical Design*; 4th ed.; Butterworth-Heinemann: Oxford, UK, **2011**.

[2] Lawn B. *Fracture of Brittle Solids* (United Kingdom: Cambridge University Press), **1993**.

[3] Garvie R C, Hannink R H J and Pascoe R T. Ceramic steel? *Nature* **1975**, 258, 703–704

[3] Bansal N and Lamon J L. *Ceramic Matrix Composites* (Germany: Wiley-VCH), **2014**.

[5] Launey M E and Ritchie R O. On the fracture toughness of advanced materials. *Adv. Mater.* **2009**, 21, 2103-2110

[6] Evans A G and Cannon R M. Toughening of brittle solids by martensitic transformations. *Acta Metall.* **1986**, 34, 761–800

[7] Wang K, Wang Y, Fan Z, Yan J and Wei T. Preparation of graphene nanosheet/alumina composites by spark plasma sintering. *Mater. Res. Bull.* **2011**, 46, 315–318

[8] Walker L S, Marotto V R, Rafiee M A, Koratkar N and Corral E L. Toughening in graphene ceramic composites. *ACS Nano* **2011**, 5, 3182–3190

[9] Hannink R H J. Toughening mechanisms for ceramics. in *Advanced Materials '93, VI/I Frontiers in Materials Science and Engineering* ed Somiya S et al. *Trans. Mat. Res. Soc. Jpn.* **1994**, 19B 925–941

[10] Ren Z and Singh G. Nonoxide polymer-derived CMCs for “super” turbines. *Ceram. Bull.* **2019**, 98, 34–39

[11] Liu D, Knol S, Ell J, Barnard H, Davies M, Vreeling J A and Ritchie R O. X-ray tomography of the crushing strength and irradiation behaviour of dedicated tristructural isotropic nuclear fuel particles at 1000 °C. *Mater. Design* **2020**, 187, 108382

[12] Fahrenholtz W G and Hilmas G E. Ultra-high temperature ceramics: materials for extreme environments. *Scripta Mater.* **2017**, **129**, 94–99

[13] Ammendola M, Kedir N, Anindya G, Slapikas R and Wolfe D. Mechanical properties of ultra-high temperature ceramic matrix composites (UHTCMCs): A review. *Ceram. Int*. **2025**, 51, 29845-29876

[14] Hannink R H J and Swain M V. Progress in transformation toughening of ceramics. *Annu. Rev. Mater. Sci.* **1994**, 24, 359–408

[15] Liens A, Reveron H, Douillard T, Blanchard N, Lughi V, Sergo V, Laquai R, Müller B, Bruno G, Schomer S, Fürderer T, Adolfsson E, Courtois N, Swain M and Chevalier J. Phase transformation induces plasticity with negligible damage in ceria-stabilized zirconia-based ceramics. *Acta Mater.* **2019**, 183, 261–273

[16] Denry I and Kelly J R. State of the art of zirconia for dental applications. *Dent. Mater.* **2008**, 24, 299–307

[17] Lughi V and Clarke D R. High Temperature Aging of YSZ Coatings and Subsequent Transformation at Low Temperature. *Surf. Coat. Technol.* **2005**, 200, 1287–1291

[18] Sayyadi-Shahraki A, Rafiaei S M, Ghadami S and Nekouee K A. Densification and mechanical properties of spark plasma sintered Si_3N_4/ZrO_2 nano-composites. *J. Alloy Compd.* **2019**, 776, 798–806

[19] Becher P F. Crack Bridging Processes in Toughened Ceramics. in *Toughening Mechanisms in Quasi-Brittle Materials* ed Shah S P (Dordrecht: Springer) NATO ASI Series **1991**, vol 195 pp 25–58

[20] Becher P F and Wei G C. Toughening Behavior in SiC-Whisker Reinforced Alumina. *J. Am. Ceram. Soc.* **1984**, 67, C267–C269

[21] Dutta S. Fracture toughness and reliability in high-temperature structural ceramics and composites: Prospects and challenges for the 21st Century. *Bull. Mater. Sci.* **2001**, 24, 117–120

[22] Budiansky B, Amazicki J C and Evans A G. Small-scale crack bridging and the fracture toughness of particulate-reinforced ceramics. *J. Mech. Phys. Solids* **1988**, 36, 167–187.

[23] Gomez-Gomez A, Ramirez C, Llorente J, Garcia A, Moreno P, Reveron H, Chevalier J, Osendi M I, Belmonte M and Miranzo P. Improved crack resistance and thermal conductivity of cubic zirconia containing graphene nanoplatelets. *J. Eur. Ceram. Soc.* **2020**, 40, 1557–1565

[24] Yin X W, Cheng L F, Zhang L T, Travitzky N and Greil P. Fibre-reinforced multifunctional SiC matrix composite materials. *Int. Mater. Rev.* **2016**, 62, 117–172

[25] Xia Z and Li L. Understanding interfaces and mechanical properties of ceramic matrix composites. in *Advances in Ceramic Matrix Composites* (Sawston, U.K.: Woodhead Publishing) **2014**, pp 367–385

[26] Gao X, Fang G and Song Y. Hysteresis loop model of unidirectional carbon fiber-reinforced ceramic matrix composites under an arbitrary cyclic load. *Compos. Part B Eng.* **2014**, 56, 92–99

[27] Yang W, Araki H, Noda T, Park J, Katoh Y, Hinoki T, Yu J and Kohyama A. Hi-Nicalon™ fiber-reinforced CVI-SiC matrix composites: I. effects of PyC and PyC-SiC multilayers on the fracture behaviors and flexural properties. *Mater. Trans.* **2002**, 43, 2568–2573

[28] Wu D F, Wang Y W, Shang L, Pu Y and Gao Z T. Thermo-mechanical properties of C/SiC composite structure under extremely high temperature environment up to 1500 °C. *Compos. Part B Eng.* **2016**, 90, 424–431

[29] Krenkel W. *Ceramic Matrix Composites: Fiber Reinforced Ceramics and Their Applications* (New York: John Wiley and Sons), **2008**.

[30] Shimoda K, Hinoki T and Kohyama A. Effect of carbon nanofibers (CNFs) content on thermal and mechanical properties of CNFs/SiC nanocomposites. *Compos. Sci. Technol.* **2010**, 70, 387–392

[31] Makurunje P, Monteverde F and Sigalas I. Self-generating oxidation protective high-temperature glass-ceramic coatings for C_f/C–SiC–TiC–TaC UHTC matrix composites. *J. Eur. Ceram. Soc.* **2017**, 37**,** 3227–3239

[32] Hirao K, Ohashi M, Brito M E B and Kanzaki S. Processing strategy for producing highly anisotropic silicon nitride. *J. Am. Ceram. Soc.* **1995**, 78, 1687–1690

[33] Patole R, Ambhore N and Agrawal D. Carbon Composites in Aerospace Application—A Comprehensive Review. *Int. Mater. Rev.* **2023**, 5, 12

[34] Nag A, Ramachandra R and Panda P K. High temperature ceramic radomes (HTCR)—A review. *Ceram. Int.* **2021**, 47, 20793–20806

[35] Nikkisha S, Rohan S, Pragyan P, Ankit Kumar M and Dheva D. Review Study on Mechanical and Thermal Properties of Ceramic Materials for Future Aerospace Applications. *Mater. Charact.* **2022**, 1, 107–113

[36] Soltys L M, Mironyuk I F, Mykytyn I M, Hnylytsia I D and Turovska L V. Synthesis and properties of silicon carbide. *Phys. Chem. Solid State* **2023**, 24, 5–16

[37] Reifsnider K, Liao K, McCormick M, Tiwari A. Fiber Fracture in Continuous Fiber Ceramic Composites: Concepts and Observations. ASME **1995** International Gas Turbine and Aeroengine Congress and Exposition. 95-GT-228, V002T04A012; 9 pages.

[38] Jimenez Alfaro S, Chang H J, Leguillon D, Denneulin S. Numerical estimation and optimization of the fracture toughness in short-fibre ceramic matrix composites. **2025**, *hal*-05048399v2

[39] Suwal R, Weck A, Chen K. Degradation and Failure Analysis of Environmental Barrier Coatings Under Adverse Operational Environment: Multi-physics Modeling. *J. Therm. Spray Tech*., **2026**. https://doi.org/10.1007/s11666-025-02152-8,

[40] Romedenne M, Pillai R, Dryepondt S, Pint B. The Impact of Oxidation-Induced Degradation on Materials Used in Hydrogen-Fired Microturbines, *J. Eng. Gas Turbines Power*. Apr **2024**, 146(4): 041010 (9 pages).

[41] Jacobson N S, Opila E J, Lee K N. Oxidation and corrosion of ceramics and ceramic matrix composites. *Curr. Opin. Solid State Mater. Sci.* **2001**, *5* 301–309.

[42] Padture N P. Environmental degradation of high-temperature protective coatings for ceramic-matrix composites in gas-turbine engines. *npj. Mater. Degrad*. **2019**, 3, 11