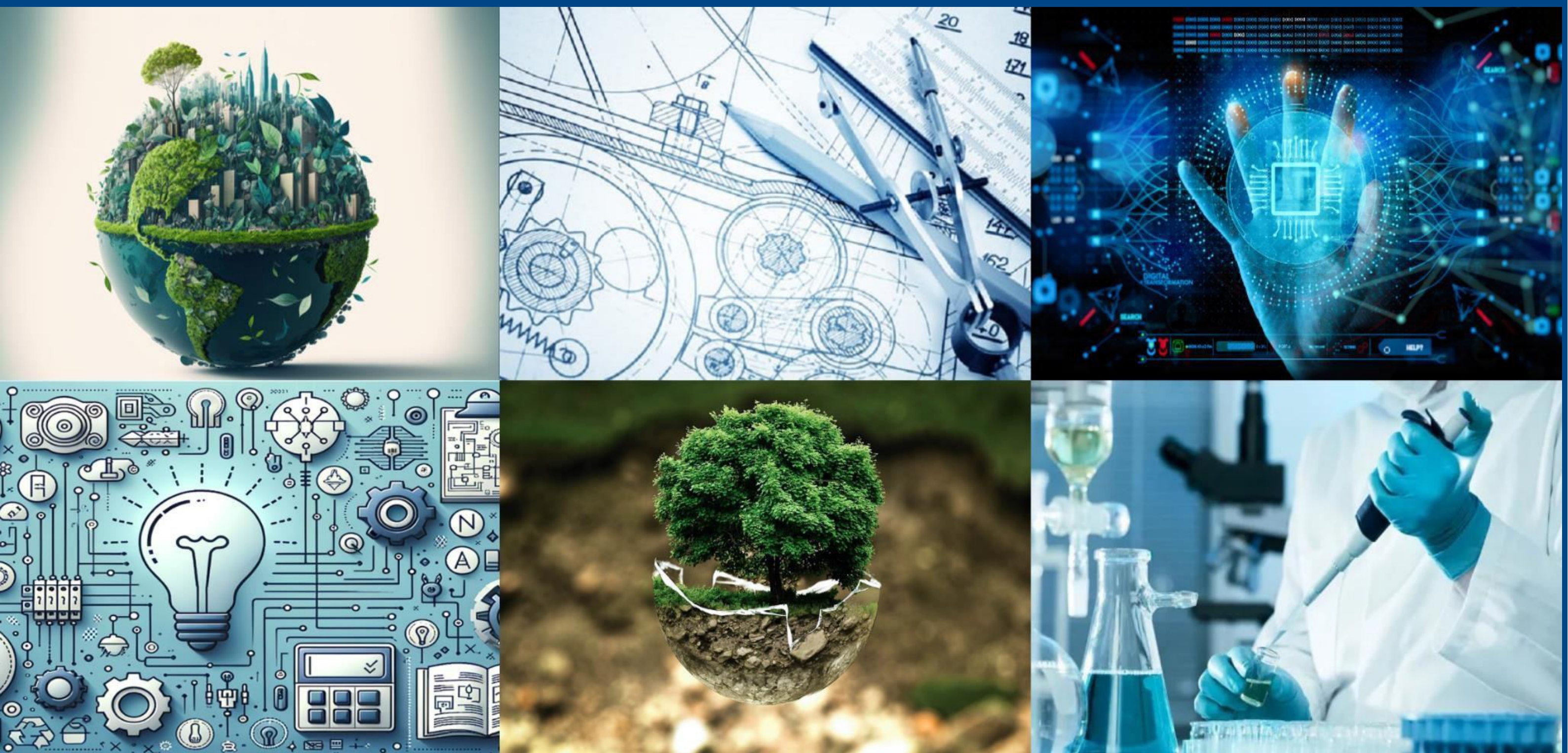
ISSN: 2582-7219

International Journal of Multidisciplinary Research in Science, Engineering and Technology

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)



Impact Factor: 8.206

Volume 8, Issue 9, September 2025

www.ijmrset.com ijmrset@gmail.com +91 6381 907 438 +91 63819 07438

© 2025 IJMRSET | Volume 8, Issue 9, September 2025| DOI:10.15680/IJMRSET.2025.0809004

ISSN: 2582-7219 | www.ijmrset.com | Impact Factor: 8.206| ESTD Year: 2018|

International Journal of Multidisciplinary Research in Science, Engineering and Technology (IJMRSET)

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)

A Review on Fracture Mechanisms and Progress in Thermal Barrier Coatings under Extreme Humid-Hot Environments

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ABSTRACT: Digital Investigation on the cloud platform is a challenging task. Preservation of evidences is the ultimate goal behind performing cloud forensics. In the Virtual Scenario, Virtual Machines contain evidences. If once VMDK (Virtual Machine Disk file) is destroyed, it is impossible to recover your VM. At present there does not exist a single mechanism that can recover a destroyed (deleted) VM again which is the flaw in VM itself. All the activities on the VM is logged in VM, whereas activities of CSP (Cloud Service Provider) is logged on the server. So even if someone deleted the VM, all the evidences will be lost. This creates a disaster for the user and acts as a barrier for a forensic investigator to dig out the private crucial data of user that was stored in the Virtual Machine sometime. We proposed with this research work, we explore the existing mechanisms and challenges in the current cloud scenario and propose an idea to prevent the unauthorized deletion of the Virtual Machines snapshots.

I. INTRODUCTION

The relentless pursuit of higher efficiency and performance in gas turbine engines for aviation and power generation necessitates continuously increasing turbine inlet temperatures. Advanced nickel-based superalloys, the workhorse materials for hot-section components, are operating near their melting point limits [1]. Thermal barrier coating (TBC) systems have become an indispensable enabling technology, providing thermal insulation that can reduce underlying metal surface temperatures by 100–300 °C, thereby enhancing component durability and allowing for higher operating temperatures or reduced cooling requirements [2].

A conventional TBC system is a multi-layered structure comprising: (i) a Ni/Co-based superalloy substrate; (ii) an oxidation-resistant metallic bond coat (BC, e.g., MCrAlY, M = Ni, Co, or Pt-modified γ-Ni/γ'-Ni3Al aluminide); (iii) a thermally grown oxide (TGO) layer, predominantly α-Al2O3, which forms at the BC/top coat interface during high-temperature exposure and provides oxidation protection; and (iv) a ceramic top coat (TC) with low thermal conductivity and high thermal stability. The state-of-the-art TC material is 6–8 wt.% yttria-stabilized zirconia (YSZ), prized for its relatively high coefficient of thermal expansion (CTE), low thermal conductivity, and good fracture toughness attributable to its metastable t' phase [3].

Under ideal high-temperature cyclic conditions, TBC failure primarily results from thermomechanical fatigue driven by CTE mismatch stresses between the metallic and ceramic layers, culminating in crack initiation, propagation, and eventual spallation of the TC [4]. However, engines operating in marine, coastal, or tropical environments—characterized by high humidity, high salinity, and pollutants—face a significantly more aggressive degradation landscape. The ingestion of moisture and airborne salts (e.g., NaCl, Na2SO4, CaO-MgO-Al2O3-SiO2 – CMAS) leads to complex thermochemical and thermomechanical interactions that severely exacerbate TBC damage [5, 6]. Fracture, often mediated by these environmental attacks, becomes the dominant failure mode, leading to premature and sometimes catastrophic spallation.

This review synthesizes the recent research progress on fracture mechanisms of TBCs under extreme humid-hot conditions. It examines the underlying damage processes induced by water vapor and molten salts, discusses advanced characterization and modeling techniques, surveys emerging strategies for performance enhancement, and outlines future research challenges and opportunities.

II. TBC SYSTEM AND HUMID-HOT ENVIRONMENTAL THREATS

1. Standard TBC Configuration
The performance of a TBC system hinges on the integrity of its constituents and their interfaces. The BC provides adhesion and oxidation resistance. The TGO, if slow-growing, dense, and adherent (α-Al_2O_3), is protective. The YSZ TC provides thermal insulation. This system is typically applied via air plasma spraying (APS), producing a lamellar, micro-cracked structure, or by electron beam physical vapor deposition (EB-PVD), yielding a columnar microstructure with superior strain tolerance [3].

2. Characteristics of Humid-Hot Environments
Extreme humid-hot environments are defined by high partial pressures of water vapor (H_2O(g)) and the presence of salt aerosols (Na^+, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}). Upon ingestion, these contaminants deposit on cooler sections and can be ingested onto hotter surfaces during transients. At high surface temperatures, water vapor becomes highly reactive, and salts melt (e.g., CMAS melts ~1200–1240 °C), initiating corrosive attacks that profoundly alter the failure mechanisms from pure thermomechanical fatigue to environment-assisted fracture [5, 7].

III. FRACTURE MECHANISMS IN HUMID-HOT ENVIRONMENTS

1. Water Vapor-Induced Fracture
Accelerated Sintering and Destabilization: High-temperature water vapor exposure accelerates the sintering of YSZ, reducing porosity, increasing elastic modulus, and diminishing strain tolerance, making the coating more brittle and susceptible to cracking [8]. Crucially, water vapor reacts with Y_2O_3 stabilizer, leading to its selective leaching via formation of volatile $Y(OH)_3$ or yttrium oxyhydroxides [9]. This depletes Y_2O_3 content in the t'-YSZ, promoting its deleterious transformation to the monoclinic (m-ZrO_2) phase upon cooling. The associated ~3–5% volume expansion generates substantial localized stresses, initiating microcracks that serve as pathways for further corrosive ingress and coalesce into macro-cracks.

TGO Degradation and Interfacial Fracture: H_2O(g) permeates through the TC porosity and cracks to the TGO interface. It drastically accelerates TGO growth by providing rapid transport paths for oxygen species [10]. More detrimentally, it disrupts the formation of protective, dense α-Al_2O_3, fostering the growth of non-protective, voluminous, and poorly adherent mixed oxides (e.g., spinels ($Ni(Cr,Al)_2O_4$), NiO, Cr_2O_3) [11]. This degraded TGO morphology, coupled with accelerated growth stresses, significantly reduces interfacial fracture toughness, promoting crack initiation and propagation along the vulnerable TC/TGO/BC interfaces.

2. Molten Salt (CMAS) Infiltration and Corrosion Fracture
Infiltration and Thermomechanical Cracking: Molten CMAS salts wet the YSZ surface and infiltrate the coating's porosity and cracks via capillary action. Upon cooling, the solidified CMAS, with a CTE often lower than YSZ, constrains the ceramic skeleton, generating tensile stresses that initiate microcracking [12].

Chemical Dissolution-Reprecipitation and Embrittlement: Molten CMAS reacts aggressively with YSZ, dissolving it and reprecipitating non-transformable, globular Y-lean ZrO_2 grains (often monoclinic or cubic) and crystalline reaction products like apatite ($Ca_2Y_8(SiO_4)_6O_2$) or garnet [13, 14]. This process destroys the beneficial microstructure (e.g., columnar gaps or strain-tolerant pores), creating a dense, infiltrated zone with altered composition and drastically reduced fracture toughness. This brittle zone is highly prone to cracking under thermal stress, leading to large-scale spallation.

3. Synergistic Thermo-Mechanical-Chemical (TMC) Fatigue
In practice, fracture results from the synergy of thermal cycling (mechanical stress), water vapor, and salt corrosion. Chemical attacks continuously degrade material properties, weaken interfaces, and introduce flaws, thereby reducing the intrinsic strength and fracture toughness. Concurrently, cyclic thermomechanical stresses facilitate the transport of corrosive species, open/close cracks for infiltration, and drive crack propagation from these stress concentrators. This TMC fatigue leads to lifetime reduction far exceeding the sum of individual damage contributions [15].

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IV. EXPERIMENTAL AND MODELING APPROACHES

1. Environmental Simulation and Testing
Furnaces with controlled atmosphere capabilities (precise H2O(g) partial pressure, salt deposition setups) are used to simulate service environments. Cyclic tests combining thermal shocks with exposure to humid air or salt spray are essential for replicating TMC fatigue damage [16].

2. Advanced Characterization
In-Situ Monitoring: Environmental SEM (ESEM), high-temperature confocal microscopy, and acoustic emission (AE) sensing allow real-time observation of crack initiation and propagation under controlled atmospheres [17].

Fracture Mechanics Testing: Four-point bend tests on notched samples, coupled with digital image correlation (DIC), are used to measure interfacial fracture toughness (e.g., at TGO/BC interface) and assess its degradation after environmental exposure [18].

Stress Analysis: Photostimulated luminescence spectroscopy (PLPS) is a powerful non-destructive technique for measuring residual stresses in the TGO layer, a key indicator of impending failure [19].

3. Computational Modeling
Multi-scale modeling is increasingly employed. Finite element analysis (FEA) simulates stress evolution and crack propagation under coupled thermal and chemical loading. First-principles calculations and molecular dynamics (MD) explore atomic-scale interactions, such as H2O adsorption on YSZ grain boundaries and ion diffusion mechanisms, providing fundamental insights into degradation physics.

V. STRATEGIES FOR ENHANCED FRACTURE RESISTANCE

1. Novel Top Coat Materials
Rare-Earth Zirconates: Materials like Gd2Zr2O7 (GZO) and Sm2Zr2O7 offer lower thermal conductivity and superior phase stability than YSZ. Their greatest advantage is exceptional CMAS resistance; they react with CMAS to form a dense, protective apatite or garnet layer that blocks further infiltration.

Doped/Composite YSZ: Co-doping YSZ with elements like Ta, Ti, or Nb can improve phase stability and sintering resistance. Compositing YSZ with Al2O3 nanoparticles can seal pores, improving erosion resistance and potentially acting as a barrier against corrosive species.

High-Entropy Ceramics (HECs): Emerging HECs (e.g., (La0.2Ce0.2Nd0.2Sm0.2Eu0.2)2Zr2O7) exhibit unique cocktail effects, promising an optimized balance of thermophysical properties, fracture toughness, and corrosion resistance due to their severe lattice distortion and slow diffusion kinetics.

2. Structural Design and Optimization
Double-Layer/Graded Designs: A common approach is a bilayer TC with a YSZ base layer (for CTE compatibility and toughness) and a rare-earth zirconate surface layer (for environmental resistance). Functionally graded materials (FGMs) with a gradual transition in composition or porosity can further mitigate interfacial stress concentrations.

Sealing Layers: Applying a thin, dense overlay coating (e.g., Al2O3, mullite, Pt) via sol-gel or ALD can effectively seal surface porosity, providing a physical barrier against CMAS and water vapor penetration.

3. Processing Innovations
New Deposition Techniques: Plasma Spray-Physical Vapor Deposition (PS-PVD) can create columnar microstructures with enhanced strain tolerance while offering higher deposition rates than EB-PVD. Spark Plasma Sintering (SPS) can produce nano-structured, dense coatings with improved mechanical properties.

Surface Modification: Laser glazing remelts the TC surface, creating a dense, segmented layer that is highly resistant to CMAS wetting and infiltration, while the segmented cracks maintain in-plane strain tolerance .

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VI. CHALLENGES AND FUTURE PERSPECTIVES

Despite significant progress, formidable challenges remain:

1. Fundamental Understanding of Multi-Field Coupling: A deeper, mechanistic understanding of the synergistic effects between thermal stress, water vapor chemistry, salt composition, and mechanical load is needed, requiring more sophisticated in-situ and operando characterization tools.
2. Materials Genomics and AI-Driven Design: Integrating computational thermodynamics, machine learning, and high-throughput experimentation will accelerate the discovery and optimization of next-generation TBC materials, particularly HECs and complex composites, tailored for humid-hot environments.
3. Long-Term Durability and Lifing Models: Developing reliable lifetime prediction models that incorporate environmental degradation factors is critical for engineering design and condition-based maintenance. These models must be validated against long-term TMC fatigue data.
4. Advanced Protection Systems: Research into more durable and self-healing sealing concepts, as well as the integration of environmental barrier coating (EBC) principles for TBCs, represents a promising frontier.

VII. CONCLUSION

The fracture of TBCs in extreme humid-hot environments is a complex failure mode driven by the synergistic interplay of water vapor corrosion, molten salt attack, and accelerated TGO degradation, all under cyclic thermomechanical loading. These processes lead to severe embrittlement, loss of strain tolerance, interfacial weakening, and ultimately, spallation. Research has made substantial strides in elucidating these mechanisms through advanced experimental and computational methods. In response, innovative strategies focusing on new material systems (e.g., zirconates, HECs), multilayer/graded architectures, and novel processing routes are being actively pursued to enhance fracture resistance. The path forward requires a concerted effort to unravel multi-field coupling phenomena, leverage materials informatics for accelerated discovery, and develop predictive models that ensure the reliability of future gas turbine engines operating in the world's most demanding environments.

Acknowledgements: This work was supported by the Hunan Provincial Natural Science Foundation, China (Grant No.2025JJ70384); Yiyang Science and Technology Plan Project (No. 2024YR04) and Innovative projects for college students in hunan city university (No. S202511527093).

REFERENCES

[1] Padture N P. Thermal barrier coatings for gas-turbine engine applications[J]. Science, 2002, 296(5566): 280-284.
[2] Clarke D R, Oechsner M, Padture N P. Thermal-barrier coatings for more efficient gas-turbine engines[J]. MRS Bulletin, 2012, 37(10): 891-898.
[3] Hutchinson J W, Evans A G. On the delamination of thermal barrier coatings in a thermal gradient[J]. Surface and Coatings Technology, 2002, 149(2): 179-184.
[4] Sundaram S, Lipkin D M, Johnson C A, Hutchinson J W. The influence of transient thermal gradients and substrate constraint on delamination of thermal barrier coatings[J]. Journal of Applied Mechanics, 2012, 80(1): 011002.
[5] Chichkov B N, Momma C, Nolte S, von Alvensleben F, Tünnermann A. Femtosecond, picosecond and nanosecond laser ablation of solids[J]. Applied Physics A, 1996, 63(2): 109-115.
[6] Chandrasekharaiah D S. Hyperbolic thermoelasticity: a review of recent literature[J]. Applied Mechanics Reviews, 1998, 51: 705-730.
[7] Ezzat M A, El-Karamany A S, Fayik M A. Fractional ultrafast laser-induced thermo-elastic behavior in metal films[J]. Journal of Thermal Stresses, 2012, 35(7): 637-651.
[8] Xu H-Y, Jiang X-Y. Time fractional dual-phase-lag heat conduction equation[J]. Chinese Physics B, 2015, 24(3): 034401.
[9] Jiang F. Taylor & Francis, 2003. Non-Fourier Heat Conduction Phenomena in Porous Material Heated by Microsecond Laser Pulse[J]. Microscale Thermophysical Engineering, 2003, 6(4): 331-346.
[10] Akwaboa S, Mensah P, Beyazouglu E, Diwan R. Thermal modeling and analysis of a thermal barrier coating structure using non-fourier heat conduction[J]. Journal of Heat Transfer, 2012, 134(11): 111301.
[11] Chen Z T, Hu K Q. Thermoelastic analysis of a cracked substrate bonded to a coating using the hyperbolic heat conduction theory[J]. Journal of Thermal Stresses, 2014, 37(3): 270-291.

[12] Zhang X, Zhang L, Chu Z. Thermomechanical coupling of non-fourier heat conduction with the c-v model: thermal propagation in coating systems[J]. Journal of Thermal Stresses, 2015, 38(10): 1104-1117.
[13] Zhang X-Y, Chen Z-T, Li X-F. Non-Fourier fractional heat conduction in two bonded dissimilar materials with a penny-shaped interface crack[J]. International Journal of Thermal Sciences, 2019, 140: 319-328.
[14] Evans A G, Hutchinson J W. The mechanics of coating delamination in thermal gradients[J]. Surface and Coatings Technology, 2007, 201(18): 7905-7916.
[15] Song Y, Zhuan X, Wang T J, Chen X. Evolution of thermal stress in a coating/substrate system during the cooling process of fabrication[J]. Mechanics of Materials, 2014, 74: 26-40.
[16] Song Y, Lv Z, Liu Y, Zhuan X, Wang T J. Effects of coating spray speed and convective heat transfer on transient thermal stress in thermal barrier coating system during the cooling process of fabrication[J]. Applied Surface Science, 2015, 324: 627-633.
[17] Fan X L, Xu R, Zhang W X, Wang T J. Effect of periodic surface cracks on the interfacial fracture of thermal barrier coating system[J]. Applied Surface Science, 2012, 258(24): 9816-9823.
[18] Ueda S, Nakano Y. A normal crack in a functionally graded thermal barrier coating bonded to a homogeneous elastic substrate under transient thermal loading[J]. Journal of Thermal Stresses, 2018, 41(10): 1487-1500.
[19] Zhang P, He T. A generalized thermoelastic problem with nonlocal effect and memorydependent derivative when subjected to a moving heat source[J]. Waves in Random and Complex Media, 2020, 30(1): 142-156.

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