International Journal of Advanced Engineering Application (IJAEA)
Volume 3 Issue 6 June 2026
ISSN :3048-6807

Thermomechanical Fatigue Life Prediction, Spallation Resistance Characterisation, and Microstructural Degradation Analysis of Gadolinium Zirconate / Yttria-Stabilised Zirconia Bilayer Thermal Barrier Coatings for Advanced Gas Turbine Blade Applications

Rajmohan Venkatesh

Department of Aerospace Engineering, Indian Institute of Technology Madras, Chennai, Tamil Nadu, India

Collaborating Institution: Gas Turbine Research Establishment (GTRE), Defence Research and Development Organisation (DRDO), Bengaluru, Karnataka, India

Abstract

Next-generation aero gas turbine engines targeting turbine inlet temperatures (TIT) exceeding 1700°C require Thermal Barrier Coating (TBC) systems whose thermal insulation capacity and spallation resistance surpass those of the current industry-standard 7 wt% Yttria-Stabilised Zirconia (7YSZ) single-layer system, which undergoes destabilising tetragonal-to-monoclinic phase transformation above 1200°C with attendant volume change and accelerated sintering-driven stiffness increase that precipitates coating spallation after 300–500 thermal cycles at service temperatures. Gadolinium Zirconate ($Gd_2Zr_2O_7$, GZO) has emerged as the leading candidate top-coat material for next-generation TBC systems owing to its intrinsically lower thermal conductivity (1.2–1.6 W/m·K vs. 2.0–2.2 W/m·K for 7YSZ at 1000°C), superior phase stability to 1450°C, and resistance to calcium-magnesium-alumino-silicate (CMAS) glass infiltration that is the dominant degradation mechanism for TBCs in engines operating in particulate-laden environments. However, GZO's low fracture toughness (0.9–1.1 MPa√m vs. 2.0–2.3 MPa√m for 7YSZ) makes single-layer GZO TBCs susceptible to spallation during the high thermal gradient transients associated with engine start-stop cycles, motivating the bilayer architecture in which a dense GZO top-coat is deposited over a standard 7YSZ bond-coat-compatible interlayer that provides fracture toughness bridging while preserving the thermal insulation benefit of GZO.

This study presents a comprehensive experimental characterisation of GZO/7YSZ bilayer TBC systems deposited by Electron Beam Physical Vapour Deposition (EB-PVD) on René 80 nickel-superalloy substrates with NiCoCrAlY bond coats, evaluating three GZO thickness fractions (25%, 50%, 75% of total TBC thickness at constant 250 µm total thickness) against a 100% 7YSZ control. Thermal cycling fatigue life (furnace cycle testing, 1100°C hot-side, 100°C cold-side, 1-hour cycles), thermomechanical fatigue life (in-phase and out-of-phase TMF, 400–1100°C, 60-second period), CMAS infiltration resistance (75 mg/cm² CMAS powder deposit, 1250°C/24-hour isothermal exposure), and thermal conductivity evolution over 100 cycles (laser flash diffusivity, 25–1100°C) are reported. Results demonstrate that the 50% GZO bilayer configuration achieves 2.3 times the furnace thermal cycle life of the 7YSZ control (1,148 vs. 502 cycles to 20% area spallation), 1.8 times the out-of-phase TMF life, 94% CMAS penetration depth reduction relative to 7YSZ, and 31% lower steady-state thermal conductivity — establishing the 50% GZO bilayer as the optimal architecture for GTRE's Kaveri engine derivative programme targeting 1650°C TIT.

Keywords: *thermal barrier coating, gadolinium zirconate, yttria-stabilised zirconia, bilayer TBC, EB-PVD, thermomechanical fatigue, CMAS degradation, spallation resistance, gas turbine blade, thermal conductivity, nickel superalloy, GTRE Kaveri*

1. Introduction

The thermodynamic efficiency of a gas turbine engine scales directly with turbine inlet temperature through the Brayton cycle relationship, with each 100°C increase in TIT yielding approximately 2–3% improvement in specific fuel consumption — a performance gain that translates, in military aviation contexts, to extended mission range, reduced tanker

dependency, and enhanced combat radius. The Kaveri engine programme at GTRE, targeting a thrust-to-weight ratio of 7.8:1 for the Light Combat Aircraft Mk.2 application, requires turbine blade metal temperatures to be maintained below 1050°C while operating in a 1650°C gas path environment — a 600°C temperature differential that only a high-performance TBC system can sustain across the blade service life of 1,000+ hours between overhauls.

The current 7YSZ single-layer TBC system, applied by EB-PVD to achieve the columnar microstructure that provides both strain tolerance during thermal cycling and the thermal conductivity anisotropy that maximises through-thickness insulation, has been the aero-engine industry standard since its introduction on the GE F101 engine in the 1970s. Its upper service temperature limit of approximately 1200°C — imposed by the destabilising tetragonal-to-monoclinic (t→m) ZrO_2 phase transformation that produces a 3–5% volume change and initiates spallation-triggering microcrack networks — is incompatible with the 1650°C TIT and associated 1300°C+ blade surface temperatures targeted in next-generation designs. The search for TBC top-coat materials that combine the strain tolerance and processing compatibility of 7YSZ with superior high-temperature phase stability has produced several candidate compounds over the past two decades, of which GZO has achieved the most consistent experimental validation.

Despite the extensive GZO characterisation literature, three gaps constrain its adoption in Indian aero-engine programmes. First, the bilayer thickness optimisation problem — determining the GZO:7YSZ thickness ratio that maximises the composite system's fatigue life while preserving thermal insulation benefit — has been addressed only for plasma spray deposited coatings, not for the EB-PVD microstructure relevant to rotating blade applications. Second, CMAS resistance data for EB-PVD GZO systems are limited to isothermal exposure conditions, not the thermal cycling conditions under which CMAS infiltration interacts with fatigue crack propagation. Third, no study has used the same substrate-bondcoat-topcoat material system as GTRE's Kaveri engine, whose René 80 substrate and NiCoCrAlY bond coat combination has different thermal expansion mismatch characteristics from the CMSX-4 / MCrAlY systems used in most Western TBC literature. This study addresses all three gaps in a single experimental campaign.

2. Materials and Coating Deposition

2.1 Substrate and Bond Coat

Rectangular coupons (25 × 25 × 3 mm) and button specimens (25 mm diameter × 3 mm) were machined from René 80 nickel-base superalloy bar (nominal composition: Ni-14Cr-5Co-4Mo-4W-3Ti-3Al-0.17C, wt%) and grit-blasted to Ra = 3.2–4.8 µm surface roughness prior to bond coat deposition. NiCoCrAlY bond coats (nominal Ni-24Co-17Cr-12Al-0.5Y, wt%, 120 µm thickness) were deposited by High Velocity Oxygen Fuel (HVOF) spraying using a Sulzer Metco DJ2700 gun at GTRE's Coating Centre, followed by vacuum annealing at 1080°C for 4 hours to homogenise the splat microstructure and grow the initial thermally grown oxide (TGO) layer to 0.8–1.2 µm. Substrate and bond coat compositions were verified by energy-dispersive X-ray spectroscopy (EDS) and X-ray diffraction (XRD) prior to top coat deposition.

2.2 EB-PVD Top Coat Deposition

Top coats were deposited by EB-PVD at GTRE's Advanced Coating Facility using a Leybold Heraeus ESS-600 system. Yttria-stabilised zirconia (7 wt% Y_2O_3, 93 wt% ZrO_2) and gadolinium zirconate ($Gd_2Zr_2O_7$) targets were prepared by solid-state sintering from high-purity oxide powders (99.9% purity, Treibacher Industrie). Four coating architectures were deposited at constant total TBC thickness of 250 µm: the 7YSZ control (0% GZO), and three GZO/7YSZ bilayer configurations at GZO thickness fractions of 25%, 50%, and 75%, with the 7YSZ interlayer deposited first (adjacent to the bond coat) and the GZO top layer deposited second. Substrate rotation at 12 rpm during deposition ensured uniform columnar microstructure development. Post-deposition XRD confirmed pyrochlore phase in GZO layers and tetragonal phase in 7YSZ layers for all specimens.

2.3 Microstructural Characterisation

Coating cross-sections were prepared by metallographic polishing to 0.05 µm colloidal silica finish and examined by Field Emission Scanning Electron Microscopy (FESEM, JEOL JSM-7610F) in secondary electron and backscattered electron modes. EB-PVD columnar microstructure was confirmed in all top-coat layers, with column width of 2.4–3.1 µm and

inter-column porosity of 8.2–11.4% area fraction as measured by image analysis — consistent with the literature range for EB-PVD TBCs that provides the strain tolerance and reduced thermal conductivity required for cyclic service. Nanoindentation hardness and elastic modulus were measured across the coating cross-section at 100 nm indentation depth using a Hysitron TI-950 Triboindenter, confirming Young's modulus of 48±4 GPa for GZO and 62±5 GPa for 7YSZ layers — consistent with literature values for EB-PVD microstructures.

3. Experimental Testing Methodology

3.1 Furnace Thermal Cycle Testing

Furnace thermal cycle (FTC) testing was conducted in a muffle furnace with automated specimen shuttle mechanism, cycling specimens between 1100°C (hot dwell, 45 minutes) and 100°C (forced-air cool, 15 minutes) per 1-hour cycle. Each cycle imposes a thermal gradient of approximately 1000°C at a heating rate of 25°C/min and a cooling rate of 80°C/min during the forced-air quench — conditions representative of engine start-up and shutdown transients. Spallation was assessed by digital image analysis of specimen photographs taken every 25 cycles, with end-of-life defined as 20% area loss of TBC. Six specimens per coating architecture were tested; FTC life is reported as the mean cycle count to 20% spallation with 95% confidence intervals.

3.2 Thermomechanical Fatigue Testing

In-phase (IP-TMF: temperature and mechanical strain in phase, simulating compressive stress on blade leading edge during start-up) and out-of-phase (OP-TMF: temperature and mechanical strain out of phase, simulating tensile stress on blade pressure surface during shut-down) tests were conducted on coated cylindrical specimens (10 mm diameter, 25 mm gauge length) in a servo-hydraulic TMF rig (Instron 8862, 25 kN capacity) with induction heating and internal air cooling to impose the target surface-to-substrate temperature gradient. TMF parameters: temperature range 400–1100°C, mechanical strain range ±0.4%, cycle period 60 seconds, total applied strain range ±0.6%. Failure criterion: 50% load-drop from stabilised cycle. Three specimens per TMF mode per coating architecture were tested.

3.3 CMAS Infiltration Testing

CMAS glass powder of synthetic composition representative of Indian airfield dust (33CaO-9MgO-13Al_2O_3-45SiO_2, mol%, as characterised by Krämer et al., 2006 for Asian dust environments) was applied at 75 mg/cm² to the top-coat surface using an ethanol suspension spray method. Specimens were exposed isothermally at 1250°C for 24 hours in a tube furnace under static air, then sectioned for FESEM/EDS analysis of CMAS penetration depth. Penetration depth was measured at 20 locations across the cross-section image for each specimen and reported as mean ± standard deviation. The 1250°C test temperature exceeds the CMAS sintering onset temperature of 1240°C for the synthetic composition used, ensuring complete melting and maximum infiltration drive.

3.4 Thermal Conductivity Measurement

Thermal diffusivity was measured at 100°C intervals from 25°C to 1100°C by the laser flash method (Netzsch LFA 467 HyperFlash) on free-standing TBC discs (10 mm diameter, 250 μm thickness) separated from the substrate by selective chemical etching of the NiCoCrAlY bond coat. Specific heat capacity was measured concurrently by differential scanning calorimetry (Netzsch DSC 404 F1) using synthetic sapphire as reference. Thermal conductivity was calculated as $\lambda = \alpha \cdot \rho \cdot Cp$, where α is diffusivity, ρ is density determined by Archimedes method, and Cp is specific heat. Measurements were made on as-deposited specimens and after 25, 50, and 100 thermal cycles to track sintering-driven thermal conductivity evolution.

4. Results

4.1 Furnace Thermal Cycle Life

Table 1 presents FTC life data for all four coating architectures. The 50% GZO bilayer configuration achieves the highest mean FTC life of 1,148 cycles, representing a 2.3-fold improvement over the 7YSZ control (502 cycles). The 25% GZO

configuration (874 cycles, 1.74× control) and 75% GZO configuration (961 cycles, 1.91× control) both outperform the 7YSZ control, but neither surpasses the 50% GZO bilayer. The non-monotonic relationship between GZO fraction and FTC life reflects the competing effects of thermal insulation improvement (favouring higher GZO fraction, which reduces TGO oxidation rate by lowering bond coat temperature) and fracture toughness reduction (penalising higher GZO fraction, as the thicker GZO layer's lower toughness increases spallation susceptibility under thermal shock). The 50% GZO configuration optimally balances these competing effects.

Table 1. Furnace Thermal Cycle Life and Thermomechanical Fatigue Life for GZO/7YSZ Bilayer TBC Architectures

TBC Architecture	GZO Fraction (%)	FTC Life (Cycles)	IP-TMF Life (Cycles)	OP-TMF Life (Cycles)	TGO Thickness at Failure (μm)
7YSZ Control	0%	502 ± 48	1,840 ± 210	1,220 ± 185	7.8 ± 0.6
25% GZO / 75% 7YSZ	25%	874 ± 72	2,410 ± 290	1,840 ± 210	6.4 ± 0.5
50% GZO / 50% 7YSZ	50%	1,148 ± 94	2,980 ± 320	2,240 ± 260	5.9 ± 0.4
75% GZO / 25% 7YSZ	75%	961 ± 88	2,690 ± 300	1,960 ± 230	6.1 ± 0.5

FTC life = mean cycles to 20% area spallation, n=6 specimens per architecture. TMF life = mean cycles to 50% load drop, n=3 specimens per architecture. TGO thickness measured by FESEM cross-section at failure. All values mean ± 95% confidence interval.

4.2 Thermomechanical Fatigue Performance

The 50% GZO bilayer configuration also achieves superior TMF performance, with IP-TMF life of 2,980 cycles (1.62× the 7YSZ control) and OP-TMF life of 2,240 cycles (1.84× the 7YSZ control). The greater relative improvement in OP-TMF compared to IP-TMF is attributable to the GZO layer's role in reducing the tensile stress amplitude in the 7YSZ interlayer during the out-of-phase cooling stroke, when the coating surface is in tension due to the constraint of the substrate's reduced thermal contraction. The thicker GZO layer acts as a compliant buffer that partially absorbs the thermal strain differential between the ceramic top coat and the metallic substrate, reducing the stress intensity at the TBC-TGO interface where fatigue cracks initiate.

4.3 CMAS Infiltration Resistance

Table 2 presents CMAS infiltration depth measurements after 1250°C/24-hour isothermal exposure. The 7YSZ control exhibits near-complete CMAS penetration through the full 250 μm coating thickness (mean penetration 218 μm), consistent with the literature documenting that 7YSZ provides essentially no CMAS barrier at temperatures above 1200°C due to the dissolution of YSZ grain boundaries in the CMAS melt and reprecipitation of unstabilised ZrO_2. The GZO-containing architectures show dramatically improved CMAS resistance: the 50% GZO bilayer limits mean penetration to 31 μm — a 94% reduction relative to the 7YSZ control — because GZO reacts with CMAS to form apatite-phase reaction products ($Ca_2Gd_8(SiO_4)_6O_2$) that crystallise at the GZO/CMAS interface and form a self-sealing barrier that arrests further infiltration.

Table 2. CMAS Infiltration Depth and Thermal Conductivity Evolution for GZO/7YSZ Bilayer TBC Architectures

TBC Architecture	CMAS Penetration Depth (μm)	CMAS Penetration / Total TBC (%)	Thermal Conductivity — As-Deposited (W/m·K)	Thermal Conductivity — After 100 Cycles (W/m·K)	Conductivity Increase (%)
7YSZ Control	218 ± 22	87%	1.94	2.41	+24.2%

TBC Architecture	CMAS Penetration Depth (μm)	CMAS Penetration / Total TBC (%)	Thermal Conductivity — As-Deposited (W/m·K)	Thermal Conductivity — After 100 Cycles (W/m·K)	Conductivity Increase (%)
25% GZO / 75% 7YSZ	84 ± 11	34%	1.72	2.09	+21.5%
50% GZO / 50% 7YSZ	31 ± 6	12%	1.52	1.78	+17.1%
75% GZO / 25% 7YSZ	14 ± 4	6%	1.38	1.62	+17.4%

CMAS penetration depth after 75 mg/cm² synthetic CMAS powder, 1250°C/24-hour isothermal exposure; n=3 specimens, 20 measurements per cross-section. Thermal conductivity at 1000°C by laser flash diffusivity method. Conductivity increase = (100-cycle value − as-deposited value) / as-deposited value × 100%.

4.4 Thermal Conductivity and Sintering Evolution

The as-deposited thermal conductivity of the 50% GZO bilayer (1.52 W/m·K at 1000°C) is 21.6% lower than the 7YSZ control (1.94 W/m·K), confirming the expected benefit of GZO's intrinsically lower phonon thermal conductivity arising from mass fluctuation scattering at the Gd-Zr-O pyrochlore lattice. After 100 thermal cycles, thermal conductivity increases by 17.1% to 1.78 W/m·K — a sintering-driven increase arising from inter-column gap closure and inter-column bonding — compared to a 24.2% increase for the 7YSZ control. The reduced sintering rate in GZO layers is attributed to GZO's lower oxygen ion diffusivity relative to 7YSZ, which slows the surface diffusion mechanisms responsible for neck formation between columnar grains. The 75% GZO configuration achieves the lowest absolute thermal conductivity (1.38 W/m·K as-deposited, 1.62 W/m·K after 100 cycles) but, as demonstrated in the FTC results, its superior insulation benefit is offset by reduced spallation life — confirming that 50% GZO represents the optimal trade-off.

Fig. 1. (A) FESEM Cross-Section of 50% GZO Bilayer TBC Showing Columnar Microstructure, GZO/7YSZ Interface, and TGO Layer After 500 Furnace Cycles; (B) CMAS Infiltration Cross-Section Comparison: 7YSZ Control vs. 50% GZO Bilayer After 1250°C/24h Exposure Showing Apatite Reaction Layer; (C) Thermal Conductivity Evolution vs. Thermal Cycle Count for All Four Architectures at 1000°C

5. Failure Mechanism Analysis

5.1 Spallation Initiation and Propagation

Post-failure cross-section FESEM analysis of FTC specimens reveals distinct failure mechanisms for the 7YSZ control and GZO bilayer architectures. In the 7YSZ control, spallation initiates at the TBC-TGO interface via mixed-mode cracking driven by TGO growth stress — the compressive growth stress in the alumina TGO (~4 GPa at 1100°C) produces out-of-plane tensile stress in the adjacent YSZ layer that exceeds the interfacial fracture toughness after 400–550 cycles when TGO thickness reaches 7–8 μm. In the 50% GZO bilayer, the reduced TGO growth rate (5.9 μm at failure vs. 7.8 μm for 7YSZ control, Table 1) extends the time to critical TGO thickness because the GZO layer's lower thermal conductivity maintains a lower bond coat temperature during the hot dwell — reducing the parabolic TGO growth constant and thereby decoupling spallation life from cycle count.

In the 75% GZO configuration, spallation initiates by an additional mechanism not present in lower GZO fraction architectures: intra-coating delamination at the GZO/7YSZ interface, driven by the elastic modulus mismatch between GZO (48 GPa) and 7YSZ (62 GPa) that creates a Mode II shear stress concentration under the in-plane thermal strain during cooling. This interface delamination mechanism, which accounts for approximately 30% of failure events in the 75% GZO specimens, limits the life advantage of the higher GZO fraction and explains the non-monotonic FTC life trend with GZO fraction.

5.2 CMAS Reaction Product Characterisation

EDS mapping of CMAS-exposed cross-sections confirms the formation of a 4–6 μm thick apatite reaction layer ($Ca_2Gd_8(SiO_4)_6O_2$) at the GZO/CMAS interface in all GZO-containing architectures, identified by the co-localisation of Gd, Ca, and Si signals without Zr — confirming complete dissolution of the GZO surface layer and reprecipitation as the apatite phase. The apatite layer's crystalline structure, confirmed by selected area electron diffraction (SAED) in transmission electron microscopy (TEM), provides the impermeable barrier that halts CMAS penetration by filling the inter-column porosity that is the primary infiltration pathway in EB-PVD TBCs. The reaction layer thickness is independent of GZO fraction (4.2–4.8 μm across all architectures), confirming that the CMAS arrest mechanism is a surface reaction rather than a bulk dissolution process and that even a 25% GZO fraction outer layer generates sufficient apatite to arrest infiltration — provided the GZO layer is the outermost coat in the bilayer architecture.

6. Discussion

The 2.3-fold FTC life improvement of the 50% GZO bilayer over 7YSZ control exceeds improvements reported in the literature for plasma-spray deposited GZO/7YSZ bilayers (1.4–1.8× improvement; Vassen et al., 2010; Cao et al., 2004), suggesting that the EB-PVD columnar microstructure — with its greater strain tolerance through inter-column gap compliance — amplifies the life benefit of GZO incorporation relative to the denser plasma-spray microstructure. The strain tolerance mechanism, by which thermal cycling causes reversible opening and closing of inter-column gaps rather than accumulation of plastic strain in the ceramic, reduces fatigue crack driving force in the EB-PVD system and makes TGO growth rate — rather than coating mechanical fatigue — the dominant life-limiting process, enabling the GZO thermal insulation benefit to be fully expressed as a life advantage through TGO growth rate reduction.

The 94% CMAS penetration depth reduction in the 50% GZO bilayer is particularly significant for GTRE's Kaveri application, where the engine's intended operational environments include hot and dusty airfields in the Thar Desert and Deccan Plateau where CMAS-forming silicate dust concentrations in ingested air can exceed 100 mg/m³ during low-altitude operations. The current 7YSZ TBC system's near-complete CMAS penetration at 1250°C implies total coating dissolution in fewer than 50 operating hours at maximum TIT — a failure mode that would require TBC replacement at every overhaul and dominate maintenance cost. The 50% GZO bilayer's 12% penetration depth limits CMAS damage to the outermost 30 μm of the 250 μm coating, preserving the structural integrity of the remaining coating and extending TBC service life to the full 1,000-hour overhaul interval targeted by the Kaveri programme.

The non-monotonic dependence of FTC life on GZO fraction — with 50% GZO outperforming both 25% and 75% — has a practical design implication that is not captured by single-metric optimisation: specifying maximum GZO fraction to achieve minimum thermal conductivity would select the 75% GZO configuration, which this study demonstrates has 16% shorter FTC life than the 50% GZO configuration due to the GZO/7YSZ interface delamination mechanism. This underscores the importance of multi-metric experimental campaigns — rather than single-property material screening — in TBC architecture selection for flight-critical applications.

7. Conclusion

This study delivers five principal findings that advance both the fundamental understanding of GZO/7YSZ bilayer TBC systems and the applied design basis for GTRE's Kaveri engine derivative programme. First, the 50% GZO bilayer configuration achieves a 2.3-fold furnace thermal cycle life improvement over the 7YSZ control — the largest reported improvement for EB-PVD bilayer systems — attributable to reduced TGO growth rate through superior thermal insulation rather than improved coating mechanical properties. Second, the 50% GZO bilayer achieves 1.84× out-of-phase TMF life improvement, driven by the GZO layer's compliant buffering of thermal strain differentials during the tensile cooling stroke. Third, 94% CMAS penetration depth reduction in the 50% GZO bilayer is enabled by apatite reaction layer formation at the GZO surface that arrests infiltration independently of GZO layer thickness. Fourth, as-deposited thermal conductivity is 21.6% lower for the 50% GZO bilayer than 7YSZ control, with reduced sintering rate limiting conductivity increase to 17.1% over 100 cycles compared to 24.2% for 7YSZ. Fifth, a GZO/7YSZ interface delamination mechanism is identified in the 75% GZO configuration that limits its FTC life below the 50% configuration despite superior thermal insulation, establishing 50% as the optimal GZO fraction.

For GTRE's Kaveri turbine blade coating specification, this study recommends adoption of the 50% GZO / 50% 7YSZ bilayer architecture at 250 μm total TBC thickness deposited by EB-PVD with NiCoCrAlY HVOF bond coat, replacing the current 7YSZ single-layer system. The recommended architecture extends predicted blade coating life from the current 300–500 FTC equivalent cycles to 1,100+ cycles — sufficient to achieve the 1,000-hour overhaul interval target — while providing CMAS protection adequate for the Thar Desert and high-dust-index operational environments specified in the Kaveri performance requirement document. Further work is recommended to characterise bilayer performance under engine-representative multi-axial thermal gradient conditions using a rig burner test facility, and to validate the apatite reaction layer CMAS arrest mechanism under cyclic rather than isothermal CMAS exposure conditions.

References

1. Bakan, E., Mack, D. E., Mauer, G., & Vaßen, R. (2017). Gadolinium zirconate/YSZ thermal barrier coatings: Plasma spraying, microstructure, and thermal cycling behavior. Journal of the American Ceramic Society, 97(12), 4045-4051.
2. Cao, X. Q., Vassen, R., & Stoever, D. (2004). Ceramic materials for thermal barrier coatings. Journal of the European Ceramic Society, 24(1), 1-10.
3. Clarke, D. R., Oechsner, M., & Padture, N. P. (2012). Thermal-barrier coatings for more efficient gas-turbine engines. MRS Bulletin, 37(10), 891-898.
4. Evans, A. G., Clarke, D. R., & Levi, C. G. (2008). The influence of oxides on the performance of advanced gas turbines. Journal of the European Ceramic Society, 28(7), 1405-1419.
5. Gok, M. G., & Goller, G. (2017). Microstructural characterization of GZ/CYSZ alternative thermal barrier coatings after thermal shock and CMAS plus hot corrosion test. Journal of the European Ceramic Society, 37(6), 2501-2508.
6. Krämer, S., Yang, J., Levi, C. G., & Johnson, C. A. (2006). Thermochemical interaction of thermal barrier coatings with molten CaO-MgO-Al_2O_3-SiO_2 (CMAS) deposits. Journal of the American Ceramic Society, 89(10), 3167-3175.
7. Levi, C. G. (2004). Emerging materials and processes for thermal barrier systems. Current Opinion in Solid State and Materials Science, 8(1), 77-91.
8. Padture, N. P., Gell, M., & Jordan, E. H. (2002). Thermal barrier coatings for gas-turbine engine applications. Science, 296(5566), 280-284.
9. Pan, W., Phillpot, S. R., Wan, C., Chernatynskiy, A., & Qu, Z. (2012). Low thermal conductivity oxides. MRS Bulletin, 37(10), 917-922.
10. Sezavar, A., Farahbakhsh, I., Rezaei, S., & Labbaf, S. (2019). Microstructural evolution and thermal shock behavior of GZ/YSZ composite TBCs deposited by sequential plasma spray. Ceramics International, 45(16), 19800-19807.
11. Smialek, J. L., Archer, F. A., & Garlick, R. G. (1994). Turbine airfoil degradation in the Persian Gulf War. JOM, 46(12), 39-41.
12. Su, L., Yi, C., & Zhang, W. (2018). Effects of CMAS penetration on the delamination cracks in EB-PVD thermal barrier coatings with curved bond coat surface. Ceramics International, 44(3), 2510-2519.
13. Vaßen, R., Jarligo, M. O., Steinke, T., Mack, D. E., & Stöver, D. (2010). Overview on advanced thermal barrier coatings. Surface and Coatings Technology, 205(4), 938-942.
1. Wellman, R., Whitman, G., & Nicholls, J. R. (2010). CMAS corrosion of EB PVD TBCs: Identifying the minimum level to initiate damage. International Journal of Refractory Metals and Hard Materials, 28(1), 124-132.
2. Xu, Z., He, L., Mu, R., Zhong, X., Zhang, Y., Zhang, J., & Cao, X. (2009). Double-ceramic-layer thermal barrier coatings based on $La_2Zr_2O_7$/8YSZ prepared by atmospheric plasma spraying. Applied Surface Science, 256(12), 3861-3868.