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Design and Performance Optimizations of Advanced Erosion-Resistant Low Conductivity Thermal Barrier Coatings for Rotorcraft Engines

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Abstract

Thermal barrier coatings will be more aggressively designed to protect gas turbine engine hot-section components in order to meet future rotorcraft engine higher fuel efficiency and lower emission goals. For thermal barrier coatings designed for rotorcraft turbine airfoil applications, further improved erosion and impact resistance are crucial for engine performance and durability, because the rotorcraft are often operated in the most severe sand erosive environments. Advanced low thermal conductivity and erosion-resistant thermal barrier coatings are being developed, with the current emphasis being placed on thermal barrier coating toughness improvements using multi-component alloying and processing optimization approaches. The performance of the advanced thermal barrier coatings has been evaluated in a high temperature erosion burner rig and a laser heat-flux rig to simulate engine erosion and thermal gradient environments. The results have shown that the coating composition and architecture optimizations can effectively improve the erosion and impact resistance of the coating systems, while maintaining low thermal conductivity and cyclic oxidation durability.

Introduction

Advanced thermal barrier coatings (TBCs) are critical for designing next generation rotorcraft turbine engines because of their ability to allow increased engine gas temperatures and reduced cooling requirements, thus helping to achieve improved engine performance and durability (Refs. 1 to 5). It has been shown that advanced turbine thermal barrier coatings can provide significant benefits in increasing engine efficiency (Ref. 5). Advanced hot-section material technology is especially critical in improving the turboshaft based rotorcraft engine performance, and a more nearly prime-reliant coating design approach is necessary to take full advantage of the thermal barrier coating technology in future rotorcraft engine systems. Turbine blade thermal barrier coatings are especially susceptible to engine ingested sand erosion and impact damage because of the high velocity flow path nature of the blades and complex particulate-coating interactions under high heat-flux combustion turbine environments. The NASA Rotary Wing Project has been addressing low thermal conductivity, high toughness and erosion resistant turbine blade thermal barrier coating development based on nano-tetragonal phase toughening design approaches (Refs. 6 to 8).

The main objective of this current effort is to evaluate and optimize the processing of advanced turbine blade thermal barrier coating systems with increased erosion and impact resistance for rotorcraft propulsion engines. The high temperature erosion performance of the turbine TBC systems will be discussed. Thermal conductivity and thermal cyclic durability of the coating systems have been evaluated. The emphasis is particularly placed on the multi-component alloying and processing optimization for the erosion resistance and the combined oxidation and erosion effects, helping understand the complex erosion mechanisms for developing comprehensive turbine blade TBC life prediction models.

Expertimental Procedures

Advanced Thermal Barrier Coatings

Advanced turbine thermal barrier coatings were designed using a multi-component defect-clustering approach and processed using an Electron Beam–Physical Vapor Deposition (EB-PVD) technique (Refs. 1 to 3). Although the high temperature multi-component turbine thermal barrier coatings have included pseudo-four component ZrO_2-Y_2O_3-Gd_2O_3-Yb_2O_3 (t’ ZrYGdYb) and pseudo-six component ZrO_2-Y_2O_3-Gd_2O_3-Yb_2O_3-TiO_2-Ta_2O_5 (t’ ZrYGdYbTT) systems, the present study is primarily focused on the four component systems because of the less complex and better controlled EB-PVD processing parameters. The EB-PVD coatings were processed at a vendor, and four processing conditions were used in the EB-PVD process by varying electron beam power, chamber pressure, and specimen deposition temperature. The advanced TBC systems, typically consisting of a 130 to 200 μm thick ceramic top coat and a 75 to 100 μm thick PtAl intermediate bond coat, were electron beam-physical vapor deposited (EB-PVD) on to 25.4 mm diameter disks of Rene N5 nickel-base superalloy substrates. The EB-PVD coatings were all deposited using pre-fabricated evaporation ingots made using the designed compositions.

A Mach 0.3 to 1.0 high velocity burner rig with erosion capability was developed for the turbine blade thermal barrier coating erosion testing in a laboratory simulated turbine engine relevant environments (Ref. 8). Computational Fluid Dynamics (CFD) modeling and experimental testing were systematically studied in the high burner velocities ranging from Mach 0.3 to 0.9, representative to turbine engine conditions. In the present study, Al_2O_3 particles were used as erodent, as similarly reported in previous work by others (Refs. 9 and 10). The nominal particle sizes used were ranged from 27 to 100 μm. The coating erosion testing was primarily conducted at 2000 °F. However, comparisons have been made for erosion tests performed at 1800 to 2200 °F. The set of the process optimization coatings were also pre-cyclically oxidized in a furnace for 128 and 256 hr at 2025 °F in 2 hr hot time cycles, and then burner erosion tested at high temperature to investigate the pre-exposure cyclic oxidation effect. In all cases, the erosion rates were determined by the erodent amount required for the coating erosion recession and coating breakthrough. A more sophisticated characterization of three-dimensional erosion surfaces and erosion behavior of thermal barrier coating systems under complexity of erosion burner conditions will be reported at a later time.

Thermal conductivity and cyclic durability tests were also conducted using the high heat flux laser test rig and cyclic furnaces at typical operating relevant temperatures, and experiment details will be discussed elsewhere (Ref. 11). The advanced t' coatings were also compared with the baseline ZrO_2-7wt%Y_2O_3 (7YSZ) in the performance.

Experimental Results and Discussion

Thermal Conductivity

Figure 1 shows the thermal conductivity of four-component ZrO_2-Y_2O_3-Gd_2O_3-Yb_2O_3 and six-component low conductivity (low k) ZrO_2-Y_2O_3-Gd_2O_3-Yb_2O_3-TiO_2-Ta_2O_5 coatings, tested at 2400°F (1316°C) using a steady-state laser heat flux rig. The four-component turbine coatings have lower thermal conductivity than the baseline 7YSZ (a yttria partially stabilized zirconia) coating, but higher conductivity than the combustor application oriented cubic-phase thermal barrier coatings and the currently less developed six-component coating systems. The four-component turbine TBCs have been developed with toughness enhancements to improve the erosion resistance required by the turbine airfoil applications. The composition and phase optimization also have ensured the basic erosion resistance requirements of the coating systems.

Figure 2 shows the furnace cyclic life comparisons of the four-component and six-component low k coatings. The coating cyclic life was optimized for a highly stable tetragonal t' phase among the different coating systems. It can be seen that the four-component coatings have an optimum durability with lower total Rare Earth (RE) oxide dopant (RE_2O_3) concentrations similar to the baseline 7YSZ, with the cyclic life of 300 to 400 hr at 2125 °F (1163 °C), as compared to the six-component coating systems having additional Ti and Ta additions. The Ti and Ta in the six component systems have the advantages of allowing increased rare earth dopants while still maintaining t' phase and lower thermal conductivities. However, the lower dopant concentration and less complexity of the four-component systems helped the initial EB-PVD processing optimizations where the homogenization and precise control of the coating compositions are highly critical.

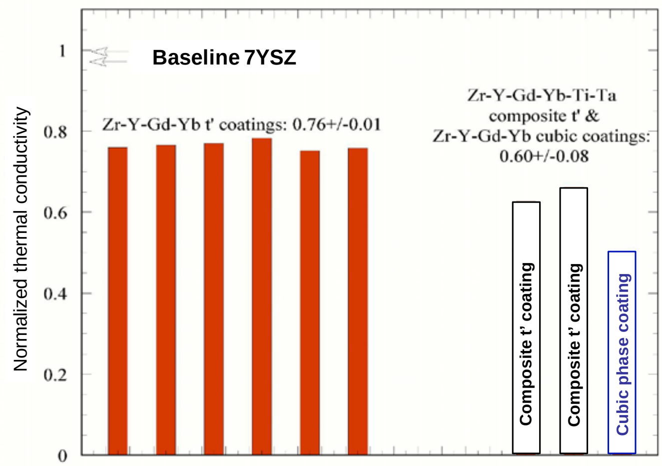

Figure 1.—Thermal conductivity of four-component ZrO_2-Y_2O_3-Gd_2O_3-Yb_2O_3 and six-component low conductivity ZrO_2-Y_2O_3-Gd_2O_3-Yb_2O_3-TiO_2-Ta_2O_5 coatings, tested at 2400 °F (1316 °C) using a steady-state laser heat flux rig. The four-component turbine coatings have lower thermal conductivity than the baseline 7YSZ coating, but higher conductivity than the combustor cubic phase thermal barrier coatings.

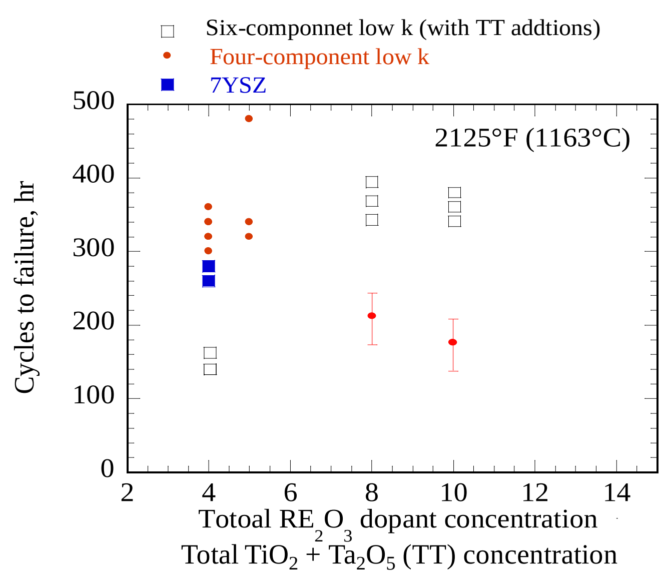

Figure 2.—Furnace cyclic life comparisons of four-component ZrO_2-Y_2O_3-Gd_2O_3-Yb_2O_3 and six-component low conductivity ZrO_2-Y_2O_3-Gd_2O_3-Yb_2O_3-TiO_2-Ta_2O_5 coatings. The cyclic life is optimized for a highly stable tetragonal t' phase for the different coating systems. The four-component coatings have an optimum life of 300 to 400 hr at 2125 °F (1163 °C), with lower total rare earth oxide (RE_2O_3) dopants as compared to the six-component coating systems with Ti and Ta additions.

Erosion Resistance

Figure 3 shows erosion behavior of a ZrO_2-2mol%Y_2O_3-1.5mol%Gd_2O_3-1.5mol%Yb_2O_3 thermal barrier coating at high temperature using the EB-PVD process optimization experiment. The coatings were tested in the erosion burner rig under Mach 0.5 conditions at the specimen temperature of 2000 °F. The Process 1 was the baseline process condition which is the same as the standard process for the 7YSZ coating and optimized for the baseline coating. The Process 2 and 3 resulted in somewhat decreased erosion resistance of the coating systems due to the less optimized coating columnar architectures and higher porosity levels. The Process 4, however, showed quite significant, approximately 30 percent erosion resistance improvements as compared to the baseline coating.

The TBC surface morphologies of process optimization specimens were examined using a Field Emission Gun-Scanning Electron Microscope (FEG-SEM), as shown in Figure 4. It can be seen that the specimens with the standard processing (Process 1) had relatively large and uniform columnar grains (~10 to 20 μm in size). However, the TBC specimens with best optimized processing (Process 4) had finer columnar structures (~ 10 μm in size), and with additional much finer smaller columns (2 to 5 μm in size). The smaller column sized coatings would expect to offer higher strength and significantly improved coating strain tolerance for improved erosion/impact resistance based on the previous erosion modeling work (Ref. 8), and also potentially providing improved furnace cyclic life durability.

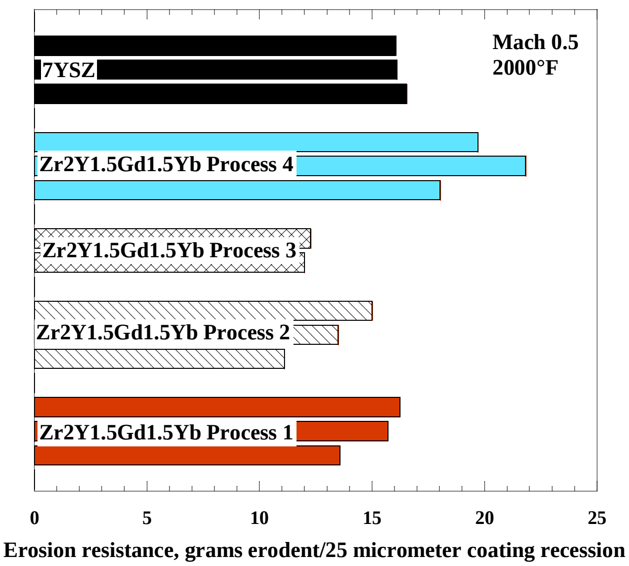

Figure 3.—High temperature erosion behavior of an optimization runs of low conductivity thermal barrier coatings. The optimized process 4 of the low conductivity thermal barrier coating showed improvements in erosion resistance due to better optimized columnar microstructures.

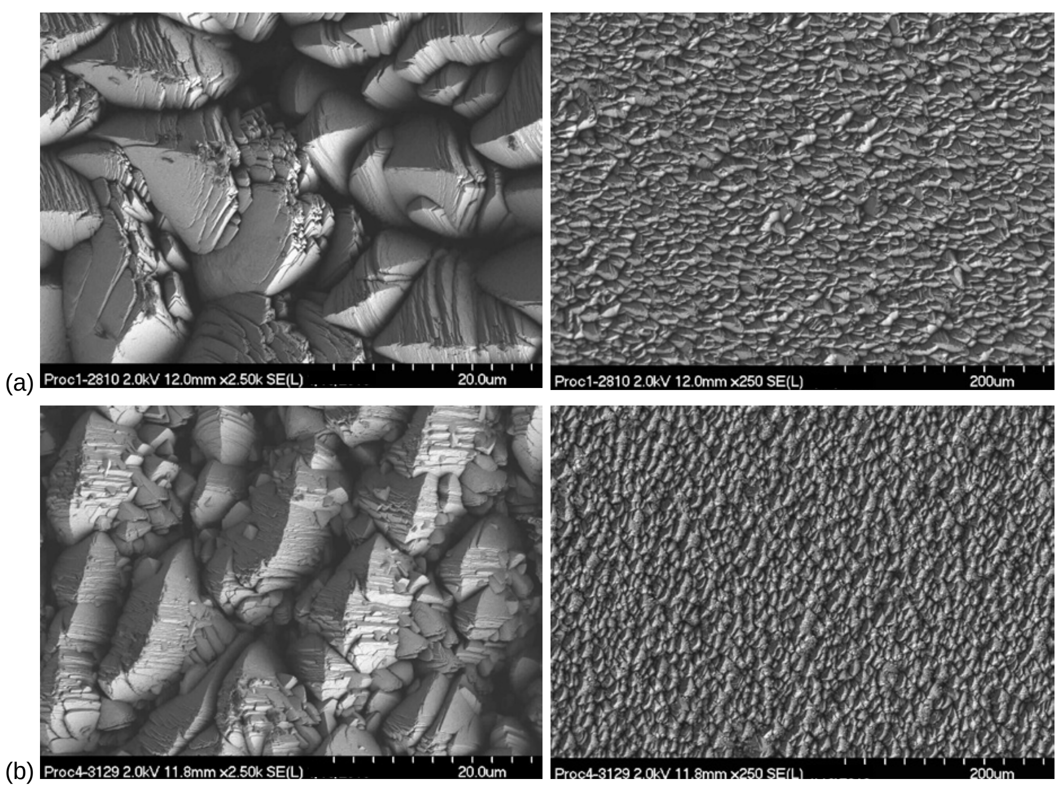

Figure 4.—The FEG-SEM surface morphologies of turbine EB-PVD thermal barrier coatings under different process conditions. (a) Standard Process 1 condition; (b) Optimized Process 2 condition.

Cyclic Oxidation Pre-Exposure on Erosion Resistance

Figure 5 shows the pre-cyclic oxidation effect on the erosion resistance of the turbine EB-PVD thermal barrier coatings. It can be seen that in most cases, the pre-cyclic oxidation under the moderate temperature (2025°F) and times (below 300 hr) seemed to increase the erosion resistance as compared to the as processed conditions. It is speculated that the cyclic exposure has moderate sintering effects which may strengthen the coating systems. Also the pre-cyclic exposure may induce certain degrees of the interface roughening as often observed, which can further strengthen the TBC/metal bond coat interface and reduce the coating spallation under the high velocity erosion/impact testing. More systematic studies are underway to further understand the oxidation and erosion behavior and to help the development of coating life prediction models.

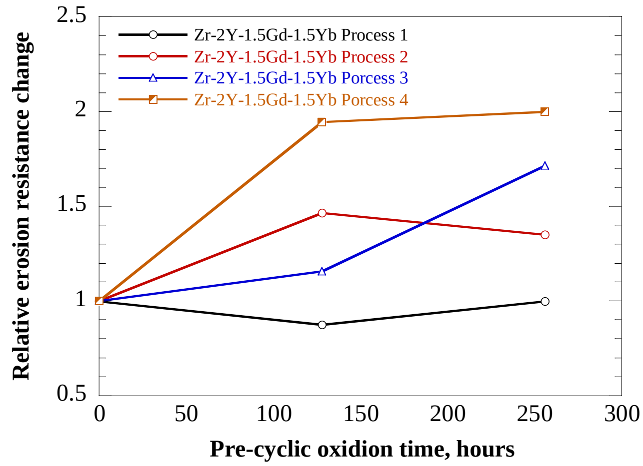

Figure 5.—The pre-cyclic oxidation effect on erosion resistance of EB-PVD thermal barrier coatings. The coatings were compared with the as processed, 128 hr oxidation, and 256 hr oxidation and at 2025 °F. The erosion was tested at 2000 °F. The results showed that the pre-cyclic oxidation seemed to increase the coating resistance to erosion.

Figure 6 shows the erosion and oxidation based failure map under turbine testing conditions. The effect of temperature on the turbine coating erosion and oxidation life is also clearly illustrated. It can be seen that in the oxidation-based failure, the coating life is exponentially reduced with increasing temperature (ln life in hours vs. 1/T), because interface damage effects are significantly increased from the accelerated oxide scale growth and increased cyclic stress-temperature amplitudes during the cycling. In contrast, the erosion-based coating failure life is generally increased with temperature because the coating toughness and plasticity increase with temperature. Therefore, one can expect that in the lower temperature regime, when coating erosion is the life limiting factor, the coating would generally fail by an erosion mechanism given sufficient erodent is present, as is frequently the case in rotorcraft operating environments. On the other hand, in the higher temperature regime, when coating oxidation is the life-limiting factor, the coating would predominantly fail by an oxidation mechanism. Under very high-temperature combined erosion and oxidation conditions (2100 to 2200 °F), significantly reduced coating life was observed in the burner erosion rig tests, and has been characterized as an oxidation-erosion mechanism as shown in Figure 6. In addition to the oxidation erosion interactions, the significant softening of the baseline 7YSZ thermal barrier coating may also have contributed to the accelerated erosion failure. The coating strain-based approaches are also being developed for turbine thermal barrier coating life predictions and will reported in future publications.

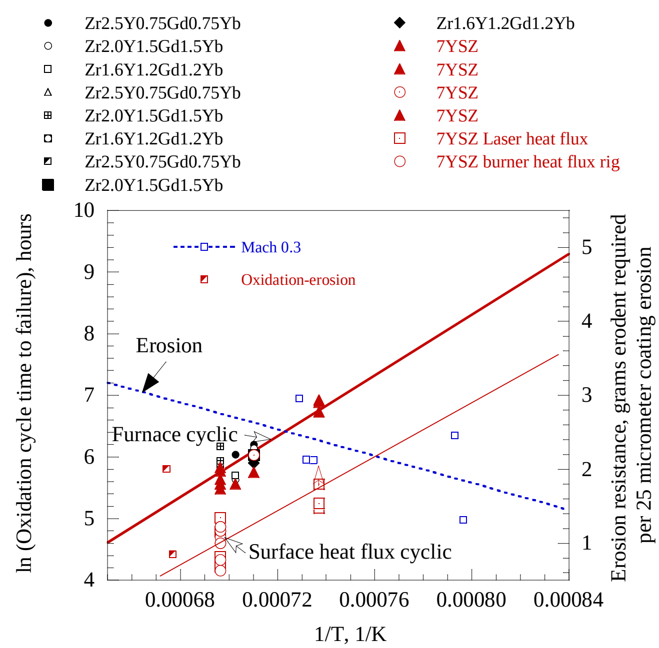

Figure 6.—The erosion and oxidation based failure map under turbine testing conditions.

Concluding Remarks

Advanced t’ phase rare earth oxide (Gd_2O_3 and Yb_2O_3 co-doped)- and TiO_2/Ta_2O_5-alloyed, ZrO_2-based thermal barrier coatings were designed and processed. The turbine thermal barrier coatings were developed for rotorcraft turbine engine applications, aimed at combined low conductivity and high toughness for improved thermal barrier performance and erosion resistance. The coating thermal conductivity, cyclic durability, and erosion resistance have been optimized from composition, phase, and processing as well as microstructure optimizations. Combined erosion and oxidation life prediction approaches based on the failure maps were also illustrated.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
Thermal barrier coatings will be more aggressively designed to protect gas turbine engine hot-section components in order to meet future rotorcraft engine higher fuel efficiency and lower emission goals. For thermal barrier coatings designed for rotorcraft turbine airfoil applications, further improved erosion and impact resistance are crucial for engine performance and durability, because the rotorcraft are often operated in the most severe sand erosive environments. Advanced low thermal conductivity and erosion-resistant thermal barrier coatings are being developed, with the current emphasis being placed on thermal barrier coating toughness improvements using multi-component alloying and processing optimization approaches. The performance of the advanced thermal barrier coatings has been evaluated in a high temperature erosion burner rig and a laser heat-flux rig to simulate engine erosion and thermal gradient environments. The results have shown that the coating composition and architecture optimizations can effectively improve the erosion and impact resistance of the coating systems, while maintaining low thermal conductivity and cyclic oxidation durability.

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