EUROPEAN
TURBINE
NETWORK

A PRACTICAL GUIDE FOR THERMAL BARRIER COATINGS

APPLICATIONS IN GAS TURBINES

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1. Introduction

- What's about the nature of TBC?
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1.1. Role of thermal barrier coating in a gas turbine application

- What's about TBC design for the gas turbines
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    - Difference with an oxidation protective bound.
    - Why some new gas turbine does not use TBC and some of them use it?
    - Criteria for thickness selection.
    - Benefit for the gas turbine.

The role of thermal barrier coatings (TBC) is to provide thermal isolation of the part.

A TBC can be used either:

- To reduce the need for blade cooling, while maintaining identical creep life of the substrate
- To increase considerably the creep life of the part while maintaining level of blade cooling
    - Therefore allowing the blade to operate at lower temperature for an identical turbine entry/inlet temperature (TIT)

The development of high temperature superalloys and cooling technology over the last six decades

References

1985

[xxxxx] Thermal barrier coatings for turbine airfoils; Strangman T. E.; Thin Solid Films, 127:1985, 93--105

2009

[xxxxx] History of thermal barrier coatings for gas turbine engines – Emphasizing NASA's role from 1942 to 1990; Miller, R.A.; NASA/TM-2009-215459; March 2009

2012

[18130] Investigations of thermal barrier coatings for turbine parts; Lepeshkin, A.

2013

[26342] Thermal barrier coatings technology: Critical review, progress update, remaining challenges and prospects; Darolia, R.; International Materials Reviews 2013 Vol. 58 No. 6

Abstract: A comprehensive and integrated review of thermal barrier coatings (TBCs) applied to turbine components is provided. Materials systems, processes, applications, durability issues, technical approaches and progress for improved TBC, and our understanding of the science and technology are discussed. Thermal barrier coating prime reliance and further advances have been hampered by TBC loss by particle impact and erosion in certain locations of the turbine blades. Accumulation of low melting eutectic containing calcia, magnesia, alumina and silica resulting in TBC spallation limits maximum surface temperature. Design methodologies to address durability and data scatter issues are discussed. Compositions, morphology, characteristics and performance data for new bonds to achieve longer TBC life are described. Further reduction in the thermal conductivity of the top layer to minimise the parasitic mass of the coating on the component is being sought via top layer composition and processing modifications as well as by alternate ceramic compositions. The progress in these areas is critically reviewed including processing, stability and durability limitations. The paper also describes effort to understand various failure mechanisms including modelling and simulation.

[xxxxx] xxxxxxxxxxxxxx

2. Processes

2.1. Introduction

2.2. Electron Beam Physical Vapor Deposition (EB-PVD) Thermal Barrier Coating

The costly and ineffective EB deposition process is a major concern for the further use in the EB-PVD process because of the relatively low deposition rate.

References

2011

[20773] A novel plasma-sprayed durable thermal barrier coating with the well-bonded YSZ interlayer between porous YSZ and bond coat; U, C.-J. et al.; ITSC 2011 Industrial Gas Turbines

Abstract: Atmospheric plasma-sprayed YSZ thermal barrier coatings (TBCs) are widely used in industrial gas turbine engines to prevent the superalloy blades from failure. The failure of TBCs in service occurs by the spalling of YSZ coating. Crack propagation leading to the failure of plasma-sprayed thermal barrier coatings usually occurs within YSZ coating near the YSZ/Bond coat interface. In the present study, a novel durable TBCs consisting of a YSZ interlayer of the well-bonded interlamellae between the bond coat and conventional YSZ top porous coat was introduced. The YSZ interlayer was deposited at different coating surface temperatures, which resulted in the formation of YSZ with significantly improved interlamellar bonding. The result shows that thermal cyclic lifetime of the novel TBCs with the 20-30□□m thick YSZ interlayer increased by factor of 4 compared with that of the conventional one. The improved thermal cyclic lifetime was attributed to the controlled transition of cracking path from the near YSZ/bond coat interface to YSZ top layer. The effect of thickness of the YSZ interlayer on the lifetime of TBCs was also investigated.

2012

[23781] PS-PVD for advanced thermal barrier coatings in aero engine applications; Schmid, R. et al.; ACES (Aerospace Coatings Europe Symposium) 2012

2.3. Atmospheric Plasma Sprayed (APS) Thermal Barrier Coating

References

2011

[xxxxx] xxxxxxxxxxxxxx

2.4. High Velocity Oxygen Fuel (HVOF)

References

2012

[23426] High Velocity Suspension Flame Spraying and Suspension Plasma Spraying of Oxide Ceramics; Killinger, A. et al.; ITSC 2012 Manufacturing and Processing

Abstract: Thermal spraying of oxide ceramic suspensions containing fine and ultra fine powder particles is a new approach for manufacturing ceramic coatings exhibiting a refined microstructure. Suspension sprayed coatings clearly differ from conventionally sprayed coatings regarding microstructure phase composition and resulting mechanical properties. Several industrial applications may take advantage in future; among these are thermal barrier structures, thermal shock protection, solid electrolytes, catalytically active surfaces and wear resistant coatings. Two methods, namely Suspension Plasma Spraying (SPS) and High Velocity Suspension Flame Spraying (HVSFS) are suitable to process suspensions but lead to rather different coating structures due to differences in the achievable particle velocities and temperature. Generally, HVSFS can lead to more dense coatings with low porosity values. With SPS on the other hand, coatings with a high volume fraction of porosity featuring a homogeneous pore structure is achievable. The presentation will compare SPS and HVSFS regarding the spray process, achieved properties of the oxide coatings and potential applications.

[xxxxx] xxxxxxxxxxxxxx

2.5. Electrostatic Spray Assisted Vapor Deposition (ESAVD)

References

[xxxxx] xxxxxxxxxxxxxx

2.6. Direct Vapor Deposition

References

[xxxxx] xxxxxxxxxxxxxx

2.7. Solution precursor plasma spray

used to create TBCs with some of the lowest reported thermal conductivities while not sacrificing thermal cyclic durability

References

[xxxxx] xxxxxxxxxxxxxx

2.8. Suspension plasma spraying

References

2011

[20656] Novel thermal barrier coatings produced by axial suspension plasma spray; Tang, Z. et al.; ITSC 2011 Aviation Industry 4

Abstract: Ceramic Thermal Barrier Coatings (TBCs) on superalloy components are being used successfully in land-based gas turbine and aircraft engines. These coatings are generally made by either air plasma spraying (APS) or electron beam physical vapour deposition (EB-PVD). In general, EB-PVD TBCs have superior durability due to the columnar structure, but they are very expensive compared to APS TBCs. EB-PVD TBCs are used primarily in the most severe applications such as turbine blades and vanes in aircraft engines. This paper presents an economical process to make durable TBCs, called Axial Suspension Plasma Spray (ASPS). This technology combines Mettech's axial injection plasma process and automatic suspension feed system. The resulting TBCs exhibit columnar structures with vertical cracks, similar to EB-PVD coatings. Such structures allow the TBC to compensate for thermal expansion differences between it and the base material. The ASPS process presents an economical alternative to EB-PVD to produce durable columnar TBCs.

[20788] Deposition and characteristics of submicrometer-structured ceramic coatings by suspension thermal spraying; Guignard, A. et al.; ITSC 2011 Nanomaterial coatings

Abstract: The manufacture of sub micrometer-structured coatings by thermal spraying is subjected nowadays to increasing research efforts in order to obtain unique and often enhanced properties compared to conventional coatings. Injecting suspensions of submicron ceramic particles into the plasma jet or the flame enables to deposit finely structured coatings. Such fine microstructures can be advantageous for applications in the field of thermal barrier coatings (TBCs) for gas turbines. Often, suspension plasma sprayed (SPS) TBCs show unique mechanical, thermal and optical properties compared to conventional atmospheric plasma sprayed (APS) TBCs. They have thus the potential of providing increased TBC performances under severe thermo-mechanical loading. Experimental results show the capability of SPS to obtain yttria-stabilized zirconia (YSZ) coatings with high density of vertical segmentation cracks, yielding high strain tolerance and low Young's modulus, while the porosity is still large compared to APS segmented coatings. Besides, sintering behavior of complete TBC systems under a thermal gradient exposure is of high importance. The evolution of the coating microstructure during thermal cycling test at very high temperature (1400°C) in our burner rigs as well as under isothermal annealing and its effects on the coating properties such as Young's modulus were investigated.

2.9. Cold spray

References

2011

[20604] The protectiveness of thermally grown oxides on cold sprayed CoNiCrAIY bond coat in thermal barrier coating; Manap. A. et al.; ITSC 2011 Aviation Industry 3

Abstract: This paper presents the results of a study of the oxidation behavior of thermal barrier coating (TBC) with air plasma sprayed (APS) yttria-stabilized zirconia (YSZ) top coat and CoNiCrAlY bond coat deposited using low pressure plasma spray (LPPS) and cold spray (CS). The TBC is subjected to isothermal oxidation and creep tests at 900 °C and evaluated using scanning electron microscopy (SEM), energy dispersive X-ray spectrometry (EDX) and transmission electron microscopy (TEM). The thermally grown oxide (TGO) developed in TBC with LPPS bond coat was composed of only □-Al2O3 and the TGO developed in TBC with CS bond coat is composed of □-Al2O3 and □-Al2O3. Despite the presence of this metastable □ phase, the TGO in the CS specimens exhibits a dense microstructure and lower amounts of mixed oxides. The correlation between □-Al2O3 and the formation of mixed oxides was investigated through the measurement of □- Al2O3 thickness ratio and mixed oxides coverage ratio. It was found that the mixed oxides coverage ratio is inversely proportional to the □- Al2O3 thickness ratio. Overall findings indicate that the oxidation behavior of the TBC with CS bond coat is superior compared to that of the TBC with LPPS bond coat.

[20748] New cold spray based technique of FeAI intermetallic compound coating synthesis; Maev, R.Gr. et al.; ITSC 2011 Cold spraying

Abstract: The FeAl intermetallic compound offers a combination of attractive properties such as thermal barrier, good strength at intermediate temperatures and an excellent corrosion resistance at elevated temperatures under oxidizing, carburizing and sulfidizing atmospheres. So they have attracted considerable attention as potential candidates for structural and coatings applications at elevated temperatures. However, the application of these intermetallics has been limited due to lack of deposition techniques and their low ductility at room temperature. To overcome the drawbacks we apply Low Pressure Cold Spray (LPCS) with following sintering for improving coating ductility and structure. The aim of this paper is to present the first results of FeAl intermetallic compound synthesis with this technique. A CS deposit is built up by the successive impact of individual powder particles that are the ''building blocks'' of the deposit. Sintering is applied to utilize reactions between the particles and obtain complex intermetallic compound. The microstructures and properties of the coatings were characterized by SEM, EDX and thermal diffusivity tests to define the structure formation mechanisms.

References

2011

[20598] TBC coating cost reduction by optimization of the atmospheric plasma spray process; Mihm, S. et al.; ITSC 2011 Industrial gas turbines 1

Abstract: The global economic growth has triggered a dramatic increase in the demand for resources over the last few years, resulting in steady price increases for energy and raw materials. In the gas turbine manufacturing sector, process optimizations of cost-intensive production steps involve a heightened savings potential and form the basis for securing future competitive advantages in the market economy. In this context, the atmospheric plasma spraying (APS) process for thermal barrier coatings (TBC) has been optimized. A constraint for the APS coating process optimization is the use of the existing coating equipment. Furthermore, the current coating quality and characteristics are not allowed to change in order to avoid new qualification and testing. Using experience in atmospheric plasma spraying and empirically gained data, the process optimization plan included the variation of e.g. the plasma gas composition and flow rate, the electrical power, the arrangement and angle of the powder injectors to the plasma jet, the grain size distribution of the spray powder and the plasma torch movement procedure like spray distance, offset and iteration. In particular, plasma properties (enthalpy, velocity, temperature), powder injection conditions (injection point, injection speed, grain size distribution,) as well as the coating lamination (coating pattern, spraying distance) are examined. The optimized process and resulting coating was compared to the current situation by several diagnostics methods. The improved process provides significantly lower costs by achieving the requirement of comparable coating quality. Furthermore, a contribution was made to a better comprehension of the atmospheric plasma spraying of ceramics and a method for future process developments was defined.

[20720] Effect of bond coat material and heat treatment on adhesion strength and characteristics of thermal barrier coating system with CGDS, HVOF and APS techniques; Lampke, T. et al.; ITSC 2011 Aviation Industry

Abstract: The most recent increase in turbine entry temperature (TET) can be obtained by the use of Thermal Barrier Coatings (TBCs) on cooled hot section components. The TBC systems are comprised of Ni-based super-alloy substrate which provides certain mechanical properties and blade geometry consisting of a ceramic top coat with low thermal conductivity applied to a metallic bond coat resulting in a significant temperature drop across the coating. The bond coat provides oxidation resistance and adherence of the top coat to the substrate. In this study different bond coat layers were applied on carbon steel substrates which were covered by yttria stabilized zirconia (YSZ) as a top coat layer using atmospheric plasma spray technique (APS). Al-12%Si and Al 99% were deposited by cold gas dynamic spray technique (CGDS) while Ni-5%Al layer was deposited by high velocity oxy fuel technique (HVOF). Heat treatment was performed on the samples under controlled atmosphere for 15 hrs. The microstructure and micro hardness of as sprayed and after heat treatment samples were investigated. Adhesion strength for top coat / bond coat interface and bond coat / substrate interface were investigated. The residual stresses for as sprayed and after heat treatment was estimated by XRD measurement on the top coat layer with different bond coat material. The results indicate that the adhesion strength either for as sprayed or after heat treatment was enhanced using this new bond coat materials compared to the traditionally as deposited Ni Co Cr Al Y bond coat material.

[20726] Optimization of plasma spray processing parameters for deposition of YSZ+Al203 coating; Alluncu, E. et al.; ITSC 2011 Ceramic coatings

Abstract: Plasma sprayed yttria stabilized zirconia (YSZ) coatings are being increasingly used as thermal barrier coatings(TBCs) for gas turbine parts. However oxidation problems are critical for durability of TBC. Al_2O_3 addition to YSZ is considered as an oxygen barrier microstructure at elevated temperature. Therefore it helps to the growth rate of the thermally grown oxide layer between top coat and bond coat. Spray properties and rapid solidification determine the final characteristics of the coating. Plasma current, plasma gas flow rate and spray distance factors have main effect on occurrence of microstructure. Therefore plasma spray parameter optimisation is required for TBC manufacturing. Statistical designs of experiments have been shown to provide efficient approaches to systematically investigate the process parameters of plasma spray process. In this study Al_2O_3-YSZ particle composite TBC deposited with different plasma spray process parameters by using Taguchi method for optimisation.

3. Materials

Yttria stabilized zirconia containing 6-8 wt% Y2O3 (7YSZ) is the most widely used ceramic material for the TBC top coat because of its low thermal conductivity, high melting point, phase compatible with alpha alumina, and combination of its good resistance to erosion and damage from large particle impacts.

7YSZ has reached its maximum temperature that it can be exposed up to 1300 °C without incurring deleterious phase changes

3.1. Top coat

References

2010

[18137] Design and performance optimizations of advanced erosion-resistant low conductivity thermal barrier coatings for rotorcraft engines; Zhu, D. et al.; NASA/TM-2012-217138; May 2012; 66th Annual Forum and Technology Display (AHS Forum 66); Phoenix, Arizona; May 11-13, 2010

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.

2012

[23358] Double Rare-Earth Oxides Co-doped Strontium Zirconate as a New Thermal Barrier Coating Material; Dong, H.-Y. et al.; ITSC 2012 Advanced Thermal Spray Coatings

Abstract: Advanced ceramic materials with perovskite structure have been developed for potential applications in thermal barrier coating (TBC) systems in an effort to overcome the properties of the pre-existing ones like 8wt% yttria stabilized zirconia (8YSZ). Y_2O_3 and Yb_2O_3 co-doped strontium zirconate with chemistry of Sr(Zr0.9Y0.05Yb0.05)O2.95 (SZYY) was synthesized using ball milling prior to solid-state sintering, and had a minor second phase of Yb_2O_3. The SZYY showed good phase stability not only from room temperature to 1400°C, but also at high temperature of 1450°C for a long period, analyzed by thermogravimetry-differential scanning calorimetry (TG-DSC) and X-ray diffraction (XRD), respectively. The thermal expansion coefficients (TECs) of the sintered bulk SZYY were recorded by a high-temperature dilatometer and revealed a positive influence on phase transitions of $SrZrO_3$ by co-doping Y_2O_3 and Yb_2O_3. The thermal conductivities of SZYY were at least ~30% lower in contrast to that of $SrZrO_3$ and 8YSZ in the whole tested temperature range. The good chemical compatibility was observed for SZYY with 8YSZ or Al_2O_3 powders after 24 h heat treatment at 1250°C. The phase stability and the microstructure evolution of the as-sprayed SZYY coating during annealing at 1400°C were also investigated in this work.

[23375] Effect of 20% Gadolinia – 80% Zirconia Thermal Barrier Coating for Diesel Engine Performance; Chandrasagar, L.; ITSC 2012 Applications and Case Study

Abstract: Thermal Barrier Coatings (TBC) is widely used to insulate the combustion chamber of Internal combustion Engines to improve their performance efficiency, reduce pollution and also to protect the metals from high temperature oxidation. In this work 80% Zirconium Oxide and 20% Gadolinium Oxide composition (GdPSZ) is used for preparation of thermal barrier coating in the laboratory and plasma spray coated on the combustion chamber of single cylinder diesel engine. The engine performance test was conducted for both base line (uncoated) and thermal barrier coated engines. It has been found that the coatings in the combustion chamber of engine were found to be well adherent even after 300 hours of rigorous test. It was observed that there was significant reduction in smoke density especially at higher loads in the case of coated engines compared to that of standard engine. In the case of coated engine, volumetric efficiency however reduce by 2-6 % and about 2% increase in brake specific fuel consumption compared to that of base line engine (uncoated engine). The results of other performance parameters of the engine have also been discussed.

[23383] Application of Granulated Nano Al2O3 Powders in Thermal Barrier Coatings at Elevated Temperatures; Hussain, M.S.; Daroonparvar, M.R.; ITSC 2012 Applications and Case Study

Abstract: Turbine blades are generally protected by thermal barrier coatings (TBCs) against high temperature oxidation and corrosion. A novel method has been developed to prepare nanostructured Al_2O_3 powders for thermal-spraying (atmospheric plasma spray) with high flowability. In this method, nano Al_2O_3 powders are granulated and then heat treated at 2000°C which become suitable to be used in thermal spraying equipment. The normal Al_2O_3 and granulated nano Al_2O_3 powders were sprayed separately by using an atmospheric plasma spray device onto a typical TBC consisting of a superalloy bond coat and an YSZ top coat. Then, TBC/ normal Al_2O_3 and TBC/ nano Al_2O_3 coatings were oxidized at 1000°C for 24h and allowed to form the thermally grown oxide (TGO) layer onto the bond coat (NiCrAlY layer). The flowability of the granulated nano Al_2O_3 powders was studied by using a Hall flowmeter. The microstructural characterization showed that the granulated nano Al_2O_3 powders had very high flowability. The increased apparent density and flowability of the granulated nano Al_2O_3 powders had substantially reduced the micro-cracks and interconnected porosities in the coating in comparison with normal Al_2O_3 coating. The thickness of the TGO layer in YSZ/ normal Al_2O_3 coating was higher in comparison with YSZ/ nano Al_2O_3 coating after oxidation. Thus by using nano Al_2O_3 as a third layer, the thickness of the TGO layer and oxidized regions inside the bond coat decreased effectively which led to less mechanical stresses and can cause the improvement of TBC life.

3.1.1. Zirconia (Zircoon oxide)

References

3.1.1.1. Stabilizing agent

References

3.2. Bond coat

References

2011

[20720] Effect of bond coat material and heat treatment on adhesion strength and characteristics of thermal barrier coating system with CGDS, HVOF and APS techniques; Lampke, T. et al.; ITSC 2011 Aviation Industry

Abstract: The most recent increase in turbine entry temperature (TET) can be obtained by the use of Thermal Barrier Coatings (TBCs) on cooled hot section components. The TBC systems are comprised of Ni-based super-alloy substrate which provides certain mechanical properties and blade geometry consisting of a ceramic top coat with low thermal conductivity applied to a metallic bond coat resulting in a significant temperature drop across the coating. The bond coat provides oxidation resistance and adherence of the top coat to the substrate. In this study different bond coat layers were applied on carbon steel substrates which were covered by yttria stabilized zirconia (YSZ) as a top coat layer using atmospheric plasma spray technique (APS). Al-12%Si and Al 99% were deposited by cold gas dynamic spray technique (CGDS) while Ni-5%Al layer was deposited by high velocity oxy fuel technique (HVOF). Heat treatment was performed on the samples under controlled atmosphere for 15 hrs. The microstructure and micro hardness of as sprayed and after heat treatment samples were investigated. Adhesion strength for top coat / bond coat interface and bond coat / substrate interface were investigated. The residual stresses for as sprayed and after heat treatment was estimated by XRD measurement on the top coat layer with different bond coat material. The results indicate that the adhesion strength either for as sprayed or after heat treatment was enhanced using this new bond coat materials compared to the traditionally as deposited Ni Co Cr Al Y bond coat material.

[26367] The development of new bond coat compositions for thermal barrier coating systems operating under industrial gas turbine conditions; Seraffon, M. et al.; Surface and Coatings Technology 206 (2011) 1529–1537

Abstract: Environmental and economic issues are driving the development of increasingly efficient gas turbines. An important step in achieving this is to engineer components which can operate with longer lifetimes and at higher metal temperatures. Inlet temperatures for gas turbines now exceed the melting temperatures of nickel-based superalloys (i.e. 1300–1350°C). The use of advanced air cooling systems coupled with thermal barrier coatings (TBCs) reduces the temperature of the underlying superalloy substrate. The bond coating, an important part of the TBC system, oxidizes to form a slow growing protective oxide layer, while also providing adhesion between the ceramic topcoat and the substrate. NiCoCrAlY overlay coatings are some of the most commonly used bond coatings for industrial gas turbines and extensive research has been undertaken over many years to find the best bond coating composition. This paper reports upon the production of new, model bond coatings with a wide range of different compositions. The focus is on their oxidation behavior at a temperature typically experienced by bond coatings on industrial turbine blades (950 °C). A physical vapor deposition technique, magnetron sputtering, has been used to deposit a range of Ni–Co–Cr–Al coatings onto 10 mm diameter sapphire substrates. This was achieved through co-sputtering two targets: a Ni–10%Cr, Ni–20%Cr, Ni–50%Cr, Ni–20%Co–40%Cr or Ni–40%Co–20%Cr target and a pure Al target. About a hundred samples with varying compositions were produced by this method. The coatings were then oxidized in air for 500 h at 950 °C. All samples were assessed by measuring the change in coating thickness, using pre- and post-exposure metrology only, and also the change in specimen weight. This approach has shown that magnetron sputtering successfully deposited 20 to 30 µm thick coatings and allowed the calculation of oxide growth rates. Energy dispersive X-ray (EDX) analysis was used to characterize the exact composition of each sample. Additionally, Xray diffraction (XRD) has been used to identify the major oxides formed during exposure. The selective growth of protective Cr_2O_3 or Al_2O_3 or other less protective mixed oxides (depending on the initial coating composition) was observed. This influenced the oxide scale growth rate, indicating which coatings produced more protective oxides and allowing future optimization of the bond coating composition, for service within the turbine section of industrial gas turbines to be planned.

3.2.1. MCrAlY coating

References

3.2.2. Platinum Aluminide diffusion coating

References

2011

[16958] Comparative performance of a thermal barrier coating system utilizing platinum aluminide bond coat on alloys CMSX-4 and MAR M002DS; Tawancy, H.M.; Al-Hadhrami, L.M.; ASME TURBO EXPO 2011 Manufacturing Materials & Metallurgy; GT2011-45028

Abstract: It is known that the relative performance of thermal barrier coatings is largely dependent upon the oxidation properties of the bond coat utilized in the system. Also, the oxidation properties of diffusion-type bond coats (aluminides and their modifications) are functions of the superalloy substrate used in blade applications. Therefore, the performance of a given coating system utilizing a diffusion-type bond coat can significantly vary from one superalloy to another. Toward the objective of developing coating systems with more universal applicability, it is essential to understand the mechanisms by which the superalloy substrate can influence the coating performance. In this study, we examined the relative performance of yttria-stabilized zirconia/platinum aluminide coating system on alloys CMSX-4 and MAR M 002DS representing single-crystal and directionally-solidified alloy systems respectively using thermal exposure tests at 1150°C with a 24-hour cycling period to room temperature. Changes in coating microstructure were characterized by various electron-optical techniques. Experiment showed that the coating system on alloy MAR M 002DS had outperformed that on alloy CMSX-4, which could be related to the high thermal stability of the bond coat on alloy MAR M 002DS. From a detailed microstructural characterization, this difference in behavior could be explained at least partially in terms of variation in chemical composition of the two alloys, which was also reflected on the exact failure mechanism of the coating system.

References

2011

[20654] Improving atmospheric plasma spraying of zirconate thermal barrier coatings based on particle diagnostics; Mauer, G. et al. ITSC 2011 Industrial gas turbines 2

Abstract: Lanthanumzirconate ($La_2Zr_2O_7$) was proposed as a promising material for thermal barrier coatings. At atmospheric plasma spraying (APS) of $La_2Zr_2O_7$ a considerable amount of La_2O_3 can evaporate in the plasma flame, resulting in a non-stoichiometric coating. As indicated in the phase diagram of the La_2O_3-ZrO_2 system, in the composition range of pyrochlore structure, the stoichiometric $La_2Zr_2O_7$ has the highest melting point and other compositions are eutectic. APS experiments were performed with a TriplexPro™-200 plasma torch at different power levels to achieve different degrees of evaporation and thus

stoichiometry. For comparison, some investigations on $Gd_2Zr_2O_7$ were included which is less prone to evaporation and formation of non-stoichiometry. Particle temperature distributions were measured by the DPV-2000 diagnostic system. In these distributions, characteristic peaks were detected at specific torch input powers indicating evaporation and solidification processes. Based on this, process parameters can be defined to provide stoichiometric coatings intended to show good thermal cycling performance.

[20657] Impact of particle size distribution on the TBC coating deposition and performance; Li, L. et al.; ITSC 2011 Aviation industry 4

Abstract: Thermal barrier coatings (TBCs) functioning in the aviation and power generation industries have heavily relied on plasma sprayed yttria stabilized zirconia (YSZ) on MCrAlY bond coated engine components. Among those factors which may impact the repeatability and reliability of a TBC coating, powder feedstock is one of the most important while being the challenging to control constituents as it is difficult to keep the powder chemistry, morphology and size distribution exact the same from lot to lot, year after year. In this study the authors systematically vary the size distribution of one type of commercial YSZ powder to explore the effect of the size distribution on the TBC deposition and the coating performance. Deposition rate and efficiency are quantitatively compared for those experimental powders. The coating microstructures and performances for different sizing are also evaluated analytically. Understanding the impact of the powder variation on the coating deposition and performance is essential to determine the quality control standards.

4. Characterization/(N)DT/Inspection

- Contributing factors

References

2011

[20651] Thermal barrier coatings on surfaces with micro-machined roughness profiles; Seiler, P.; Baker, M.; ITSC 2011 Pre- & post-treatment 1

Abstract: Thermal barrier coating systems are used to enhance the temperature resistance of hot section components in gas turbines. The coatings protect the underlying nickel based components and consist of the bond coat (BC) the thermal barrier coating (TBC) and a thermally grown oxide (TGO) between the BC and TBC. The coating systems fail in service at or near the TBC/TGO interface. To study the failure mechanisms a simplified coating system is introduced which consists of a MCrAlY bond-coat material as the substrate, a TGO, and a yttria-stabilised zirconia TBC as a topcoat. The TBC is applied by atmospheric plasma spraying on top of specimens with defined roughness profiles, manufactured by a micromachining process. The main advantage of micro-machining is a defined interfacial roughness between the TBC and the BC in contrast to sandblasted specimens. Furthermore, a FEM simulation of the coating system was developed which approximates the interface by sinusoidal functions. This simplified model system and additional FEM calculations show the influence of varying the interfacial roughness between the BC and the TBC.

[26429] Thermal properties of plasma-sprayed thermal barrier coating with bimodal structure; Yu, Q. et al.; Ceramics International 37 (2011) 1093–1099

Abstract: Nanostructured zirconia coatings have been prepared by atmospherical plasma spraying (APS) on NiCrAlY-coated superalloy substrates. The isothermal oxidation test results indicate that the oxidation kinetics of nanostructured TBC follows a parabolic law and the oxidation resistance of the nanostructured TBC is comparable to that of the conventional TBC. The nanostructured thermal barrier coatings exhibit excellent thermal cyclic resistance and low thermal diffusivity. The failure of the nanostructured TBC occurs within the top coat and close to the YSZ/thermal growth oxide interface. The thermal diffusivity of the coating is 90% of that of conventional thermal barrier coatings, and it increases after heat treatment at 1050 8C for 34 h. The increase in the thermal diffusivity of the coating is ascribed to grain growth, the crack healing as well as sintering neck formation.

2012

[19078] The Influence of Humidity on the Creep Life of a High Pressure Gas Turbine Blade: Part I — Heat Transfer Model; Eshati, S. et al.; ASME TURBO EXPO 2012 Cycle innovations; GT2012-69455

Abstract: The cooling of high temperature gas turbines has been the subject of intensive work over the past few decades. Analysis of the metal temperature of cooled blades requires the solution of the equations governing the heat flow through the blade given the internal and external distributions of the boundary gas temperatures and heat transfer coefficients. An analytical model to investigate the influence of Water Air Ratio (WAR) on turbine blade heat transfer and cooling processes (and thus the blade creep life) of industrial gas turbines is presented. The method is based on a blade with convective cooling and a thermal barrier coating (TBC). The approach is based on engine performance, heat transfer models (hot side and cold side model), in addition to a method that accounts for the changes in thermal conductivity, viscosity, density and the gas properties of moist air as a function of WAR. The evaluation of heat transfer data in this model is considered by using undimensional parameters namely: Reynolds number, Nusselt number, Stanton number, Prandtl number and other related parameters. The aim of this paper is to present an analytical model to investigate the influence of humidity on the turbine blade heat transfer and cooling processes which, in turn, affect blade creep life. The developed model can be used to assess the main parameters that influence blade cooling performance, such as cooling methods, alternative cooling fluids, blade geometry, gas properties and material and thermal barrier coatings. For a given off-design point, the WAR was varied from dry to humid air (air/water vapour mixtures). The whole cooled blade row is regarded as a heat exchanger with the presence of TBC subjected to a mainstream hot gas flow from the combustion chamber.

[22321] The effect of water vapor and superalloy composition on thermal barrier coating lifetime; Pint, B.A. et al.; Superalloys 2012, Twelfth International Symposium Alloy & coating development; pp. 723

Abstract: New power generation concepts may contain higher water vapor in the turbine combustion gas due to the fuel or to steam dilution. To assess the effect of higher water vapor content on thermal barrier coating performance, furnace cycle (1h) testing was conducted in air with 10, 50 and 90 vol.% water vapor and compared to prior results in dry O2. The first series of experiments examined Pt diffusion (γ+γ') and Pt-modified aluminide (β) bond coatings on second-generation superalloy N5 at 1150°C with commercially vapor-deposited yttria-stabilized zirconia (YSZ) top coats. Compared to dry O2, the average coating lifetimes with Pt diffusion coatings were unaffected by the addition of water vapor while the Pt-modified aluminide coating average lifetime was reduced by >50% with 10% water vapor, but less reduction was observed with higher water contents. A similar set of coatings on low Re superalloy N515 showed no debit in lifetime with Pt aluminide bond coatings exposed to 10% water vapor. Characterization of the alumina scale thickness at failure showed a thicker oxide beneath the YSZ coating (compared to the scale without a top coating) for both types of bond coatings, and an increase in the oxide thickness with the addition of 10% water vapor. These observations were further studied using analytical transmission electron microscopy. The second series of experiments examined high velocity oxygen fuel (HVOF) MCrAlY and MCrAlYHfSi bond coatings and air-plasma sprayed YSZ top coatings on X4 superalloy substrates with and without Y and La additions. Compared to a dry O_2 baseline, the addition of 10% water vapor decreased the YSZ coating lifetime for either bond coating by ~30% at 1100°C. Substrates with Y and La additions showed no change in the average lifetime in 10% water vapor compared to standard X4. A further increase to 50% water vapor did not further decrease the average lifetime of one group of coatings. To better simulate base-load power generation, one group of specimens was cycled with 100h cycles, which substantially increased the coating lifetime. In each case, higher average lifetimes were observed with Hf in the bond coating. Initial characterization of the alumina scales formed at failure showed little effect of the water vapor addition, bond coating composition or substrate composition. For both series of coatings, the addition of 10% water vapor to the experiment reduced YSZ coating lifetime. However, increasing to 50% or 90% H2O showed no additional decrease in average YSZ lifetime.

[23354] Influence of Processes and Parameters on the Microstructure and Properties of Thermal Barrier Coatings Produced with a Nanostructured YSZ Powder; Bobzin, K. et al.; ITSC 2012 Advanced Thermal Spray Coatings

Abstract: In this study, a ZrO_2 – 7 % Y_2O_3 (YSZ) powder (-90 +16 µm) was nanostructured by high energy ball milling and sprayed using a modern three-cathode plasma generator TriplexPro- 210 as well as a conventional plasma generator F4MB-XL. The parameters were varied in order to investigate their influence on build-up, microstructure and properties of the thermal barrier coatings (TBC). Powders and coatings were characterized in terms of their morphology, microstructure and phase composition by means of light microscopy (LM), scanning electron microscopy (SEM), transmission electron microscopy (TEM) and X-ray analysis (XRD). Thermo-shock behavior of TBC was evaluated using thermal cyclic tests at 1300 °C and 1150 °C. The results show that the milled powder contained nano-sized particles. TBC from the nanostructured powder by TriplexPro-210 had high porosities and numerous fine pores, leading to lower microhardness and higher thermoshock resistance than the reference TBC.

2013

[25323] Investigation of factors that contribute to deposition formation on turbine components in a high-pressure combustion facility; Murphy, R.G. et al.; ASME TURBO EXPO 2013 Heat Transfer: Film Cooling; GT2013-

Abstract: Researchers at West Virginia University worked with the U.S. Department of Energy, National Energy Technology Laboratory (NETL) to study particulate deposition in a high pressure and high-temperature environment. To simulate deposition of particulate from combustion of coal synthesis gas on the pressure side of an Integrated Gasification Combined Cycle (IGCC) turbine first stage vane, angled film cooled thermal barrier coated (TBC) test articles scaled toturbine flow conditions using Reynolds similarity were subjected to accelerated deposition at a pressure of approximately 4 bar and a gas temperature ranging from 1373- 1560K. The effects on deposition rates of five different factors were examined; free stream temperature, impaction angle, blowing ratio, particulate loading, and TBC vs. non- TBC coated surface. As the free stream temperature increased the results showed that the deposition also increased. The amount of deposition increased as the impaction angle increased from 10o to 20o. The effect of blowing ratio (M, mass flux ratio) was examined at M=0.0, 0.25 and 1.0. As the blowing ratio increased the amount of deposition decreased. The particulate loading was varied from 100 ppmw to 200 ppmw. The amount of deposition increased with the higher particulate loading case; however, coverage on the test article face did not increase significantly. Finally, a comparison test was performed between a TBC coated test article and a bare metal test article. This test showed that more deposition formed on the TBC coated article than the bare metal article. During testing, the deposition that formed on the TBC coated test articles demonstrated a resistance to adhering to the surface once the mainstream temperature was reduced during facility shut down. The results of this work will aid gas turbine manufacturers to better understand and develop mitigations for the five factors studied that cause deposit formations in IGCC engines. This work will also give insight to researchers studying deposition on the methods developed and issues encountered in simulating particulate matter into a high-pressure combustion facility.

References

2011

[16960] Mechanical properties of titania-doped yttria stabilized zirconia (TiYSZ) for use as thermal barrier coating (TBC); Kibsey, M. et al.; ASME TURBO EXPO 2011 Manufacturing Materials & Metallurgy; GT2011-45643

Abstract: Representative samples of Yttria Stabilized Zirconia (7YSZ) co-doped with varying concentrations of TiO_2 were fabricated using plasma spraying. Samples were sintered in order to minimize porosity and to simulate the bulk material properties. After sintering, porosity levels of less than 1.25% were achieved. Both as-sprayed and sintered samples with 5, 10 and 15 wt% TiO_2 addition levels were microstructurally characterized using SEM, XRD and optical image analysis methods. Vickers hardness, Young's modulus, and fracture toughness were measured using nano and macroindentation methods. Microstructural analysis revealed that sintering of the TiO_2 doped samples was required to achieve a homogeneous composition distribution, with TiO2 predominantly residing in solid solution within the ZrO_2 matrix. Sintering for 325 hours at 1200ºC resulted in sufficient diffusion of TiO2 into the 7YSZ. The addition of TiO_2 stabilized more tetragonal phase as revealed by XRD measurement. Sintering also showed significant improvements in fracture toughness in all co-doped samples. Fracture toughness values calculated using load-independent equations provided a clear trend in fracture toughness improvement with TiO2 addition. Ferroelastic toughening of the tetragonal phase was believed to have played an effect. There was also a reduction in monoclinic phase content with TiO_2 addition, which may have limited microcrack formation and consequently increased the fracture toughness. With the addition of 10 wt% TiO_2, the fracture toughness was improved by over 50%; however, this improvement started to decline at 15 wt% TiO_2 addition. Volumetric porosity measurements also revealed significant improvements in fracture toughness with respect to lowering the porosity content as observed in all sintered samples.

[26477] Quality evaluation for air plasma spray thermal barrier coatings with pulsed thermography; Zhao, S.-b. et al.; Progress in Natural Science: Materials International 21 (2011) 301-306

Abstract: Pulsed thermography (PT) as a non-contact non-destructive evaluation (NDE) technique was employed to examine as-sprayed air plasma spray (APS) thermal barrier coatings (TBCs) for quality evaluation. Thickness and microstructural characteristics play a vital role in determining the quality. In this paper, PT logarithmic peak second-derivative method was adopted to measure the thickness of top coat. Time dependent thermal images were used to characterize the microstructure which was confirmed by scanning electron microscope (SEM). The results showed that there was relationship between the temperature distribution of the surface and microstructure change in TBCs. Temperature distribution in thermal images and measurement results of thickness were in fairly good agreement with the microstructure change. It can be concluded that it was possible to employ these NDE methods as quality evaluation for as-sprayed TBCs.

2012

[19376] Examples of the Use of Optical Spectroscopy to Detect Damage of Thermal Barrier Coatings During Cyclic Oxidation; Rinaldi, C. et al.; ASME TURBO EXPO 2012 Manufacturing materials and metallurgy; GT2012-69786

Abstract: This paper describes some examples of the use of two optical spectroscopy techniques to study thermal barrier coating (TBC) degradation preceding failure. The first part describes photoluminescence piezospectroscopy (PLPS) results obtained on a series of specimens with EB-PVD TBC and Pt -aluminised bond coats. The monotonic decrease of the alumina compressive stress level with ageing and thermal cycling confirms that TGO compressive stress levels can be used as residual life indicators in this type of coating. The automatic mapping system implemented by RSE (Ricerca sul Sistema Energetico) provides precise and reliable results about the level of damage at the BC/TBC interface, well before failure; mapping provides data regarding the precise positions where the first macroscopic detachment (a few millimeters wide) occurs. As PLPS is not applicable to thermal-sprayed APS TBCs, the second part of the paper describes some examples of the contribution that Raman spectroscopy can provide to detect phase changes due to degradation preceding failure of the TBCs. Possible problems relating to the presence of undesired RE elements in the ceramic layer due to strong fluorescence are also described; solutions are proposed. Finally, examples of how innovative confocal micro Raman produces maps evidencing areas where high temperature exposure and thermal cycling-produced phase transformation of the Yttria partially stabilised Zirconia from tetragonal to monoclinic (which typically occurs during cracking processes preceding final TBC failure) are provided.

[23370] Studies of Air Plasma Sprayed Thermal Barrier Coatings and Their Surface Roughness for Applications in Siemens Medium Size Gas Turbines; Li, X.-H. et al.; ITSC 2012 Applications and Case Study

Abstract: To understand performance of thermal barrier coatings (TBCs) in various industrial applications of Siemens medium size gas turbines, effects of three types of thermal exposures i.e., high temperature isothermal exposure, thermal cycle fatigue (TCF) test, and burner rig test (BRT) on adhesion strength of an air plasma sprayed (APS) TBC have been studied and reported in this paper. It has been seen that the TBC adhesion strength is influenced by the type of thermal exposures differently. Together with a microscopic examination on TBC microstructures and fractography, a correlation between failure mechanisms and types of thermal exposures is discussed. In addition to the impact of various engine operation conditions on behavior of TBC, impacts of TBC surface roughness on turbine performance have also been evaluated. Surface profile and surface roughness on as sprayed and polished TBC and cast metal (uncoated) have been measured and two different polishing methods have been compared. As a result, a requirement of TBC surface roughness and a preferable polishing method are suggested.

[23379] Role of Process Conditions on the Interfacial Fracture Toughness of Plasma Sprayed Zirconia; Okajima, Y. et al.; ITSC 2012 Applications and Case Study

Abstract: Adhesive strength of the plasma-sprayed thermal barrier coating (TBC) is one of the most important parameters which influence the reliability during service. In the past, numerous test methods are reported to measure the coating adhesion. However, most of them require careful and time consuming preparation. Consequently, limited information could be obtained to establish the relationship between the processing conditions and the adhesive property. To produce more measurements using a simpler procedure, the interfacial indentation test and the modified tensile adhesive test are examined. In this paper, the interfacial fracture toughness of the plasma-sprayed ZrO2 coatings, deposited on Al substrates, were evaluated by these two tests. In order to study the effects of the powder injection, samples were sprayed with various carrier gas flow rates. The test results show a certain correlation between the melting index and the interfacial fracture toughness. In addition, variations between the results obtained from the two different methods are discussed.

[25104] Quantitative non-destructive evaluation of thermal barrier coating erosion using photoluminescent layers; Pilgrim, C.C. et al.; NDT 201 - 3B2

Abstract: The ongoing drive to improve efficiency and thrust of high performance gas turbines has led to the integration of thermal barrier coatings. These coatings enable the components to operate at higher temperatures whilst maintaining economic service life. It is recognised that further increases in operating temperature are the primary route to achieving higher performance. As such the thermal barrier coatings will need to become prime reliant. Quantitative non-destructive methods are, therefore, required to evaluate the degradation of the coatings to improve lifing estimates and develop condition-based maintenance procedures. In certain operating regimes, particularly in environments with contaminated intake air, degradation of the coating can occur by gradual thinning from the surface leading to complete failure. Current inspection routines cannot identify these gradual degradation mechanisms. The introduction of small amounts of rare-earth oxides into the standard thermal barrier coating materials makes the coating phosphorescent. The dopant ions act as atomic scale sensors which can be interrogated non-destructively through their phosphorescent properties. The dopant ions can be introduced in distinct layers through the coating thickness as a means to detect gradual thinning. The first detailed characterisation of this technique has been conducted. The phosphorescence was imaged using standard instrumentation to provide a rapid quantitative assessment of the erosion damage. After image processing the thickness profile of the coating was reconstructed and correlates to two forms of validation measurements. Testing, on a thermal gradient rig and on an aeroengine test bed, has demonstrated that the sensor function can be introduced whilst maintaining the primary function of the coating.

[26474] Quantitative evaluation of thermal barrier coating based on eddy current technique; Li, Y. et al.; NDT&E International 50 (2012) 29–35

Abstract: Thermal Barrier Coating (TBC), as the insulation between high-temperature gas and the alloying bodies of gas turbine blades, is adopted for protection and long-term service of gas turbines. It is imperative to non-destructively evaluate TBC of blades, since the TBC with thin thickness or delamination will lead to catastrophic accidents of gas turbines. In this paper, Eddy Current inspection (EC) is proposed for quantitative evaluation of TBC, which involves estimation of: (1) thickness of the top coating to identify possible thinning and (2) thickness and conductivity of bond coating to detect delamination and degradation. In an effort to implement the fast inversion, the closed - form expressions of the Jacobian matrix are derived based on Truncated Region Eigen function Expansion (TREE) modeling. The Levenberg–Marquardt (LM) algorithm is also adopted in the inversion for the parameters. The proposed inverse algorithm is verified by hybrid numerical modeling and experiments, which indicates that the quantitative evaluation of TBC by using EC in conjunction with the proposed inverse algorithm is valid and applicable to the engineering application.

[26479] Acoustic emission analysis on tensile failure of air plasma-sprayed thermal barrier coatings; Yao, W.B. et al.; Surface and Coatings Technology 206 (2012) 3803–3807

Abstract: An acoustic emission technique was used to monitor the cracking behavior and fracture process of thermal barrier coatings subjected to tensile loading. Acoustic emission signals were extracted and performed by fast Fourier transform, and their characteristic frequency spectrums and dominant bands were obtained to reveal fracture modes. Three different characteristic frequency bands were confirmed, corresponding to substrate deformation, surface vertical cracking and interface delamination, with the aid of scanning electronic microscopy observations. A map of the tensile failure mechanism of air plasma-sprayed thermal barrier coatings was established. The fracture strength and interfacial shear strength were estimated as 45.73±3.92 MPa and 20.51±1.74 MPa, respectively, which are well in agreement with available results.

<u>2013</u>

[24894] Development of Nondestructive Testing Method for Examining Thermal Resistance of Thermal Barrier Coatings on Gas Turbine Blades; Ozeki, T. et al.; ASME TURBO EXPO 2013 Ceramics; GT2013-94748

Abstract: In order to improve the efficiency of electric power generation with gas turbines, the turbine inlet gas temperature needs to be increased. Hence, it is necessary to apply thermal barrier coatings (TBCs) to various hot gas path components. Although TBCs protect the substrate of hot gas path components from high-temperature gas, their thermal resistance degrades over time because of erosion and sintering of the topcoat. When the thermal resistance of TBCs degrades, the surface temperature of the substrate becomes higher, and this temperature increase affects the durability of the hot gas path components. Therefore, to understand the performance of serviced TBCs, the thermal resistance of TBCs needs to be examined by the nondestructive testing (NDT) method. This method has already been reported for TBCs applied to a combustion liner. However, recently, TBCs have been applied to gas turbine blades that have complex three-dimensional shapes, and therefore, an NDT method for examining the thermal resistance of TBCs on blades was developed. This method is based on active thermography using carbon dioxide laser heating and surface temperature measurement of the topcoat by using an infrared camera. The thermal resistance of TBCs is calculated from the topcoat surface temperature when the laser beam heats the surface. In this study, the developed method was applied to a cylindrical TBC sample that simulated curvature on the suction side of a blade, and the results showed the appropriate laser heating condition for this method. Under the appropriate condition, this method could also examine the thermal resistance of TBCs present at 70% of the height of the blade. With these results, this method could determine the thermal resistance within an error range of 4%, as compared to destructive testing.

[25089] Thermal and mechanical properties with vertical cracks in thick thermal barrier coatings; Lu, Z. et al.; 9th International Conference on Fracture & Strength of Solids; June 9-13, 2013, Jeju, Korea

Abstract: The thermal stability and failure mechanism of thick thermal barrier coatings (TBCs) with and without vertical-type cracks have been investigated through the thermal cyclic exposure and thermal shock tests. The TBC systems with thickness of about 2000 μm in the top coat were prepared by an air plasma spray (APS) on the bond coat of about 150 μm prepared by the APS. The thermal cyclic exposure tests were performed with a dwell time of 60 min for 1143 cycles at a surface temperature of 1100℃ and a bottom temperature of 950℃. The thermal shock tests were also conducted with a dwell time of 60 min till more than 50% delamination or for 1143 cycles. The adhesive strength values of the as-prepared TBCs with and without vertical cracks are determined to be 24.7 and 11.0 MPa, respectively, indicating the better interface stability of the TBC with vertical cracks. It is verified from the cyclic thermal exposure and thermal shock test that the TBC with vertical cracks shows a better thermal durability than the TBC without vertical cracks. The hardness values of the as-prepared TBCs with and without vertical cracks are found to be 6.6 and 5.3 GPa, respectively, which are increased to 9.5 and 5.5 GPa, respectively, after the thermal cyclic exposure tests. These results indicate that the vertical-type cracks developed in the top coat are important in proposing efficient microstructure to improve the lifetime performance of thick TBC in high temperature environment.

[26625] Characterization of bond coats produced by high velocity oxy-fuel and cold gas dynamic sprayed N_2 gas; Rathod, W.S. et al.; International Journal of Engineering and Innovative Technology (IJEIT); Volume 2, Issue 12, June 2013

Abstract: To protect hot- sections of power generation components of gas turbine and aircraft, thermal barrier coatings (TBC's) are widely used. Conventional TBC's consist of a MCrAlY alloys (where M stand for Co, Ni or FeNi etc,) bond coating for oxidation resistance and a ceramic top coating for thermal insulation (mainly yttria stabilized zirconia, YSZ). The purpose of the current study was to investigate the microstructure and oxidation behavior of CoNiCrAlY coatings, deposited by the HVOF and CGDS techniques. The quality of the as-sprayed and oxidized bond coats was assessed in terms of their microstructure, especially porosity and oxide inclusion and mechanical properties, especially hardness. Sprayed samples were exposed to isothermal oxidation at 900 0C in air. Oxide growth rates were obtained from a series of mass gain measurements, while oxide scale compositions were determined using SEM, XRD and EDX analysis. Results obtained in this study show HVOF coating features high levels of visible defects, oxide content, spinel- type oxide and high oxide growth rate, whereas CGDS coatings show low oxide growth rate as a result of low porosity, oxide content and high hardness. The oxide scale on the CGDS coating after 1000 hrs of oxidation was composed of alumina and initiation of spinal type of oxides.

[26466] Transient thermography testing of unpainted thermal barrier coating (TBC) systems; Ptaszek, G. et al.; NDT&E International 59 (2013) 48–56

Abstract: Test piece surfaces are sometimes coated with a black, energy absorbing paint before transient thermography is applied. This practice is not acceptable to some thermal barrier coating (TBC) manufacturers and servicers of these systems since thermal barrier coatings are porous so the paint contaminates the coating and it is very difficult and costly to remove. Unfortunately, unpainted TBC surfaces have low emissivity, and after service their colour is usually uneven. The low emissivity gives low signal levels and also problems with reflections of the incident heat pulse, while the variation in emissivity over the surface gives strong variation in the contrast obtained even in the absence of defects. Additionally, the TBC is translucent to mid-wavelength IR radiation which negatively affects the location of disbonds based on the thermal responses. This paper investigates the effects of uneven discolouration of the surface and of IR translucency on the thermal responses. It has been shown that unpainted TBC systems can be inspected reliably by using higher power flash heating equipment assembled with an IR glass filter and a long wavelength IR camera. The paper also shows that the problem with uneven surface emissivity can be overcome by applying 2nd time derivative processing of the log–log surface cooling curves.

[26481] The role of beam dispersion in Raman and photo-stimulated luminescence piezo-spectroscopy of yttria-stabilized zirconia in multi-layered coatings; Liu, D. et al.; Acta Materialia 61 (2013) 12-21

Abstract: Laser beam dispersion affects the resolution of Raman and photo-stimulated luminescence piezo-spectroscopy measurements of transparent materials. In this paper, we investigate the lateral spreading of the laser beam and the axial sampling depth of Raman spectroscopy measurements within thermal sprayed yttria-stabilized zirconia (YSZ) thin coatings. The lateral diameters of the laser beams (k = 632.8 nm and 514 nm) reach approximately 160 lm after travelling through a thickness of 200 lm of air plasma sprayed (APS) YSZ and 80 lm after travelling through 120 lm of electron beam physical vapour deposited YSZ. The Raman spectroscopy sampling depth was found to be between 30 and 40 lm in APS YSZ. The beam dispersions within these two coatings were simulated using the ray tracing software ZEMAX to understand the observed scattering patterns. The results are discussed with respect to the application of these two spectroscopic techniques in multi-layered thermal barrier coating systems.

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5. Loading and environmental conditions

5.1.

6. Service performance

6.1. Spallation

References

6.2. Oxidation

References

2011

[20717] Study of oxidation behavior of TBCs with APS and HVOF CoNiCrAlY bond coatings; Karaoglanli, A.C. et al.; ITSC 2011 Aviation industry

Abstract: The use of Thermal Barrier Coatings (TBCs) has resulted in a significant improvement of the efficiency of gas turbines and diesel engines. A typical TBC is a multilayered coating system that comprises an oxidation resistant metallic bond coating (BC) and a thermally insulating ceramic top coating (TC). Under service condition an Al_2O_3 inter-layer, the Thermally Grown Oxide (TGO), forms in the interface between bond and top coating using aluminium from the BC material and oxygen that attains from the environment through pore channels of the TC. The aim of the present study is to describe the TGO formation on metallic bond coats deposited by different thermal spraying techniques. Therefore, TBCs that consist of a typical bond layer / top layer system (CoNiCrAlY bond layers and YSZ top layers) are deposited on Inconel 718 superalloy substrates. The metallic bond coatings are applied via Atmospheric Plasma Spraying (APS) and High Velocity Oxygen Fuel (HVOF); the ceramic top coatings via APS. Investigations are done concerning the oxidation behavior of this TBC system at 1100 °C in normal atmosphere for 8h, 24h, 50 h and 100 hours. The oxidation behaviour and microstructural properties during the oxidation test are evaluated and compared.

[26390] Oxidation failure of TBC systems: An assessment of mechanisms; Evans, H.E.; Surface and coatings technology 206 (2011) 1512–1521

Abstract: The spallation of thermal barrier coatings can be life-limiting but its prediction has proven to be a difficult problem. The final spallation event can often occur by buckling and is driven by the release of strain energy within the ceramic top coat and within the underlying thermally-grown oxide (TGO) layer if the delamination interface is at the TGO/bond-coat interface. Prior to this event, substantial sub-critical damage must develop at one or both of the TGO interfaces. It is argued in this paper that it is only the strain energy within the TGO produced during cooling that contributes significantly to this damage development and not that within the top coat. A critical strain energy within the TGO layer is suggested as a possible pragmatic method of predicting spallation. A critical assessment of proposed mechanisms which implicate bond coat oxidation in the failure process is also undertaken in the paper. Attention is given to: the role of phase changes in the bond coat; the influence of the mechanical constraint imposed by the top coat on the mechanical stability of the bond coat interface; the effect of the growth of the TGO on a non-planar interface on stress development; the importance of localised Al depletion in nucleating a fast-growing non-protective TGO.

2012

[25087] Oxidation behavior of thermal barrier coatings with cold gas dynamic sprayed CoNiCrAlY bond coats; Karaoglanli, A.C. et al.; 13th International Conference on Plasma Surface Engineering, September 10-14, 2012, in Garmisch-Partenkirchen, Germany

Abstract: The paper presents the results of investigation into the oxidation resistance and thermally grown oxide (TGO) of thermal barrier coatings (TBC). TGO occurred during in service affect the lifetime of the component by introducing several kinds of degradation mechanisms such as decreasing bonding strength, initiation of stress concentration and thermal stresses which lead to crack initiation and propagation associated with delamination or spallation failure. Therefore, TGO plays important role on TBC durability. In this study, TBCs that consist of a typical bond layer / top layer system (CoNiCrAlY bond layers and YSZ top layers) are deposited on Inconel 718 superalloy substrates. The metallic bond coatings are applied via Cold Gas Dynamic Spraying (CGDS); the ceramic top coatings via Atmospheric Plasma Spraying (APS). Investigations are done concerning the oxidation behavior of this TBC system at 1100 °C in normal atmosphere for 8h, 24h, 50 h and 100 hours. The oxidation behaviour and microstructural properties during the oxidation test were evaluated and compared, and TGO growth behavior was also investigated under high temperature oxidation. The microstructural features and oxidation behaviours were characterized by scanning electron microscopy and energy dispersive X-ray spectroscopy. Phase stability of TBCs were evaluated by means of X-ray diffraction method.

[26456] An investigation on the microstructure and oxidation behavior of laser remelted air plasma sprayed thermal barrier coatings; Zhu, C. et al.; Surface and Coatings Technology 206 (2012) 3739–3746

Abstract: NiCrAlY bond-coat was coated on Inconel 718 substrate by air plasma spraying (APS) followed by APS ZrO_2-8 wt.%Y_2O_3 as top-coat. Using CO_2 laser of different energy densities, ceramic top-coat surface was remelted. Laser remelting with high energy density (4 J/mm2) produced a dense microstructure over the whole thickness of top-coat, while low energy density (0.67 J/mm2) laser remelting produced a ~50 μm thick dense layer on the top-coat surface. It was found that the volume fraction of monoclinic phase decreased from 9% in as-sprayed coating to 4% and 3% after laser remelting with high and low energy density respectively. After isothermal oxidation at 1200 °C for 200 h, the thickness of oxide layer (TGO) in the sample produced by low energy density laser remelting was ~5.6 μm, which was thinner than that of oxide layer in as-sprayed (~7.6 μm) and high energy density laser remelted (~7.5 μm) samples. A uniform and continuous oxide layer was found to develop on the bond-coat surface after low energy density laser remelting. Thicker oxide layer containing Cr_2O_3, NiO and spinel oxides was observed in both as-sprayed and high energy density laser remelted coatings. After cyclic oxidation at 1200 °C for 240 h, the weight gain per unit area of as-sprayed coating was similar to that of high energy density laser remelted coating while a significantly smaller weight gain was found in low energy density laser remelted coating.

2013

[25078] On the oxidation of high-temperature alloys, and its role in failure of thermal barrier coatings; Loeffel, K.A.; Thesis - Massachusetts Institute of Technology; February 2013

Abstract: Thermal barrier coating (TBC) systems are applied to superalloy turbine blades to provide thermal insulation and oxidation protection. A TBC system consists of (a) an outer oxide layer that imparts thermal insulation, and (b) a metallic layer that affords oxidation protection for the substrate through the formation of a second, protective oxide layer. This slow oxidation of the metallic layer controls the mechanical integrity of the TBC system since it is accompanied by a large, anisotropic volumetric change on the order of 30 percent. To describe this coupled process at the micro scale, in this thesis we formulate a continuum-level, chemo-thermo-mechanically coupled, thermodynamically-consistent theory which integrates (a) diffusion of oxygen, (b) oxidation with accompanying anisotropic volume change, © thermo-elasto-viscoplastic deformations that may locally large, and (d) transient heat conduction. We numerically implement ou theory in an implicit

finite-element program, and calibrate the material parameters in our theory for an GeCrAlY alloy experimentally studied in the literature. We simulate the high-temperature oxidation of FeCrAlY, and show that our theory is capable of reproducing with reasonable accuracy the oxide thickness evolution with time at different temperatures, the shape distortion of the specimens, as well as the development of large compressive residual stresses in the protective surface oxide which forms. For the consideration of failure of thermal-barrier-coated components at the macroscale, a limitation of this type of model is that numerical simulations become challenging due to the sub-micro resolution of the required mesh. In a second part of this thesis, we therefore present a framework that facilitates macroscopic simulations by noting that the macroscopic effect of oxidation is simply to degrade some mechanical properties in the TBC system. In this framework oxidation is thus not modeled explicitly, but only indirectly manifested by affecting failure-related material parameters. We implement this model in an explicit finite-element program, apply it to a plasma-sprayed TBC system, and calibrate the material parameters. We then shoe that the model is capable of predicting with reasonable accuracy the load at which crack initiation occurs in a notched four-point bend test experimentally studied in the literature, as well as the overall qualitative load-displacement behavior in this test.

6.2.1. Static oxidation

References

2011

[20774] Isothermal oxidation behavior of NiCoCrAlTaY coating deposited by high velocity air-fuel spraying; Yang, G.-J.; Xiang, X.-D.; ITSC 2011 industrial gas turbines

Abstract: The performance of a thermal barrier coating is influenced by the high temperature oxidation behavior of bond coat. In this paper, NiCoCrAlTaY bond coat was deposited by high velocity air-fuel (HVAF) spraying, and the microstructure and surface morphology of the bond coat before and after oxidation were examined. Results show that the HVAF sprayed NiCoCrAlTaY coating presented a dense microstructure and some partially melted particles in a near spherical morphology were deposited on the coating surface. A uniform α-Al2O3 oxide was formed on the HVAF sprayed MCrAlY coating surface after the pre-oxidation treatment in an argon atmosphere. A small fraction of nodular-shaped mixed oxides was formed when the MCrAlY coating was oxidized at 1000oC for 100 h. The amount of the mixed oxides did not significantly increase after 200 h oxidation. The large particles on the bond coat surface maintained homogeneous α-Al2O3 oxide scale in 200 h oxidation at 1000oC in air. A model is proposed to explain the formation of nodular-shaped mixed oxides.

6.2.2. Cyclic oxidation

References

2011

[26393] Processing, repairing and cyclic oxidation behaviour of sol–gel thermal barrier coatings; Pin, L. et al.; Surface and coatings technology 206 (2011) 1609–1614

Abstract: Sol–gel Thermal Barriers Coatings (TBCs) are manufactured using the dip-coating technique optimised in terms of process parameters including sol formulation, rate of withdrawing and heat treatment. The specific mechanisms of sol–gel TBCs, deposited on either NiAl or NiPtAl bond-coated superalloy substrates, are described. The possibility to reinforce and stabilise the crack network formed during the heat treatment or the first oxidation cycles using supplementary dip-coatings and appropriate process parameters is investigated. It is shown that implementing this technique that can be further regarded as an attractive way for repairing TBCs, significantly improves the cyclic oxidation behaviour of the multi-materials systems

2013

[26414[Thermal cyclic oxidation performance of plasma sprayed zirconia thermal barrier coatings with modified high velocity oxygen fuel sprayed bond coatings; Tsai, P.-C. et al.; Surface and Coatings Technology 228 (2013) S11-S14

Abstract: In this study, the Hastelloy-X superalloy samples were overlaid by a CoNiCrAlY bond coating using a high pressure high velocity oxygen fuel (HVOF) spray process. A thin platinum film around 7.5 μm thick was further applied to the surface of CoNiCrAlY coating by the magnetron sputtering deposition. Then the superalloy coupons with bare bond coat and with Pt deposited bond coat were pack aluminized at 850 °C for 4 h to produce (Ni,Co)Al and PtAl2 phases on surfaces, respectively. After that, all samples were overlaid with the yttria-stabilized zirconia (YSZ) top coats by air plasma spraying (APS). Then specimens were subjected to a thermal cycling test at 1100 °C. Thermal cycling tests were 1 h at 1100 °C followed by 10 min of forced-air cooling to ambient temperature outside the furnace. The weights of all the specimens were measured every 2 cycles. Then effects of aluminizing and Pt-aluminizing on the cyclic oxidation performance and microstructure evolutions of the coatings were evaluated. Scanning electron microscopy (SEM), X-ray diffractometry (XRD) and electron probe microanalyzer (EPMA) were used to identify crystalline phases and microstructures of each coating. The results proved that the roughness of the CoNiCrAlY coating was not changed after the aluminizing or the Pt-aluminizing process. The specific weight gain of the thermal barrier coatings (TBCs) with aluminizing or with Pt-aluminizing bond coating was lower than that of TBCs with only HVOF sprayed bond coat. The cyclic oxidation life of sprayed MCrAlY/ZrO2–Y2O3 thermal barrier coating can be improved effectively by either aluminizing or Pt-aluminizing treatment.

6.3. Hot corrosion

References

2011

[20725] Study of plasma sprayed mullite coating using mullite and a mixture of alumina and silica powder particles; Salimi Jazi, H.; Hosseini, M.; ITSC 2011 Ceramic coatings

Abstract: Plasma sprayed ceramic coatings are widely used for thermal barrier coating applications. Commercially available mullite powder particles and a mixture of mechanically alloyed alumina and silica powder particles were used to deposit mullite ceramic coatings by plasma spraying. Microstructure and morphology of both powder particles as well as coatings were investigated by using scanning electron microscopy (SEM). Phase formation and degree of crystallization of coatings were analyzed and estimated by using X-ray diffraction technique. Differential thermal analysis (DTA) method was used to study the phase transformation of coatings. Results indicated that the porosity level in the coating deposited using mullite as initial powder particles was lower than that deposited using the mixed powder particles. The crystallization degree of the coating deposited using the mixed powder particles are higher than that deposited using mullite powder particles. DTA curves of coatings deposited using the mixed powders have showed some phase transformation due to the crystallization of the retained amorphous phases such as mullite and alumina in the coatings. The degree of crystallization of both as sprayed coatings was significantly increased after post deposition heat treatments.

2012

[26470] Hot Corrosion Behavior of Double-ceramic-layer $LaTi_2Al_9O_{19}$/YSZ Thermal Barrier Coatings; Xie, X. et al.; Chinese Journal of Aeronautics 25 (2012) 137-142

6.3.1. Static hot corrosion

References

2011

[23643] Evolution of hot corrosion resistance of YSZ, $Gd_2Zr_2O_7$ and $Gd_2Zr_2O_7$+YSZ composite thermal barrier coatings in Na_2SO_4+V_2O_5 at 1050°C; Habibi, M.H. et al.; UTSR (University Turbine Systems Research) Workshop 2011

6.3.2 Cyclic hot corrosion

References

2013

[24898] Cyclic Hot Corrosion of Thermal Barrier Coatings and Overlay Coatings; Eriksson, R. et al.; ASME TURBO EXPO 2013 Ceramics; GT2013-95526

Abstract: The influence, and interdependence, of water vapor and Na_2SO_4–50 mol% NaCl on the oxidation of a NiCoCrAlY coating and a thermal barrier coating (TBC) were studied at 750 °C. Water vapor was found to have a negligible effect on oxide composition, but influenced the oxide morphology on the NiCoCrAlY coating. Na_2SO_4–50 mol% NaCl deposits on the coatings influenced oxide composition, most notably by the promotion of a Y rich phase. The effect of Na_2SO_4–50 mol% NaCl deposits was also evident for the TBC coated specimen, where the formed metal/ceramic interface oxide was affected by salt reaching the interface by penetration of the zirconia TBC.

6.4. Erosion resistance

References

2011

[18197] Burner rig with an unattached duct for evaluating the erosion resistance of thermal barrier coatings; Miller, R.A. et al. NASA/TM-2011-217008; June 2011

Abstract: Extensive computational fluid dynamics (CFD) modeling backed by experimental observation has demonstrated the feasibility of using an unattached duct to increase the velocity and spatial spread of erodent particles exiting from a burner rig. It was shown that gas velocity and temperature are mostly retained if the inner diameter of the unattached duct equaled the exit diameter of the burner rig nozzle. For particles having a mean diameter of 550 μm, the modeled velocity attained at a distance 2.0 in. (50.8 mm) beyond the exit of a 12 in. (305 mm) long duct was approximately twice as large as the velocity the same distance from the nozzle when the duct was not present. For finer particles, the relative enhancement was somewhat less—approximately 1.5 times greater. CFD modeling was also used to guide the construction of a device for slowing down the velocity of the particles being injected into the burner rig. This device used a simple 45° fitting to slow the particle velocity in the feed line from 20 m/s, which is in the range needed to convey the particles, to about 3 m/s just as they are injected into the burner. This lower injection velocity would lessen the severity of the collision of large particles with the wall of the burner liner opposite the injection port, thereby reducing potential damage to the burner liner by high-velocity particles.

[26419] Solid particle erosion of thermal spray and physical vapour deposition thermal barrier coatings; Cernuschi, F. et al.; Wear 271 (2011) 2909– 2918

Abstract: Thermal barrier coatings (TBC) are used to protect hot path components of gas turbines from hot combustion gases. For a number of decades, in the case of aero engines TBCs are usually deposited by electron beam physical vapour deposition (EB-PVD). EB-PVD coatings have a columnar microstructure that guarantees high strain compliance and better solid particle erosion than PS TBCs. The main drawback of EB-PVD coating is the deposition cost that is higher than that of air plasma sprayed (APS) TBC. The major scientific and technical objective of the UE project TOPPCOAT was the development of improved TBC systems using advanced bonding concepts in combination with additional protective functional coatings. The first specific objective was to use these developments to provide a significant improvement to state-of-the-art APS coatings and hence provide a cost-effective alternative to EB-PVD. In this perspective one standard porous APS, two segmented APS, one EB-PVD and one PS-PVDTM were tested at 700 ◦C in a solid particle erosion jet tester, with EB-PVD and standard porous APS being the two reference systems. Tests were performed at impingement angles of 30◦ and 90◦, representative for particle impingement on trailing and leading edges of gas turbine blades and vanes, respectively. Microquartz was chosen as the erodent being one of the main constituents of sand and fly volcanic ashes. After the end of the tests, the TBC microstructure was investigated using electron microscopy to characterise the failure mechanisms taking place in the TBC. It was found that PS-PVDTM and highly segmented TBCs showed erosion rates comparable or better than EB-PVD samples.

2012

[19364] Erosion Resistance of Titania Co-Doped Yttria Stabilized Zirconia; O'Brien, A. et al.; ASME TURBO EXPO 2012 Manufacturing materials and metallurgy; GT2012-68172

Abstract: The standard yttria-stabilized zirconia (YSZ) has been used as thermal barrier coatings (TBCs) in the hot sections of gas turbine engines for several decades. To achieve further improvement to the thermal insulation capability of current TBCs, doping of alternative oxides to zirconia or co-doping of oxides to YSZ has been employed. In our previous study, it has been shown that doping of 7YSZ with titania (TiO_2) reduces thermal conductivity of 7YSZ substantially. As TBCs are susceptible to various failure mechanisms, in this study the erosion resistance of TiYSZ at high impingement speed and angle is evaluated along with measurements of hardness (H) and elastic modulus (E). Specimens with 5 different TiO_2 doping amounts (5%, 7.5%, 10%, 12.5% and 15%) are fabricated using plasma spraying and high temperature sintering. The erosion test results show that sample with 5% TiO_2 (5TiYSZ) suffers the most erosion damage at high impingement angle due to brittle fracture while 10-15TiYSZ samples exhibit less brittle erosion damage which leads to lower erosion rates under the same test condition. When comparing the erosion rates (defined as the loss of sample mass per mass unit of abrasive particles) to the hardness values, they were found to follow the same trend. The addition of TiO_2 (10- 15 wt%) had the effect of reducing the erosion rate of 7YSZ at high impingement angle.

6.4.1.

6.5. Degradation

References

2011

[16434] Strength Degradation of Oxide/Oxide and SiC/SiC Ceramic Matrix Composites in CMAS and CMAS/Salt Exposures; Choi, S.R.; Faucett, D.C.; ASME TURBO EXPO 2011 Ceramics; GT2011-46771

Abstract: CMAS (Calcium-Magnesium-Aluminosilicate) has shown to induce some deleterious effects on yittria-stabilized-zirconia (YSZ) based thermal barrier coatings (TBCs) of hot section components of aeroengines. The effects were shown to be dependent on the types and operating conditions of engines/components. The work presented ere explored how CMAS would affect ceramic matrix composites (CMCs) in terms of strength degradation. Four different, gas-turbine grade CMCs were utilized including two types of MI SiC/SiCs and other two types of oxides/oxides (N720/aluminisilicate and N720/alumina). Test specimens in a simple flexure configuration were CMAS-created at 1200 oC in air under either isothermal or thermal cycling condition. The effects of CMAS were quantified via residual strengths of treated test specimens. Strength degradatioh respect to as-received strengths ranged from 10 to 20 % depending on the types of CMCs. It was further observed tignificnat degradation of strength up to 90% occurred in an oxide/oxide CMC when sodium sulfate was added to CMAS.

[25069] High-temperature degradation of plasma sprayed thermal barrier coating systems; Eriksson, R.; Linköping University; April 2011

Abstract: Thermal barrier coating systems (TBCs) are used in gas turbines to prevent high-temperature degradation of metallic materials in the combustor and turbine. One of the main concerns regarding TBCs is poor reliability, and accurate life prediction models are necessary in order to fully utilise the beneficial effects of TBCs. This research project aims at developing deeper understanding of the degradation and failure mechanisms acting on TBCs during high temperature exposure, and to use this knowledge to improve life assessments of TBCs. The present work includes a study on the influence of coating interface morphology on the fatigue life of TBCs and a study on the influence of some different heat treatments on the adhesive properties of TBCs. The influence of coating interface morphology on fatigue life has been studied both experimentally and by modelling. Large interface roughness has been found experimentally to increase fatigue life of TBCs. The modelling work do, to some extent, capture this behaviour. It is evident, from the study, that interface morphology has a large impact on fatigue life of TBCs. Three thermal testing methods, that degrade TBCs, have been investigated: isothermal oxidation, furnace cycling and burner rig test. The degraded TBCs have been evaluated by adhesion tests and microscopy. The adhesion of TBCs has been found to depend on heat treatment type and length. Cyclic heat treatments, (furnace cycling and burner rig test), lower the adhesion of TBCs while isothermal oxidation increases adhesion. The fracture surfaces from the adhesion tests reveal that failure strongly depends on the pre-existing defects in the TBC.

[26392] Performance and degradation mechanisms of thermal barrier coatings for turbine blades: a review of Onera activities; Bacos, M.-P. et al.; Journal AeroSpace lab; issue 3 - November 2011

Abstract: Thermal barrier coatings are used to protect blades and vanes in the hot sections of gas turbines. They consist of a thick porous ceramic layer deposited on a alumina forming metallic bond coat in contact with the nickel-based superalloy substrate. They are designed to prolong the components lifetimes or to increase gas temperature, and therefore efficiency. In service, the structure and composition of the various layers evolve, due to sintering of the ceramic layer, oxidation of the bond coat, and interdiffusion phenomena with the substrate. As a result, the properties of each layer are affected, as is the interfacial toughness. These evolutions, combined with applied external stresses, may lead to bond coat rumpling, crack formation at the bond coat/ceramic interface and the ceramic layer may eventually spall off. In addition to these intrinsic degradation modes, interactions with the environment can accelerate the system degradation. This paper reviews the aging phenomena occurring in thermal barrier coatings at high temperatures and describes their degradation mechanisms, with illustrations from service experience and laboratory tests

<u>2012</u>

[25107] Degradation of EB-PVD thermal barrier coatings caused by CMAS deposits; Peng, H. et al.; Progress in Natural Science: Materials International; 2012;22(5):461–467

Abstract: In aero-turbine engines, thermal barrier coatings (TBCs) must be capable to withstand harsh environments, such as high-temperature oxidation and hot-corrosion. Recently, a new failure mode of TBCs caused by calcium–magnesium–alumina–silicate (CMAS) glass has attracted increasing attention. In this paper, yttria stabilized zirconia (YSZ) TBCs produced by electron beam physical vapor deposition (EB-PVD) were exposed to CMAS deposits at 1250 C. The microstructure evolution and failure mechanism of the coatings were investigated. It has been shown that CMAS glass penetrated into the YSZ ceramic layer along the inter-columnar gaps and interacted with YSZ. As a result, an interaction zone of about 20 mm thickness, which was the mixture of CMAS and YSZ with equiaxial structure, was formed in the YSZ surface layer after 4h heat-treatment at 1250 C. Meanwhile, yttria in YSZ layer as a stabilizer was dissolved in CMAS glass and caused accelerated monoclinic phase transformation. After 8h heat-treatment, degradation of YSZ TBC occurred by delamination cracking of YSZ layer, which is quite different from the traditional failure caused by interfacial cracking at the YSZ/metallic bondcoat. Physical models have been built to describe the failure mechanism of EB-PVD TBCs attacked by CMAS deposits

[25109] Degradation of thermal barrier coatings from deposits and its mitigation; Padture, N.P.; Ohio State university; April 2012

Abstract: Ceramic thermal barrier coatings (TBCs) used in gas-turbine engines afford higher operating temperatures, resulting in enhanced efficiencies and performance. However, in the case of syngas-fired engines, fly ash particulate impurities that may be present in syngas can melt on the hotter TBC surfaces and form glassy deposits. These deposits can penetrate the TBCs leading to their failure. In experiments using lignite fly ash to simulate these conditions we show that conventional TBCs of composition 93wt% ZrO_2 + 7wt% Y_2O_3 (7YSZ) fabricated using the air plasma spray (APS) process are completely destroyed by the molten fly ash. The molten fly ash is found to penetrate the full thickness of the TBC. The mechanisms by which this occurs appear to be similar to those observed in degradation of 7YSZ TBCs by molten calcium-magnesium-aluminosilicate (CMAS) sand and by molten volcanic ash in aircraft engines. In contrast, APS TBCs of $Gd_2Zr_2O_7$ composition are highly resistant to attack by molten lignite fly ash under identical conditions, where the molten ash penetrates ~25% of TBC thickness. This damage mitigation appears to be due to the formation of an impervious, stable crystalline layer at the fly ash/$Gd_2Zr_2O_7$ TBC interface arresting the penetrating moltenfly- ash front. Additionally, these TBCs were tested using a rig with thermal gradient and simultaneous accumulation of ash. Modeling using an established mechanics model has been performed to illustrate the modes of delamination, as well as further opportunities to optimize coating microstructure. Transfer of the technology was developed in this program to all interested parties.

6.6. Surface cracking

References

<u>2011</u>

[26412] The surface cracking behavior in air plasma sprayed thermal barrier coating system incorporating interface roughness effect; Zhang, W.X. et al.; Applied Surface Science 258 (2011) 811– 817

Abstract: The objective of this work is to understand the effect of interface roughness on the strain energy release rate and surface cracking behavior in air plasma sprayed thermal barrier coating system. This is achieved by a parameter investigation of the interfacial shapes, in which the extended finite element method (XFEM) and periodic boundary condition are used. Predictions for the stress field and driving force of multiple surface cracks in the film/substrate system are presented. It is seen that the interface roughness has significant effects on the strain energy release rate, the interfacial

stress distribution, and the crack propagation patterns. One can see the completely different distributions of stress and strain energy release rate in the regions of convex and concave asperities of the substrate. Variation of the interface asperity is responsible for the oscillatory characteristics of strain energy release rate, which can cause the local arrest of surface cracks. It is concluded that artificially created rough interface can enhance the durability of film/substrate system with multiple cracks.

6.7. High temperature aging behavior

References

2011

[20597] High temperature aging behavior and order-disorder transformation of plasma sprayed Sm2Zr207 coatings; Tao, S. et al.; ITSC 2011 Industrial Gas Turbines 1

Abstract: Rare-earth zirconates with a pyrochlore structure have attracted great attention for potential application in thermal barrier coatings to further improve the performance and durability of gas turbines. In present work, the $Sm_2Zr_2O_7$ coating was deposited by air plasma spraying technology, and its microstructure and phase composition were examined. The as-sprayed $Sm_2Zr_2O_7$ coating exhibited anion-disordered while cation-ordered fluorite-type structure. Degree of ordering was considerable enhanced after high temperature aging, and transformed to ordered pyrochlore-type structure after thermal aging at temperatures above 1200 ºC. The typical lamellar structure for the as-sprayed $Sm_2Zr_2O_7$ coating gradually decreased with increasing thermal aging temperature, which was caused by microcrack healing at high temperatures.

6.8. Phase stability

References

2011

[20659] Phase stability and thermal conductivity of plasma sprayed scandia, yttria-stabilized zirconia TBCs ; Li, Q.; Gong, S.; ITSC 2011 Aviation industry 4

Abstract: Zirconia stabilized with a combination of scandia and yttria (ScYSZ) powder for plasma spraying was synthesized by chemical co-precipitation process in the experiment, and the ScYSZ powder contains 7.0mol% scandia and 1.5mol% yttria. The microstructure, phase stability and thermal conductivity of plasma sprayed ScYSZ thermal barrier coatings (TBCs) were investigated. The results revealed that the ScYSZ TBCs had excellent stability to retain single metastable tetragonal t′phase even after high temperature (1500°C) exposure for 300 hours and did not undergo a tetragonal-to-monoclinic phase transition upon cooling. Furthermore, the ScYSZ TBCs had lower thermal conductivity than 3.5-4.5mol% yttria-stabilized zirconia TBCs currently used in gas turbine engine industry. ScYSZ TBCs could be developed as a novel TBCs for advanced gas turbine engines.

6.9. Delamination

References

2011

[18205] Monitoring delamination of thermal barrier coatings during interrupted high-heat-flux laser testing using luminiscence imaging; Eldridge, J.I.; Wolfe, D.E.; The 35th International Conference on Advanced Ceramics & Composites; January 23-28, 2011

Abstract: This presentation showed progress made in extending luminescence-base delamination monitoring to TBCs exposed to high heat fluxes, which is an environment that much better simulates actual turbine engine conditions. This was done by performing up conversion luminescence imaging during interruptions in laser testing, where a high-power CO_2 laser was employed to create the desired heat flux. Up conversion luminescence refers to luminescence where the emission is at a higher energy (shorter wavelength) than the excitation. Since there will be negligible background emission at higher energies than the excitation, this methods produces superb contrast. Delamination contrast is produced because both the excitation and emission wavelengths are reflected at delamination cracks so that substantially higher luminescence intensity is observed in regions containing delamination cracks. Erbium was selected as the dopant for luminescence specifically because it exhibits up conversion luminescence. The high power CO_2 10.6 micron wavelength laser facility at NASA GRC was used to produce the heat flux in combination with forced air backside cooling. Testing was performed at a lower (95 W/cm2) and higher (125 W/cm2) heat flux as well as furnace cycling at 1163C for comparison. The lower heat flux showed the same general behavior as furnace cycling, a gradual, "spotty" increase in luminescence associated with debond progression; however, a significant difference was a pronounced incubation period followed by acceleration delamination progression. These results indicate that extrapolating behavior from furnace cycling measurements will grossly overestimate remaining life under high heat flux conditions. The higher heat flux results were not only accelerated, but much different in character. Extreme bond coat rumpling occurred, and delamination propagation extended over much larger areas before precipitating macroscopic TBC failure. This indicates that under the higher heat flux (and surface & interface temperatures), the TBC was more tolerant of damage. The main conclusions were that high heat flux conditions can not only accelerate TBC debond progression but can also grossly alter the pathway of delamination.

References

2011

[20677] The influence of CMAS attack on the lifetime of thermal barrier coatings; Steinke, T. et al.; ITSC 2011 Characterization & Testing 4

Abstract: Oxide compounds basically composed of calcium, magnesium, aluminum and silicon cations also known as CMAS, can be deposited on the surface of thermal barrier coatings (TBC) of gas turbine blades. Under certain operation conditions these compounds have been found to aggressively degrade the TBC, hence affecting the thermo-mechanical properties of the underlying component. Detailed investigation on the interaction of CMAS and the atmospheric plasma sprayed (APS) yttria-stabilized zirconia (YSZ) TBC was performed in a burner rig test facility under thermal gradient cycling conditions and at the same time CMAS deposition. This novel and unique test approach promises a coating screening and characterization test under service conditions. Variable exposure times at approximately 1250°C/1050°C surface/substrate temperatures were applied. The lifetime of the TBC was indicated by the number of thermal cycles until significant spallation occurred. X-ray spectroscopy and microstructural analyses were conducted on the cycled samples to determine the effect of thermo-chemical interactions. It was found that with extended heating period of 10 times the standard cycle, the number of sustainable load alternations heating/cooling was reduced. Interaction of CMAS and YSZ induces formation of glassy soda-silicate phase. Thermal cycling of thermo-physically mismatched TBC and glass melt causes crack formation and coating failure.

2012

[19529] Evolution of Thermal Barrier Coating Strain Tolerance During Engine Operation and its Application to Lifing Models; Schaudinn, M. et al.; ASME TURBO EXPO 2012 Structures and dynamics: Fatigue, fracture and life prediction; GT2012-68123

Abstract: Models for thermal barrier coating lifetime prediction are often based on bondcoat oxidation models leading to an end of life criterion either based on bondcoat full consumption or a critical thermally grown oxide thickness. Such models can be satisfactory on turbine parts where the most common coating delamination modes are black or grey failure which are linked to the bondcoat behaviour. Such models are not reliable for combustor parts with thick thermal barrier coating systems where the most common life limiting factor is the formation of cracks appearing in the ceramic layer few tens of microns above the bondcoat interface. This behaviour is linked to the TBC layer mechanical properties and should be described by a model taking into account the evolution of the TBC mechanical properties during engine operation, the mechanical loads in the ceramic layer and a crack propagation model in the TBC. A study of the strain tolerance of TBC from combustor parts after engine operation was performed by taking samples from combustor liners at various locations having different TBC surface temperature. The strain tolerance of TBC samples was measured by four-point bending and correlated with the TBC microstructure and various engine operation parameters. It was shown that the TBC microstructure has an influence on TBC strain tolerance, and that the evolution of the TBC strain tolerance during engine operation is linked to the TBC temperature as well as the operating hours. The data have been used to develop a predictive model of the evolution of the TBC strain tolerance during engine operation. This model allows optimization of parts reconditioning interval, and provides tools for determining the residual life of coated components.

7. Failure mechanisms

Because they allow surface temperatures higher than the melting point of the substrate, ensuring the integrity of TBCs is critical. Understanding the mechanisms of TBC failure is an active area of research. The failure is linked with large residual compression in the underlying thermally grown oxide (TGO), but details of the mechanism only begin to be understood [xxxx]

7.1. Foreign Object Damage (FOD)

References

2011

[18116] Ongoing research into the impact durability of thermal barrier coatings; Minor, P.M. et al.

2013

[24895] Foreign Object Damage (FOD) of Ceramic Thermal Barrier Coatings (TBCs) in Gas Turbine Airfoils; Choi, S.R. et al.; ASME TURBO EXPO 2013 Ceramics; GT2013-95054

Abstract: Ceramic thermal barrier coatings (TBCs), attributed to their inherent brittle nature, are highly susceptible to damage by impacting foreign particles when the impacting kinetic energy exceeds certain limits. The damage is termed foreign object damage (FOD) in related turbine components and results in various issues/problems to coatings as well as to substrates from delamination to spallation to cracking to catastrophic failure depending on the severity of impact. The FOD testing was performed using a ballistic impact gun for turbine airfoil components coated with 7% yittria stabilized zirconia (7YSZ) by electron beam physical vapor deposit (EB-PVD). A range of impact velocities up to Mach 1 was applied with three different projectile materials of steel, silicon nitride, and glass balls. The damage was assessed and characterized in terms of impact velocity, projectile material, and remaining life of turbine components. An energy-balance approach was made to develop a model to predict delamination of the TBCs upon impact.

7.2. Delamination

References

2012

[23369] Study of Delamination Induced by Laser-Drilling of Thermally-Sprayed TBC Interfaces; Guinard, C. et al.; ITSC 2012 Applications and Case Study

Abstract: The efficiency of aero-engines combustion chambers with thermal barrier coating (TBC) is improved when numerous cooling holes are laser drilled with inclined angles. However, during the laser drilling process, especially in the percussion mode, a detrimental crack can be generated at the TBC interface. Thus, each hole could be edged with a non-visible delaminated area underneath the ceramic top-coat. The present work is focused on the thorough study of the delamination induced by laser percussion drilling when interrupted drilling conditions are presented. Shallow angle drilling was applied on separated holes with 1 to 4 laser pulses respectively and various acute incident angles. Crack length was assessed by conventional metallographic preparation. A special experimental method was carried out in order to inspect the delaminated interface and the lateral edge of a semi-hole. This non-destructive assessment of the delamination of laser drilled TBC was complemented by a 3D imaging of a semi-hole using X-Ray microscopy. Results are presented with attention on both crack initiation and propagation during the laser percussion drilling of plasma-sprayed TBC.

[26676] Delamination induced by laser drilling on a base cobalt superalloy; Girardot, J. et al.; ICALEO 2012 - Paper P104

Abstract: Temperatures in the high pressure chamber of aircraft engines are continuously increasing to improve the engine efficiency and constitutive materials need to be thermally protected. The first protection is a ceramic thermal barrier coating (TBC) cast on all the hot gas exposed structure. The second protection is provided by a cool air layer realized by the use of a thousand of drills on the parts where a cool air is flowing through. The laser drilling process is used to realize these holes at acute angles on this coated multi material. The present work aims at characterizing interfacial cracking induced by laser drilling on coated cobalt base super alloy. This work attached to quantify the crack by several microscopic observations with regards to the most significant process parameters related as the angle beam. The difference between the laser/ceramic and the laser/substrate interaction is also studied with real time observation by using a fast movie camera.

7.3. Thermal shock

References

2011

[20600] Thermal shock resistance of gadolinium zirconate coating with addition of nanostructured yttria partially stabilized zirconia; Zhong, H. et al.; ITSC 2011 Industrial Gas Turbines 1

Abstract: Gadolinium zirconate (Gd2Zr2O7, GZ) as one of the promising thermal barrier coating materials for high temperature application in gas turbine was toughened by nanostructured 3mol% yttria partially-stabilized zirconia (3YSZ) incorporation. The fracture toughness of the composite of 90mol%GZ-10mol% 3YSZ (GZ-YSZ) was increased by about 60% relative to the monolithic GZ. Both the GZ and GZ-YSZ composite coatings were deposited by atmospheric plasma spraying on Ni-base superalloys and then thermal-shock tested under the same conditions. The thermal-shock resistance of GZ-YSZ composite coating was improved significantly, which is believed to be mainly attributed to the enhancement of fracture toughness by the addition of nanostructured 3YSZ. In addition, the failure mechanisms of the thermal-shock tested GZ and GZ-YSZ composite coatings were also discussed.

[20733] Thermal shock resistance of plasma-sprayed thermal barrier coatings; Takahashi, S. et al.; ITSC 2011 Characterization & Testing

Abstract: The thermal shock resistance of plasma-sprayed thermal barrier coatings (TBCs) with different top coats was investigated according to the Japanese Industrial Standard "Testing methods for thermal cycle and thermal shock resistance of thermal barrier coatings" (JIS H 8451:2008). Three types of ceramics powders, namely, Al2O3, 8 mass % Y2O3-stabilized ZrO2 (YSZ) and La2Zr2O7 (LZ) were used in the top-coat spray. After the specimens were subjected to a thermal shock, the tensile adhesive strength of the TBCs was measured and the thermal shock resistance as defined in JIS H8451 was determined. The thermal shock properties of the TBCs were found to depend strongly on the chemical composition of the top-coat material. For TBCs with Al2O3 and LZ, the adhesive strength decreased with increasing thermal shock temperature difference (ΔT). On the other hand, little change in the adhesive strength was observed with increasing ΔT for YSZ TBC. From these results, the thermal shock resistance, ΔT_c, was determined to be 480 °C for Al2O3, 680 °C for LZ and more than 880 °C for YSZ TBC. Furthermore, the influence of thermal shock on the adhesive strength of TBCs was investigated in detail through observations of cross-sectional microstructures and fracture surfaces after adhesive testing.

2012

[24226] Thermal shock damage and microstructure evolution of thermal barrier coatings on Mar-M247 superalloy in a combustion gas environment; Mei, H.; Metallurgical and Materials Transactions A Vol.43A; June 2012

Abstract: The effect of pre-oxidation on the thermal shock of air plasma sprayed thermal barrier coatings (TBCs) was completely investigated in a combustion gas environment by burning jet fuel with high speed air. Results show that with increasing cycles, the as-oxidized TBCs lost more weight and enlarged larger spallation area than the as-sprayed ones. Thermally grown oxide (TGO) growth and thermal mismatch stress were proven to play critical roles on the as-oxidized TBC failure. Two types of significant cracks were identified: the type I crack was vertical to the TGO interface and the type II crack was parallel to the TGO interface. The former accelerated the TGO growth to develop the latter as long as the oxidizing gas continuously diffused inward and then oxidized the more bond coat (BC). The pre-oxidation treatment directly increased the TGO thickness, formed the parallel cracks earlier in the TGO during the thermal shocks, and eventually resulted in the worse thermal shock resistance.

7.4.

References

2001

[xxxxx] Mechanisms controlling the durability of thermal barrier coatings; Evans, A.G. et al., Prog. Mater. Sci., 46:2001, 505-553

2011

[20704] Failure mechanism of non-stoichiometric Mg-Al-Spinel abradable coatings under thermal cyclic loading; Eberet, S.; Steike, T.; ITSC 2011 Young professionals

Abstract: Plasma-sprayed ceramic coatings are often used as thermal barrier or abradable coatings in high-pressure stages of gas turbines. They are exposed to high thermo-mechanical loadings, due to the harsh operating conditions. Today, a material typically used in engines as thermal barrier coating material is yttria-stabilised zirconia (YSZ). This material has a low conductivity and a high thermal expansion coefficient, but a limited temperature capability of about 1200°C in long-term applications. For the use as abradable coatings, thicker coatings with a thickness above one millimetre are necessary. However with increasing coating thickness and limited cooling efficiency there is a risk of premature failure. As a result new ceramic materials have been developed. For the lifetime analysis they were tested by thermal gradient cycling tests. In the present work an APS ceramic double-layer topcoat composed of 7YSZ and a top layer of non-stoichiometric magnesia alumina spinel (Mg-Al-Spinel) was used. The layer was sprayed on disc-shaped IN738 superalloy substrates which were coated with a VPS bondcoat. Under specific thermal cycling conditions with temperatures above 1400°C, these samples showed a typical failure mechanism with exfoliation of thin coating lamellae, starting from the coating surface. This failure mechanism was analysed in detail, e.g. by scanning electron microscopy (SEM), X-ray diffraction, and chemical analysis. From these findings, a description of the failure mechanism was developed.

2012

[22290] Specific failures of superalloys with thermal barrier coatings subjected to thermo-mechanical fatigue loadings with a thermal gradient in a simulated combustion environment; Okazaki, M. et al.; Superalloys 2012, Twelfth International Symposium Creep and Fatigue; pp. 445

Abstract: A new test system has been developed which enables us to apply complicated thermo-mechanical fatigue (TMF) loadings to superalloy specimens in order to simulate the conditions and significant temperature gradients that are experienced in components that operate in a combustion gas flow environment. Employing this system, some TMF tests were carried out for superalloy specimens with thermal barrier coatings (TBCs) under a combined condition in which the external load was superimposed on the thermal cycles. Here, special attention was paid to the specific damage morphologies and the deformation under this kind of complicated TMF loadings. Based on the experimental results, a new mechanistic model was proposed for the specific failure modes, especially for a creep-induced ratcheting phenomenon as well as for failures of ceramic top coat. Finally, this understanding is summarized in a damage map, which is defined in terms of some mechanical criteria.

[25106] Thermal barrier coatings for gas turbine applications: Failure mechanisms and key microstructural features; Osorio, J.D. et al.; Dyna, year 79, Nro. 176, pp. 149-158. Medellin, December, 2012.

Abstract: Advances in new materials for current power generation devices, such as gas turbines, have led to more efficient and durable engines that supply rising energy demands. High efficiencies in gas turbines, due to higher operating temperatures, have been accomplished through the development of thermal barrier coatings. These are multilayered systems that provide thermal isolation and protection against corrosion and high temperature erosion. In this work, we describe barrier application processes, their microstructural characteristics and their main failure mechanisms. Two different thermal barrier coatings are characterized and the latest trends of these systems are summarized.

[26379] Failure characteristics and life prediction for thermally cycled thermal barrier coatings; Zhang, Y.Y. et al.; Surface and Coatings Technology 206 (2012) 2977–2985

Abstract: The effect of high temperature hold time at 1050 °C on thermal fatigue properties and failure characteristics of electron beam-physical vapor deposited (EB-PVD) thermal barrier coated samples (TBCs) was investigated in this work. To clarify this effect, the microstructure, especially that near the interface after certain thermal cycles was characterized by scanning electron microscopy (SEM). Results revealed that with increasing hold time at high temperature, fatigue life first increased then decreased and the failure mode diverted from the interfacial failure mode to one that consisted of both the interfacial failure mode and failure within the TBC. Failure was determined by strain energy density in the ceramic coating and the TGO, the fracture toughness of the ceramic coating, the TGO and the interface, and their correlations with microstructure defects near the interface. Based on analysis of the failure mechanism and the microstructure evolution near the interface, and by combining the simulation modeling of the thermal cycling response, a damage accumulation life prediction model was developed in terms of the TGO thickness. This model, which considered the evolution of the fatigue stress due to the increase in TGO thickness, was able to predict thermal fatigue life of the TBCs/nickel based superalloy system under different thermal cycling histories.

2013

[26423] Effect of water vapor on thermally grown alumina scales on bond coatings; Unocic, K.A.; Pint, B.A.; Surface and Coatings Technology 215 (2013) 3038

Abstract: The role of water vapor on thermal barrier coating (TBC) performance has been investigated for both Pt-modified aluminide and Pt-diffusion bond coatings by characterizing the alumina scale after exposures at 1150 °C. For both types of bond coatings, the average oxide scale thickness formed in dry O_2 at 1150 °C was lower than that formed in wet air, especially for air+10%H_2O. In all cases, the average thickness was higher beneath the yttria-stabilized zirconia (YSZ) top coat. Characterization of

the alumina scale formed without a YSZ top coat showed differences in morphology and Hf- and Ta-rich oxide precipitates at the gas interface depending on the environment. With and without water vapor, the β-(Ni,Pt)Al coatings showed a martensitic structure with 10–50 nm α-Cr(Re) precipitates. Alumina grain boundary segregation of Y and Hf from the superalloy substrate was easier to detect for the Pt-diffusion coatings.

[26425] Influence of water-air ratio on the heat transfer and creep life of a high pressure gas turbine blade; Eshati, S. et al.; Applied Thermal Engineering 60 (2013) 335-347

Abstract: An analytical model to investigate the influence of Water-Air Ratio (WAR) on turbine blade heat transfer and cooling processes (and thus the blade creep life) of industrial gas turbines is presented. The effects of WAR are emphasised for the modelling of the gas properties and the subsequent heat transfer process. The approach considers convective/film cooling and includes the influence of a thermal barrier coating. In addition, the approach is based on the thermodynamic outputs of a gas turbine performance simulation, heat transfer model, as well as a method that accounts for the changes in the properties of moist air as a function of WAR. For a given off-design point, the variation of WAR (0.0e0.10) was investigated using the heat transfer model. Results showed that with increasing WAR the blade inlet coolant temperature reduced along the blade span. The blade metal temperature at each section was reduced as WAR increased, which in turn increased the blade creep life. The increase in WAR increased the specific heat of the coolant and increased the heat transfer capacity of the coolant air flow. The model can be implemented by using the thermodynamic cycle of the engine, without knowing the turbine cooling details in the conceptual design stage. Also, this generic method assists the end user to understand the effect of operating conditions and design parameter on the creep life of a high pressure turbine blade.

8. Modelling

References

2011

[16963] Simulation of Combustor Damage Mechanisms and Material System Performance via a Sub-Element Configured Specimen Test; Rudrapatna, N.; Peterson, B.; ASME TURBO EXPO 2011 Manufacturing Materials & Metallurgy; GT2011-45761

Abstract: Modern gas turbine combustors are made of high temperature alloys, employ effusion cooling and are protected by a Thermal Barrier Coating (TBC). Standard material characterization tests such as creep, oxidation and low cycle fatigue are indicators of a material's potential performance but they neither fully represent the combustor geometric/material system nor fully represent the thermal fatigue conditions a combustor is subjected to during engine operation. Combustor rig tests and/or engine cyclic endurance tests to determine the suitability of new material systems for combustors are time consuming and costly. Therefore, a simple test method for screening material systems under representative combustor conditions is needed. This experimental system was recently developed at Honeywell Aerospace to characterize various gas turbine combustor damage mechanisms and assess state-of-the-art and developmental materials. A configured specimen is fabricated using materials and processes similarly to actual combustor hardware, including sheet metal forming, welding, TBC coating, and effusion hole laser drilling. The configured specimen is cyclically exposed to hot spot thermal gradients typically experienced by fielded hardware using a jet-fueled burner and heated cooling air. Damage mechanisms simulated include bond coat oxidation, TBC spallation, thermal fatigue and distortion. A summary of these damage mechanisms and lessons learned from test development are presented. Results from recent combustor liner, bond coat, and top coat material modifications are also discussed. The effect of combustor liner material creep and thermal fatigue resistance, bond coat composition and processing, and TBC composition and structure on combustor durability is presented.

[17601] Ab initio modeling of thermal barrier coatings: Effects of dopants and impurities on interface adhesion, diffusion and grain boundary strength; Ozfidan, A.I.; University of Ottowa, 2011

Abstract: The aim of this thesis is to investigate the effects of additives, reactive elements and impurities, on the lifetime of thermal barrier coatings. The thesis consists of a number of studies on interface adhesion, impurity diffusion, grain boundary sliding and cleavage processes and their impact on the mechanical behaviour of grain boundaries. The effects of additives and impurity on interface adhesion were elaborated by using total energy calculations, electron localization and density of states, and by looking into the atomic separations. The results of these calculations allow the assessment of atomic level contributions to changes in the adhesive trend. Formation of new bonds across the interface is determined to improve the adhesion in reactive element (RE)-doped structures. Breaking of the cross interface bonds and sulfur(S)-oxygen (O) repulsion is found responsible for the decreased adhesion after S segregation. Interstitial and vacancy mediated S diffusion and the effects of Hf and Pt on the diffusion rate of S in bulk NiAl are studied. Hf is shown to reduce the diffusion rate, and the preferred diffusion mechanism of S and the influence of Pt are revealed to be temperature dependent. Finally, the effects of reactive elements on alumina grain boundary strength are studied. Reactive elements are shown to improve both the sliding and cleavage resistance, and the analysis of atomic separations suggest an increased ductility after the addition of quadrivalent Hf and Zr to the alumina grain boundaries.

[18119] Numerical simulation of thermal barrier coating system under thermo-mechanical loadings; Moridi, A. et al.; WCE 2011; Proceedings of the World Congress on Engineering 2011, Vol III; July 6-8, 2011; London, U.K.

Abstract: In the present paper, numerical simulation of thermal barrier coating system under thermo-mechanical loadings is performed, using the finite element method in ABAQUS software. The base material is Aluminum-silicon alloy, A356.0 which is widely used in automotive components such as diesel engine cylinder heads. Thermal barrier coatings (TBCs) are applied to combustion chamber in order to reduce fuel consumption and pollutions and also improve fatigue life of components. The roughness effect of coating layers on stress distribution of test specimens is investigated. Semi-ellipsoid roughness of the interfaces between substrate/bond coat and bond coat/top coat are simulated to get the stress distribution by considering different wave lengths and roughness amplitudes. Mutual influence of waves positioning (in phase and out of phase) is also studied in present investigation. Results show that separation of the TBC system from substrate (in cylinder heads application) is more probable than separation of BC and TC due to higher stresses in substrate/BC interface. Moreover the magnitude of stress increases when the roughness amplitude enhances and wave length shortens which leads to crack initiation in TBC system. Crack propagation and failure in TBCs accelerate when the peak regions of asperities position on each other, leading to more tensile zones in BC layer.

[20641] Modelling ceramic droplet impingement; Tabbara, H.; Kamnis, S.; ITSC 2011 Modeling & Simulation 2

Abstract: Ceramic powders such as zirconia and titania are especially useful in their application as thermal barrier coatings, but are also useful in the production of more advanced coatings such as the dye-sensitized solar cell and functionally gradient prosthetic coatings. Due to their low thermal conductivity large temperature gradients through the powder particles are experienced during plasma spray deposition. As a result the particles often impinge at the substrate in a semi-molten form, which in turn substantially affects the final performance characteristics of the coating. This paper firstly summarizes some simulations and key results for completely solid and completely liquid particles. The modelling of semi-molten droplet impingement is then outlined, which is applicable to ceramic powders. The study examines the semi-solid impingement process during impact, spreading and solidification, and contributes to the growing insight being provided by numerical simulations on the topic of particle impingement in thermal spraying.

[20780] A 3D finite-difference model for the effective thermal conductivity of thermal barrier coatings; Qiao, J.H.; Bolot, R.; ITSC 2011 Modeling & Simulation

Abstract: Effective properties of TBCs may be quantified thanks to different measurement techniques. Image-based analysis represents an alternative method for predicting these effective properties. During the last 10 years, 2D modelling was intensively applied to estimate the thermal conductivity from coating cross-sectional images. However, real coatings present a complex 3D architecture so that the use of 2D computations based on cross-sections has to be validated. In the recent decade, 3D imaging approaches were applied for capturing 3D images of thermal spray coatings with relatively high resolution (up to 1 micrometer). Nevertheless, high resolution brings very large computational systems for which finite-element (FE) methods seem to be unsuitable due to high requirements in terms of computer memory (RAM) capacity. In the present study, a three-dimensional finite-difference-based heat transfer model was developed for analyzing the heat transfer mechanisms through a porous structure by saving RAM usage. An artificial 3D coating image, containing 300×300×300 voxels, was generated from microstructural information measured for a real coating cross-sectional image. In particular, this 3D artificial pore network was generated so that calculations performed on its cross-sections present similar results in comparison with those concerning SEM images of real coating cross-sections. Then, the results computed for the 3D image were compared with those obtained from 2D computations performed on cross-sections of the same 3D image, revealing the differences between 2D and 3D image-based analyses. Finally, the results were then compared with those computed by FE packages (OOF2 and ANSYS).

[25085] Constitutive and numerical modeling of chemical and mechanical phenomena in thermal barrier coatings for gas turbine blades of aircraft engines; Zolochevsky, A. et al.

[26384] Interfacial damage based life model for EB-PVD thermal barrier coating; Courcier, C. et al.; Surface and coatings technology 205 (2011) 3763–3773

Abstract: Thermal barrier coating life modelling is a major challenge for industrial applications. This study aims to highlight critical damage mechanisms involved in TBC failure for both isothermal and cyclic oxidation conditions. Experimental database is analysed in relation to elastic buckling of the ceramic top coat obtained by mechanical compressive tests. Ageing is modelled thanks to an original damage approach dealing with the evolution of interfacial properties and loading history. This methodology is successfully applied as a postprocessor to a 3D blade simulation for typical thermo-mechanical fatigue in-service loading.

2012

[19649] Parametric studies of nonlinear damping behavior of APS thermal barrier coatings based on cohesive interface model; Chen, Y.; Dong, W.; ASME TURBO EXPO 2012 Structures and dynamics: Damping technologies; GT2012-69343

Abstract: Thermal barrier coatings (TBCs) could reduce the temperature of the turbine blades and allow them working at higher temperatures, which leads to higher durability and reliability of turbine blades, and improves engine performance and fuel efficiency. Recent researches shown that thermal barrier coatings have very good damping properties, which means it could also improve the high cycle fatigue (HCF) life of the turbine blades. Previous studies found that damping of air plasma spray (APS) thermal barrier coatings exhibit nonlinearities (amplitude-dependent) due to its microstructures, which consists of several layers of splats with inter- and intra-microstructural micro-cracks. The main purpose of this paper is on the application of a bilinear cohesive interface model to simulate the microstructural features, the damage process and the contact friction between the interfaces of microstructural faults in APS ceramic topcoat. A representative volume element (RVE) model which coupled with the cohesive interface model is built and parametric relations, in terms of interface strength and stiffness, vibration amplitude and vibration cycles, are computed in this paper for understanding the effect of interfacial degradation, de-bonding, sliding, and contact friction between the interfaces of microstructural faults on the nonlinear damping properties. The calculation results could provide a fundamental understanding of the mechanisms responsible for the observed nonlinear energy dissipation and damping properties in APS ceramic coatings.

2013

[26462] Design of next generation thermal barrier coatings — Experiments and modelling; Gupta, M. et al.; Surface and Coatings Technology 220 (2013) 20–26

Abstract: Thermal barrier coating (TBC) systems have been used in the gas turbine industry since the 1980s. The future needs both the air and land based turbine industry involve higher operating temperatures with longer lifetime on the component so as to increase power and efficiency of gas turbines. The aim of this study was to meet these future needs by further development of zirconia coatings. The intention was to design a coating system which could be implemented in industry within the next 3 years. Different morphologies of ceramic topcoat were evaluated; using dual layer systems and polymers to generate porosity. Dysprosia stabilised zirconia was also included in this study as a topcoat material along with the state-of-the-art yttria stabilised zirconia (YSZ). High purity powders were selected in this work. Microstructure was assessed with scanning electron microscope and an in-house developed image analysis routine was used to characterise porosity content. Evaluations were carried out using the laser flash technique to measure thermal conductivity. Lifetime was assessed using thermo-cyclic fatigue testing. Finite element analysis was utilised to evaluate thermal–mechanical material behaviour and to design the morphology of the coating with the help of an artificial coating morphology generator through establishment of relationships between microstructure, thermal conductivity and stiffness. It was shown that the combined empirical and numerical approach is an effective tool for developing high performance coatings. The results show that large globular pores and connected cracks inherited within the coating microstructure result in a coating with best performance. A low thermal conductivity coating with twice the lifetime compared to the industrial standard today was fabricated in this work

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9. Lifing

9.1.

References

2011

[17423] Life Estimation of TBC on an Aero Gas Turbine Combustor: A Finite Element Approach ; Mishra, R.K. et al.; ASME TURBO EXPO 2011 Heat Transfer: Structures; GT2011-45027

Abstract: Thermal barrier coatings (TBCs) are used for the thermal protection of turbine engine hot end components to have increased life and or better performance. Due to extreme environments and cyclic loads experienced by these components, the TBC may also fail prematurely. Once the TBC fails, it exposes the underlying substrate to very high gas temperatures and the life of the component gets reduced drastically and it can fail within its prescribed service life. This has necessitated the accurate possible estimation of TBC life. The TBC coated transition liner of an aero engine reverse flow combustion chamber has been analysed using finite element approach for life estimation. Stress analysis followed by fatigue analysis is carried out based on a typical mission cycle of the component for life estimation. The approach focuses on the mismatch in thermo-physical properties, operational conditions, Thermally Grown Oxide (TGO) layer surface finish and its growth. Increase in TGO thickness leads to decrease in life – this fact is modelled appropriately and proved using this FEM based methodology. Actual failure data of service engines has also been analysed and compared with that of predicted. This approach can be extended for parametric studies and life evaluation of any TBC system. The present approach will be adopted for qualification of prime reliant TBC for Aero engine application.

[20772] Correlation between process parameters and thermal cycling life time for thermal barrier coatings; Altuncu, E. et al.; ITSC 2011 Industrial gas turbines

Abstract: With the modification of plasma spray parameters, porosity ratio of top coat can control along the cross-section. This improve the thermal cycle resistance and decrease the thermal conductivity. Plasma sprayed ZrO2/8 wt.–% Y2O3–NiCrAlY TBC systems which have different porosity (%8-12) and range of 250-350μm thicknesses of top coats, during thermal cycling tests with different hold times at 1350 °C have been performed. The main failure modes: delamination cracking, TGO growth rate and phase transformation are strongly dependent on the hold temperature and time. The correlation between TBC thermal cycle lifetimes and duration of high temperature hold time per cycle is shown and discussed with depending on thickness and porosity ratio.

2012

[19528] Determination of thermal barrier coatings average surface temperature after engine operation for lifetime validation; Witz, G; Bossmann, H.-P.; ASME TURBO EXPO 2012 Structures and dynamics: Fatigue, fracture and life prediction; GT2012-68122

Abstract: Assessment of ex-service parts is important for power generation industry. It gives the opportunity to correlate part conditions to specific operating conditions like fuel used, local atmospheric conditions, operating regime, and temperature load. For assessment of thermal barrier coatings, one of the most valuable information is the local thermal condition. A method has been developed in Alstom, allowing determination of a thermal barrier coating average surface temperature after engine operation. It is based on the analysis of the phase composition of the thermal barrier coating by the acquisition of an X-Ray diffraction spectrum of the coating surface, and its analysis using Rietveld refinement. The method has been validated by comparing its outcome to thermal models and base metal temperature mapping data. It is used for assessment of combustor and turbine coatings with various purposes: determination of remnant coating life, building of lifing models, or determination of the coating degradation mechanisms under some specific operating conditions. Examples will be presented showing applications of this method.

[26379] Failure characteristics and life prediction for thermally cycled thermal barrier coatings; Zhang, Y.Y. et al.; Surface and Coatings Technology 206 (2012) 2977–2985

Abstract: The effect of high temperature hold time at 1050 °C on thermal fatigue properties and failure characteristics of electron beam-physical vapor deposited (EB-PVD) thermal barrier coated samples (TBCs) was investigated in this work. To clarify this effect, the microstructure, especially that near the interface after certain thermal cycles was characterized by scanning electron microscopy (SEM). Results revealed that with increasing hold time at high temperature, fatigue life first increased then decreased and the failure mode diverted from the interfacial failure mode to one that consisted of both the interfacial failure mode and failure within the TBC. Failure was determined by strain energy density in the ceramic coating and the TGO, the fracture toughness of the ceramic coating, the TGO and the interface, and their correlations with microstructure defects near the interface. Based on analysis of the failure mechanism and the microstructure evolution near the interface, and by combining the simulation modeling of the thermal cycling response, a damage accumulation life prediction model was developed in terms of the TGO thickness. This model, which considered the evolution of the fatigue stress due to the increase in TGO thickness, was able to predict thermal fatigue life of the TBCs/nickel based superalloy system under different thermal cycling histories.

[26459] Effects of surface modification on thermal cycling lifetime of thermal barrier coatings with HVOF NiCrAlY bondcoat; Ni, L.; Zhou, C.; Progress in Natural Science: Materials International 2012; 22(3):237–243

Abstract: NiCrAlY bond coat was prepared by HVOF (high-velocity oxygen fuel) spray on nickel-based superalloy. Surface treatments like grit-blasting, shot-peening and vacuum treatment methods were carried out in order to study the effects of surface modification on thermal cycling lifetime of TBCs. The surface-modified TBCs exhibited better thermal shock resistance. Failure of TBCs with the as-sprayed bondcoat occurred within the topcoat and at the interface between spinels and the topcoat, while that of after shot-peening, grit-blasting and vacuum treatment occurred mainly within the topcoat. TGO (thermally grown oxide) formed on as-sprayed bond coat was composed of a Ni(Al,Cr)2O4 spinels outer layer and a Al2O3 inner layer. But, a continuous and uniform Al2O3 formed after surface modification. Formation of the mixed oxides (spinels) on the as-sprayed bondcoat accelerated the failure of TBCs.

2013

[24376] Assessment of cyclic lifetime of NiCoCrAlY/ZrO_2-based EB-PVD TBC systems via reactive element enrichment in the mixed zone of the TGO scale; Fritscher, K. et al.; Metallurgical Transactions A vol. 44A; May 2013

Abstract: The chemical composition of the alumina-zirconia mixed zone (MZ) of an electron beam physical vapor deposited thermal barrier coating (EB-PVD TBC) system is affected by service conditions and by the interdiffusion of elements from the substrate alloy below and the zirconia top coat. Three NiCoCrAlY bond-coated Ni-base substrates with YPSZ or CeSZ EB-PVD TBCs were subjected to a cyclic furnace oxidation test (FCT) at 1373 K (1100 C) in order to provide experimental evidence of a link between chemistry of the MZ, the substrate alloy, the ceramic top coat, and the time in the FCT. Energy dispersive spectroscopy of the MZ revealed preferred accumulation of Cr, Zr, Y, and Ce. The concentration of the reactive elements (RE = Ce+Y+Zr) was related to the respective average lifetimes of the TBC systems at 1373 K (1100 C). The RE content in the MZ turned out to be a life-limiting parameter for YPSZ and CeSZ TBC systems which can be utilized to predict their relative lifetimes on th individual substrates. Conversely, the TBC failure mechanisms of YPSZ and CeSZ TBC systems are dissimilar.

[26406] Lifetime prediction of plasma-sprayed thermal barrier coating systems; Wei, S. et al.; Surface and Coatings Technology 217 (2013) 39-45

Abstract: Relying on the statistical treatment of the morphological characteristics of the interface between yttria stabilized zicronia (YSZ) top coat (TC) and metallic bond coat (BC), finite element model of thermal barrier coating (TBC) is generated by a sinusoidal function. Meanwhile, considering the thermally grown oxide (TGO) growth, creep effects and top coating sintering, lifetime prediction methodology is proposed. Furthermore, stress development during thermal cycling is calculated by finite element method (FEM). Comparing the numerically predicted TBC stresses with the failure stress of top coating, the lifetime of plasma-sprayed (PS) TBC is predicted between 810 and 900 cycles, in agreement with experimental result of about 860 cycles, the average data of 8 specimen lifetimes. Different factors to the failure of TBC are compared.

[26436] Effect of oxygen content in NiCoCrAlY bondcoat on the lifetimes of EB-PVD and APS thermal barrier coatings; Surface and Coatings Technology 221 (2013) 207-213

Abstract: The effect of oxygen content in NiCoCrAlY bondcoat on the cyclic oxidation lifetimes of EB-PVD and APS thermal barrier coatings (TBC) has been studied. The EB-PVD TBC system with an oxygen content of 0.05 wt. % in NiCoCrAlY bondcoat shows five times longer lifetimes compared to a TBC system with 0.2 wt% oxygen in the bondcoat. In the bondcoat with the high oxygen content the minor (0.3 wt.%) yttrium addition was found to be tied up by oxygen into fine precipitates of yttrium aluminates. Thereby the beneficial effect of yttrium onto the adherence of the alumina scale was significantly reduced. The critical scale thickness at failure was by about a factor of two lower for the high oxygen bondcoat than for the low oxygen bondcoat. In contrast to EB-PVD TBC systems, no detrimental effect of increasing oxygen content on the lifetime of APS-TBC systems was observed. This can be explained by a different failure mechanism of APS-TBC systems, whereby the lifetime is mainly determined by the rate of crack propagation through the ceramic topcoat.

10. New developments

10.1.

References

2011

[20724] Advanced thermal barrier coatings from Ti-doped YSZ systems; Jarligo, M.O.; Mauer, G.; ITSC 2011 Ceramic coatings

Abstract: Fracture toughness and phase stability are crucial properties of thermal barrier coatings (TBC) during highly loaded thermomechanical operations in gas turbines. While several alternative TBC materials have exhibited excellent thermal resistance, their potential applicability has been limited due to poor endurance to cyclic stresses. The addition of TiO_2 to the non-transformable tetragonal t´-YSZ has been found to effectively enhance the fracture toughness and phase stability of YSZ at high temperature exposures. Thermal cycling tests in a burner rig were conducted on TBCs prepared from atmospheric plasma sprayed titania-doped YSZ to verify this phenomena. Exposure temperature was 1400°C at the surface and thermal gradient across the sample was provided by simultaneous back-cooling treatment. Cycling tests reveal that the slight increase in the tetragonality of the deposited coatings with increasing amount of dopant did not cause a significant effect to the lifetime of the TBCs. Moreover, increasing amount of Ti-substitution did not influence the fracture toughness of the bulk YSZ.

[23663] High temperature unique low thermal conductivity thermal barrier coating (TBC) architectures; Rai, A.K. et al.; UTSR (University Turbine Systems Research) Workshop 2011

[23668] Hafnia-based nanostructured thermal barrier coatings for advanced hydrogen turbine technology – presentation; Ramana, C.V.; Choudhuri, A.R.; UTSR (University Turbine Systems Research) Workshop 2011

[26367] The development of new bond coat compositions for thermal barrier coating systems operating under industrial gas turbine conditions; Seraffon, M. et al.; Surface and Coatings Technology 206 (2011) 1529–1537

Abstract: Environmental and economic issues are driving the development of increasingly efficient gas turbines. An important step in achieving this is to engineer components which can operate with longer lifetimes and at higher metal temperatures. Inlet temperatures for gas turbines now exceed the melting temperatures of nickel-based superalloys (i.e. 1300–1350 °C). The use of advanced air cooling systems coupled with thermal barrier coatings (TBCs) reduces the temperature of the underlying superalloy substrate. The bond coating, an important part of the TBC system, oxidizes to form a slow growing protective oxide layer, while also providing adhesion between the ceramic topcoat and the substrate. NiCoCrAlY overlay coatings are some of the most commonly used bond coatings for industrial gas turbines and extensive research has been undertaken over many years to find the best bond coating composition. This paper reports upon the production of new, model bond coatings with a wide range of different compositions. The focus is on their oxidation behavior at a temperature typically experienced by bond coatings on industrial turbine blades (950 °C). A physical vapor deposition technique, magnetron sputtering, has been used to deposit a range of Ni–Co–Cr–Al coatings onto 10 mm diameter sapphire substrates. This was achieved through co-sputtering two targets: a Ni–10%Cr, Ni–20%Cr, Ni–50%Cr, Ni–20%Co–40%Cr or Ni–40%Co–20%Cr target and a pure Al target. About a hundred samples with varying compositions were produced by this method. The coatings were then oxidized in air for 500 h at 950 °C. All samples were assessed by measuring the change in coating thickness, using pre- and post-exposure metrology only, and also the change in specimen weight. This approach has shown that magnetron sputtering successfully deposited 20 to 30 μm thick coatings and allowed the calculation of oxide growth rates. Energy dispersive X-ray (EDX) analysis was used to characterize the exact composition of each sample. Additionally, Xray diffraction (XRD) has been used to identify the major oxides formed during exposure. The selective growth of protective Cr_2O_3 or Al_2O_3 or other less protective mixed oxides (depending on the initial coating composition) was observed. This influenced the oxide scale growth rate, indicating which coatings produced more protective oxides and allowing future optimization of the bond coating composition, for service within the turbine section of industrial gas turbines to be planned.

[26665] Engineering a new class of thermal spray nano-based microstructures from agglomerated nanostructured particles, suspensions and solutions: An invited review; Fauchais, P. et al.; Journal of Physics D: Applied Physics 44, 9 (2011) 93001

Abstract: From the pioneering works of McPherson in 1973 who identified nanometer-sized features in thermal spray conventional alumina coatings (using sprayed particles in the tens of micrometers range) to the most recent and most advanced work aimed at manufacturing nanostructured coatings from nanometersized feedstock particles, the thermal spray community has been involved with nanometer-sized features and feedstock for more than 30 years. The development of feedstock, especially through cryo-milling, and processes able to manufacture coatings structured at the sub-micrometer or nanometer sizes, such as micrometer-sized agglomerates made of nanometer-sized particles for feedstock and emerging thermal spray processes such as suspension and liquid precursor thermal spray techniques have been driven by the need of manufacturing coatings with enhanced properties. These techniques result in two different types of coatings: on the one hand those with a so-called bimodal structure having nanometer-sized zones embedded within micrometer ones, for which the spray process is similar to that of conventional coatings and on the other hand sub-micrometer or nanostructured coatings achieved by suspension or solution spraying. Compared to suspension spraying, solution precursor spraying uses molecularly mixed precursors as liquids, avoiding a separate processing route for the preparation of powders and enabling the synthesis of a wide range of oxide powders and coatings. Such coatings are intended for use in various applications ranging from improved thermal barrier layer and wear-resistant surfaces to thin solid electrolytes for solid oxide fuel cell systems, among other numerous applications. Meanwhile these processes are more complex to operate since they are more sensitive to parameter variations compared to conventional thermal spray processes. Progress in this area has resulted from the unique combination of modeling activities, the evolution of diagnostic tools and strategies, and experimental advances that have enabled the development of a wide range of coating structures exhibiting in numerous cases unique properties. Several examples are detailed. In this paper the following aspects are presented successively i) the two spray techniques used for manufacturing such coatings: thermal plasma and HVOF, ii) sensors developed for in-flight diagnostics of micrometer-sized particles and the interaction of a liquid and hot gas flow, iii) the three spray processes: conventional spraying using micrometer-sized agglomerates of nanometer-sized particles, suspension spraying and solution spraying and iv) the emerging issues resulting from the specific structures of these materials in particular the characterization of these coatings and, lastly, the potential industrial applications. Further advances require the scientific and industrial communities to undertake new research and development activities to address, understand and control the complex mechanisms occurring, in particular, thermal flow - liquid drops or stream interactions when considering suspension and liquid precursor thermal spray techniques. Work is still needed to develop new measurement devices to diagnose in-flight droplets or particles below 2 μm, average diameter and to validate that the assumptions made for liquid-hot gas interactions. Efforts are also still required to further develop some of the characterization protocols suitable to address the specificities of such nanostructured coatings, as some existing "conventional" protocols usually implemented on thermal

spray coatings are not suitable anymore, in particular to address the void network architectures from which derive numerous coatings properties

2012

[19424] Evaluation of a New Coating for Application to Ramjet Engine Combustion Chamber; Heshmat, H. et al.; ASME TURBO EXPO 2012 Microturbines and small turbomachinery; GT2012-68725

Abstract: In the present study, the adhesion and thermal characteristics of a new high temperature coating are evaluated. The new Korolon™ 1350A is applied by a conventional spray gun process at room temperature and does not require a bond coat when applied to Ni-based alloys. The coating thickness was varied from 127 to 254 μm. The coating/substrate adhesion was evaluated using a conventional bend test that subjects the coating to large elastic/plastic deformations. The coating showed no sign of delamination or fracture when subjected to 180o bend. Bend testing was also conducted following thermal cycling (95 to 815 °C) of the specimens in air. The coating showed no sign of oxidative degradation or delamination in bend testing. The thermal characteristics of the coating were evaluated under both convective and conductive heating conditions, including a guarded hot plate apparatus. After extensive testing and measurement of differential temperatures across the test specimens, it was estimated that the thermal conductivity of the coating is approximately 1 W/m K. The coating was then applied to aero throttle panels and tested in a ramjet simulation test facility with flowing hot air at 1,200 °C. During this experiment the surface temperature on the coated panels reached 720 °C. Examination of the panels subsequent to testing showed no sign of degradation. Consistent with bench testing, a maximum temperature difference of 316 °C was measured between the heated surface and the back face with the coating applied to the heated surface. The results confirmed that the new coating is promising for elevated temperature use as a thermal barrier coating.

[19735] Development and Assessment of Coatings for Future Power Generation Turbines; Alvin, M.A. et al.; ASME TURBO EXPO 2012 Manufacturing materials and metallurgy; GT2012-69654

Abstract: In the present work, time-accurate simulations were performed to investigate the unsteady flow fields in the tip region of a low-speed large-scale axial compressor rotor at near-stall condition. Firstly, the steady performance characteristic of the rotor was obtained by steady simulations. Secondly, a series of unsteady simulations were carried out to investigate the physical processes as the rotor approaching stall and the role of complex tip flow mechanism on flow instability in the rotor. The characteristics of tip leakage vortex were compared between design condition and near-stall condition. Detailed analyses were then employed to emphasize the development of stall inception and the comprehensions of the internal flow field. Two flow phenomena, spillage at the leading edge and backflow at the trailing edge, are found beyond the flow solution limit, which are both linked to the tip leakage flow. And the breakdown of the tip leakage vortex has been captured. The flow visualization and the quantification of passage blockage expose that the tip leakage vortex and corner vortex contribute most to the total passage blockage. Therefore, they are considered to be the key flow structures contributing to the rotating stall. Further analyses indicate that, in the current rotor, the interaction of the tip leakage flow and the corner vortex is clarified to be the key factor that leads to the rotating stall. In addition, the very initial disturbances of stall inception are discussed. And the interaction of the boundary layer migration on the blade suction side and the tip leakage vortex also plays a significant role in the stall inception.

[21421] Recent advances in energy materials for hot sections of modern gas-turbine engines; Huda, Z.; World Academy of Science, Engineering and Technology 62 2012

Abstract: This presentation reviews recent advances in superalloys and thermal barrier coating (TBC) for application in hot sections of energy-efficient gas-turbine engines. It has been reviewed that in the modern combined-cycle gas turbines (CCGT) applying single-crystal energy materials (SC superalloys) and thermal barrier coatings (TBC), and – in one design – closed-loop steam cooling, thermal efficiency can reach more than 60%. These technological advancements contribute to profitable and clean power generation with reduced emission. Alternatively, the use of advanced superalloys (e.g. GTD-111 superalloy, Allvac 718Plus superalloy) and advanced thermal barrier coatings (TBC) in modern gas-turbines has been shown to yield higher energy-efficiency in power generation.

[23297] Advanced thermal barrier coatings for high temperature corrosion applications in gas turbines; Mack, D.E. et al.; The Future of Gas Turbine Technology, 6th International Conference 2012 F – Materials

Abstract: Integrated gasification combined cycle (IGCC) is currently one of the most attractive technologies for the high-efficiency use of coal. However, the insulating thermal barrier coating (TBC) applied on turbine blades of an IGCC engine is greatly affected by the operating environments under high thermomechanical stresses and potential corrosion attack. Both can be even more severe in hydrogen rich combustion environment due to the higher mass flow and accidental contaminants from fuel cleaning or debris along the gas path. Thermal barrier coatings having top coats f advanced candidate TBC materials are able to withstand anticipated temperature levels above 1300°C better than the state of the art zirconia based coatings. In the current study those coatings are manufactured by commercially established VPS and AS technology and have been subjected to thermal gradient burner rig testing with simultaneous attack from deposits of CaO-MgO-Al2O3-SiO2-Fe2O3 melts. X-ray crystallography and microstructural analyses were then conducted on the cycled samples to determine the reaction products and the extent of corrosion damage in the coatings. The resulting life the coatings at the investigated temperature range suggest promising applicability of aluminates for high temperature corrosion protection against CMAS in gas turbine components

2013

[25438] Extreme Temperature Coatings for Future Gas Turbine Engines; Alvin, M.A. et al.; ASME TURBO EXPO 2013 Manufacturing Materials and Metallurgy; GT2013-94432

Abstract: The National Energy Technology Laboratory-Regional University Alliance (NETL-RUA) has been developing extreme temperature coating systems that consist of a diffusion barrier coating (DBC), a low-cost wet slurry bond coat, a commercial yttria stabilized zirconia (YSZ) thermal barrier coating (TBC), and an extreme temperature external coating that are deposited along the surface of nickel-based superalloys and single crystal metal substrates. Thermal cyclic testing of these multi-layer coatings was conducted in steam-containing environments at temperatures ranging between 1100-1550ºC. This paper discusses the response of these materials during bench-scale testing, and their potential use in advanced H- and J-class land-based gas turbine engines.

Acronyms

TBC Thermal barrier coating
TGO Thermally grown oxide (layer)
TIT Turbine inlet temperature

Descriptions

Steam augmentation

Steam injection for power augmentation in GE Energy turbine units includes a signal that activates or shuts off the steam injection system, due to gas turbine and/or load limitations. The maximum steam injection for power augmentation typically is 5% of the compressor airflow for E class gas turbines.

The power augmentation steam is injected into the compressor discharge airflow. As an additional benefit, a portion of all steam reacts in the combustion zone of the combustor thereby reducing the NOx levels.

Features & Benefits

- Increase in unit power
- Decrease the unit heat rate