Coatings for Use at High Temperatures
Room Grand Exhibit Hall - Session AP

Symposium A Poster Session

AP-2 Fracture Behavior and Thermal Durability of Lanthanum Zirconate Based Thermal Barrier Coatings with Buffer Layer in Thermally Graded Mechanical Fatigue Environments*, **BongGu Kim**, G Lyu, S Jung, S Lee, Y Jung,* Changwon National University, Republic of Korea*; J Zhang,* Purdue University, USA

The effects of buffer layer on the fracture behavior and lifetime performance of lanthanum zirconate ($La_2Zr_2O_7$; LZO)-based thermal barrier coatings (TBCs) were investigated through thermally graded mechanical fatigue (TGMF) tests, which is designed to simulate the operating conditions of rotation parts in gas turbines. To improve the thermal durability of LZO-based TBCs, composite top coats, consisting of two feedstock powders of LZO and 8 wt% yttria-doped stabilized zirconia (8YSZ), were prepared by mixing in different volume ratios (50:50 and 25:75, respectively). In addition, buffer layers were introduced in layered LZO-based TBCs deposited using an air-plasma spray method. The TGMF tests with a tensile load of 60 MPa were performed until 2000 cycles at a surface temperature of 1100°C for a dwell time of 10 min, and then the samples were cooled at room temperature for 10 min in each cycle. For the single layer TBCs, the thermal durability was enhanced by controlling the LZO:8YSZ ratio as 25:75 vol.%. The TBC with the double buffer layer showed the best thermal cycle performance among all samples, suggesting the buffer layer was efficient in improving lifetime performance. It is noted that failure modes were different in TBC samples. Delamination and/or cracks were created at the interface between the bond and top coats or above the interface in the single-layer TBCs, but the TBCs with the buffer layer was delaminated and/or cracked at the interface between the buffer layer and the top coat, independent of buffer layer species. This study allows us to further understand the LZO-based TBC's failure mechanisms in operating conditions, especially in the thermal and mechanical environments, in order to design reliable TBC systems.

AP-3 Correlation of Thermal Characteristics and Microstructure of 7YSZ/$La_2Zr_2O_7$ and 7YSZ/$Gd_2Zr_2O_7$ Quadruple Layer EB-PVD Thermal Barrier Coatings*, K Bobzin, T Brögelmann, C Kalscheuer, **Tiancheng Liang**, M Welters,* Surface Engineering Institute - RWTH Aachen University, Germany

Referring to the increasing amount of aviation until the year 2030, energy and fuel efficiency as well as the emission of harmful gases are of prime importance to the technological and ecological evaluation of aircraft engines. Minimizing fuel consumption and improving energy efficiency of jet engines can be reached by increased turbine entry temperatures. However, the permitted combustion temperatures are restricted by material-dependent maximum operating temperatures. Nowadays, yttria stabilized zirconia (YSZ) is commonly used as thermal barrier coating (TBC). YSZ generally withstand a permanent surface temperature of T = 1,200 °C, which is limited due to thermally induced phase transformation. Therefore, lanthanum zirconate ($La_2Zr_2O_7$) and gadolinium zirconate ($Gd_2Zr_2O_7$) with their exceptional properties concerning thermal conductivities, melting points and phase stabilities, get into the focus. However, the mismatch of thermal expansion coefficient α of the new ceramic layers and the bond coats or substrates can lead to delamination under thermal load. In recent years, research projects have shown that multilayer systems might be a solution to combine the advantages of different ceramic layers, avoiding detrimental effects such as delamination. In order to assess this potential of multilayer systems, quadruple multilayer systems consisting of 7wt.% YSZ and $La_2Zr_2O_7$ or 7wt.% YSZ and $Gd_2Zr_2O_7$ were deposited on Inconel 600 by electron beam-physical vapor deposition (EB-PVD). To evaluate the long term behavior under thermal cycling and isothermal load, extended thermal cycling tests were conducted at temperatures of T = 1,200 °C and T = 1,300 °C for n = 1,000 cycles as well as isothermal oxidation tests were performed at a temperatures of T = 1,100 °C for t = 50 h. Furthermore, different analyses regarding the basic characteristics of TBC such as thermal conductivity via laser flash method, phase analyses via X-ray diffraction, microstructure analyses via scanning electron microscope and element analyses by means of X-ray spectroscopy were conducted and correlated with each other. The results of the quadruple TBC were compared to those of mono and double layer TBC. These investigations showed a systematic relationship between porosity and thermal conductivity. Moreover, the thermal cycling tests highlight the great advantages of multilayer systems regarding the thermal expansion properties, compared to the monolayer. In this manner, the multilayer systems illustrated the potential of an adapted coating architecture, which leads to an improved TBC lifetimeunder alternating thermal and isothermal load.

AP-5 Oxidation Behavior of Nb–Si–N Coatings*, **Yung-I Chen**, Y Gao,* National Taiwan Ocean University, Taiwan*; L Chang,* Ming Chi University of Technology, Taiwan

Nb–Si–N coatings were fabricated using reactive direct current magnetron cosputtering on Si substrates. The N contents of Nb–Si–N coatings ranged from 39 to 48 at.% as varying the sputter powers for Nb and Si targets. The Nb–Si–N coatings with a Si content less than 13 at.% exhibited a face centered cubic phase, whereas the coatings with a Si content higher than 17 at.% exhibited near-amorphous. The nanohardness increased from 22.8 GPa for Nb–N coatings to 25.4 GPa for the coating with a 4 at.% Si, and then decreased continuously to 13.3 GPa as increasing the Si content to 23 at.%. The oxidation experiments of Nb–Si–N coatings were conducted at 600 °C in a 1% O_2–99% Ar atmosphere. The results indicated that crystalline Nb–Si–N coatings was oxidized to form Nb_2O_5 after they were annealed for 4 h, whereas no evident oxide scale was observed for the near-amorphous $Nb_{32}Si_{23}N_{45}$ coatings after annealing up to 24 h.

AP-6 Corrosion Behavior of Amorphous and Crystalline Zn-Mg Coating in NaCl Solution*, **JoungHyun La**, K Bae, S Kim, S Lee, Y Hong,* Korea Aerospace University, Republic of Korea

Recently, Zn-Mg coatings have been studied extensively for the protective coatings of steel sheets due to the excellent corrosion resistance of Zn-Mg coatings compared with pure Zn coatings. However, the structure of Zn-Mg coatings changed with deposition conditions such as power density, pressure, and temperature. In this study, the amorphous and crystalline Zn-Mg coatings were synthesized on the steel substrates using sputtering process at various temperatures. The microstructure, the crystal phase, and corrosion resistance of the Zn-Mg coatings were investigated using the field emission scanning electron microscopy (FE-SEM), X-ray diffraction (XRD), and salt spray test (SST), respectively. The synthesized Zn-Mg coatings at low temperature below 50°C showed the amorphous and featureless microstructure. By contrast, the porous crystalline Zn-Mg coatings were synthesized at the temperature above 100°C. The amorphous Zn-Mg coatings showed the enhanced corrosion resistance in NaCl solution compared to the crystalline Zn-Mg coatings. The featureless microstructure of the amorphous Zn-Mg coatings improved its corrosion resistance by obstructing the direct pathway between a corrosive environment and the substrate as well as inhibiting localized corrosion.

Acknowledgement

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AP-7 Nanocomposite Multilayered Coatings with High Thermal Stability and Oxidation Resistance*, **Dmitry Shtansky**, K Kuptsov, M Golizadeh, P Kiryukhantsev-Korneev,* National University of Science and Technology "MISiS", Russian Federation

High thermal stability and oxidation resistance are important properties for various high-temperature applications. Superhard TiAlSiCN coatings with "comb"-like nanocomposite structure, in which fine (Ti,Al)(C,N) columnar grains were separated by well-developed amorphous SiCN interlayers, recently developed in our group, exhibited the highest thermal stability reported to date for nanocomposite coatings. The main drawback of the TiAlSiCN coating is a relatively large difference in temperatures between its thermal stability (1300 °C) and oxidation resistance (1000 °C), which limits their use at high temperatures.

In this work we applied a multi-layering approach to close the gap between thermal stability and oxidation resistance. The coatings were deposited on Al_2O_3 substrate by reactive DC magnetron sputtering of TiAlSiCN target and ion sputtering of SiBC or Al_2O_3 targets in a gaseous mixture of Ar + 15% N_2. The coatings were annealed in vacuum at 1000, 1300 and 1400°C as well as in air at 1000, 1100 and 1200°C for 1 hour to investigate thermal stability and oxidation resistance. XRD, SEM and EDX studies showed that TiAlSiCN/Al_2O_3 coating mostly lost its multilayer structure already after annealing at 1300°C and experienced significant grain growth, while TiAlSiCN/SiBCN coating maintained its multilayer structure with negligible grain growth. Annealing at 1400°C led to a partial recrystallization of top layers of TiAlSiCN/SiBCN coating, while most of the coating remained its structure. After annealing at 1100°C in air, TiAlSiCN/Al_2O_3 coatings were only partly oxidized due to the formation of a dense Al_2O_3 top layer, while TiAlSiCN monolayer and TiAlSiCN /SiBCN coatings were almost completely oxidized. However, incorporated amorphous Al_2O_3 layers in TiAlSiCN/Al_2O_3 coating were crystallized to a certain degree, which shortened initial and transient stages of oxidation by providing preferred nucleation sites and facilitating lateral growth of the oxide.

AP-10 Structure, Mechanical, Tribological, And Chemical Properties Of Mo-Si-B And Mo-Al-Si-B Coatings*, Philipp Kiryukhantsev-Korneev, A Sheveyko, A Bondarev,* National University of Science and Technology "MISiS", Russian Federation*; K Kuptsov,* National University of Science and Technology "MISIS", Russian Federation*; E Levashov, D Shtansky,* National University of Science and Technology "MISiS", Russian Federation

Mo-Si-B and Mo-Al-Si-B coatings were deposited by DC magnetron sputtering and ion implantation assisted magnetron sputtering (IIAMS) of the MoSiB and MoAlSiB composite targets fabricated by the self-propagating high-temperature synthesis method. The structure, element and phase composition of coatings were studied by means of scanning and transmission electron microscopy, X-ray diffraction, X-ray photoelectron spectroscopy, energy-dispersive spectroscopy, and glow discharge optical emission spectroscopy. The mechanical properties of the coatings were measured using nanoindentation. The tribological properties were evaluated in air using impact-tester and high-temperature ball-on-disc tribometer. To evaluate oxidation resistance, the coatings were annealed in air in the temperature range of 1200-1700 °C during different time slots between 10 min and 5 h. The results obtained demonstrate that the Mo-Si-B coatings possess higher hardness, improved oxidation resistance and better thermal stability compared with their Mo-Al-Si-B counterparts. The 7-mm thick Mo-Si-B coatings were shown to withstand successfully oxidation during short-time exposure for 10 min at temperature as high as 1700 ^oC due to the formation of protective silica scale. The oxidation of Mo-Al-Si-B coatings was accompanied by the diffusion of aluminum to the coating surfaces and the formation of a single Al_2O_3 layer at 1200-1300 °C and a double Al_2O_3-SiO_2 layer at 1500 °C which were less protective against oxidation. The surface oxidation processes were also accompanied by phase transformations inside the oxygen-free part of both Mo-Si-B and Mo-Al-Si-B coatings with the formation of MoB and Mo_5Si_3 phases.

AP-11 Oxidation Resistance of Ta–Si–N Coatings*, Y Chen, **Yu-Xiang Gao**,* National Taiwan Ocean University, Taiwan*; L Chang,* Ming Chi University of Technology, Taiwan

Ta–Si–N coatings with a high Si content of 18–21 at.% were fabricated using reactive direct current magnetron cosputtering as the sputter power was set at 100W for each target, and these coatings exhibited near-amorphous in the as-deposited state. The N contents of Ta–Si–N coatings increased from 31 to 47 at.% as varying the nitrogen flow ratio from 0.1 to 0.4, accompanied with decrease trends of nanohardness from 20 to 14 GPa and Young's modulus from 220 to 196 GPa. By contrast, Ta–Si–N coatings prepared using substrate-holder rotating speeds of 1–30 rpm and a nitrogen flow ratio of 0.4 exhibited a similar chemical composition, accompanied with a nanohardness of 12–14 GPa and a Young's modulus of 187–199 GPa. The oxidation resistance of Ta–Si–N coatings was evaluated by performing annealing at 800 °C in ambient air, which showed notably oxidation resistance related to TaN coatings because the oxide scales formed with restricted thicknesses. The oxidation behavior of near-amorphous Ta–Si–N coatings was examined using transmission electron microscopy and X-ray photoelectron spectroscopy.

AP-12 Effect of Hot-dip Aluminum Coating on Dissimilar Weldment between Low Carbon Steel and 304 Stainless Steel in NaCl/Na_2SO_4 Mixture Salts Induced Hot Corrosion*, **Huan-Chang Liang**, K Tsai, C Wnag,* National Taiwan University of Science and Technology, Taiwan

The effect of hot-dip aluminum (HDA) coating on the hot-corrosion behavior of dissimilar weldment was studied. The dissimilar weldment of low carbon steel and 304 stainless steel (SS 304) was joined by gas tungsten arc welding, using 309L stainless steel (SS 309L) filler. Weldment was coated by hot-dipping into pure molten aluminum for 60 and 120 seconds respectively. Prior to hot corrosion of as-welded and aluminized specimens in static air at 750 °C, specimens were coated with 2 mg/cm^2 of a various portions of NaCl and Na_2SO_4 salt mixtures. The results of as-welded specimens show that the intergranular corrosion took place in both SS 304 and SS 309 L, also especially in the heat-affected zone (HAZ) of SS 304 due to chromium depletion as a results of sensitization. In addition, the interface between low carbon steel and SS 309L was under severe corrosion attributed to difference in chemical composition. The results of HDA for 60 seconds show that there was no intergranular corrosion observed in each zone of stainless steel. Results also show that the low carbon steel/SS 309L interface was protected by aluminide, which eliminate the compositional effect on the surface. Same phenomenon was also observed for HDA 120 seconds, however, more cracks were observed in the aluminide layer on the interface of low carbon steel/SS 309L. It therefore shows that HDA processing on dissimilar weldment performed better hot-corrosion resistance with less difference of chemical composition.

AP-13 Influence of Arc Power and Spray Distance on Mechanical Properties of ZrO_2-10%Y_2O_3-18%TiO_2 Coatings Produced by Plasma Spray*, **Sugehis Liscano**, L Gil,* Universidad Nacional Politecnica UNEXPO, Venezuela (Bolivarian Republic of)*; A Portoles,* Universidad Politecnica de Madrid, Spain*; K Silva,* Universidad Nacional Central de Venezuela, Venezuela (Bolivarian Republic of)

Torch Power and spraying distance during the deposition have been referred as important factors in the coating microstructure and properties. ZrO_2-10%Y_2O_3-18%TiO_2 coatings were prepared on NiCrAlCoYO bond coat and metal substrate by atmospheric plasma spraying (APS) to evaluate the effect of these parameters on the mechanicals properties. The microstructures of the coatings were characterized using scanning electron microscopy (SEM) technique coupled with X-Ray microanalysis (EDS). The coatings microhardness and adhesion strength were determined using ASTM E384-2010 for Vickers microhardness and ASTM-C633 for adhesion test. The results corroborate that torch power and spraying distance have significant influence on the mechanical properties in the range evaluate. The adhesion strength of the prepared coatings was between 7 - 14 MPa, while the microhardness measurement was more between 251 - 942 $HV_{(0,5)}$. It was concluded that the best coatings properties, for the level of the variables studied in this work, could be obtained if the torch power is maintained at 34 KW and the spraying distance in 100 mm.

AP-14 A Parametric Study for Minimizing Thermal Stress of a Thermal Barrier Coating System*, **JangGyun Lim**, M Kim,* Sungkyunkwan University, Republic of Korea

1. Introduction

Thermal barrier coating (TBC) is presently used as thermal insulating coating to protect hot component of gas turbines. Commonly, TBC system consists of four layers; a substrate, an aluminum containing metallic bond-coat, a thermally grown oxide (TGO), and a thermally insulating ceramic layer called top-coat. However, its full usage is limited by unexpected pre-failure mainly caused by thermal stress. Temperature change in an operation cycle induces thermal stress on TBC due to mismatch of material properties. Additionally, growth and wavy deformation of TGO, creep, delamination complicate this failure mechanism. Despite of intensive research on pre-failure for several decades, it is difficult to predict the lifetime because of the variety of specifications, operating conditions, and the emergence of new materials. Therefore, it is necessary to understand the influence of the design parameters of the TBC system on the thermal stress, including the properties and specifications, in consideration of interplays.

2. Modeling and conditions

We constructed a 2D rectangular unit cell model in the axis symmetry and periodic conditions. The topological features of TGO and depletion region were figured out by a microstructural analysis so that TGO was represented by sinusoidal wave. In addition, temperature-dependent-properties were assigned to elasto-plastic deformation and the creep behavior was also considered by power-law creep strain rate. Particularly, nano-indentation was conducted on aluminum depletion area in bond-coat to measure elastic modulus. After constructing a model considering interplays, heat transfer analysis and thermal stress analysis are sequentially conducted. Based on the proposed model, an intensive parameter study with 144 different cases was conducted to investigate the effects of various design parameters on thermal stress. They are elastic modulus, thermal expansion coefficient of the top-coat, and thickness of both bond-coat and top-coat.

3. Results and discussion

As a result, it is observed that elastic modulus is the most influential parameter to thermal stress and thermal expansion coefficient, top-coat thickness, and bond-coat thickness follow. Also, the smaller mismatch of thermal expansion coefficient between bond-coat and TGO is in favor of thermal stress reduction. This parametric study will play an important role in an optimal design of TBC system.

AP-15 Investigation of the Influence of Subcoating on Thermal Shock and Corrosion Resistance in the Liquid Zinc of APS ZrO_2 Coating Doped with MgO*, Aleksander Iwaniak,* Silesian University of Technology, Poland*; A Moscicki,* Jolanta Mzyk Silesian University of Technology, Poland*; G Wieclaw,* Krzysztof Rosner Certech, Poland

Liquid zinc is an aggressive corrosive medium and poses a considerable problem for steels that come into contact with it. In the paper, the thermal shock and corrosion resistance of APS coating ZrO_2-24MgO to the action of molten zinc was examined. Various types of bond coats were used: Ni-Cr single-layer and layer with different contents of NiCr and ZrO_2-24MgO. The tests of thermal shock and corrosion resistance involved cyclical exposure of coated specimens in a molten zinc bath for one hour and subsequently, their rapid cooling in water. The coatings were subjected to structural examination (SEM, EPMA, XRD, 3D topography of surface) before and after the test. Macroscopic evaluation of the condition of coatings' surfaces after thermal shock test in liquid zinc, in comparison with their original state after spraying, showed the following changes in their image: surface discoloration, spots, and local fractures in case of ground coating. It was noticed that sectional view of all tested samples was reduced after corrosion resistance test (cyclic exposure to liquid zinc). It was connected with coating thickness decrease. Structural tests proved formation of zinc and zinc oxide on samples' surfaces. Coating thickness decrease after the test was caused by dissolution of ZrO2-24MgO coating in liquid zinc. Strong relation between the kind of subcoating and fractures formation in ZrO2-24MgO coating was not noticed. Only in case of a single subcoating sample, a slight flake in the upper section of ZrO2-24MgO coating was noticed after corrosion resistance test.

Author Index

Bold page numbers indicate presenter