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Selected Abstracts of Thermal Spray Literature

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Applications

Biomaterials and Bioactive Materials

Bonding strength investigation of plasma sprayed HA coatings on alumina substrate with porcelain intermediate layer. Hydroxyapatite (HA) has recently been used as a bone substitute in orthopedic and dental surgery applications, owing to its excellent biocompatibility. However, the poor mechanical properties of HA limit the material's application in the loading condition. In this study, HA was coated onto the surface of alumina substrate, with a view to overcome the poor mechanical properties of HA and the biocompatibility of alumina. Improvement of the bonding strength of HA coatings to alumina substrate was attempted by adding a bond coat of porcelain via plasma spraying and by post heat treatment. HA-50 wt.%-porcelain and pure porcelain were used to manufacture two kinds of bond coat before HA coating, and then all the specimens were heat treated at 750, 800, 850, and 900 °C for 0.5 h. The results shows that the bond strength between HA coating and Al_2O_3 substrate could be improved by employing the porcelain as the bond coat after the heat treatment. The strengthening mechanisms of the two systems are discussed.

Keywords: alumina, biocompatibility, bond coat, bond strength (chemical), dental surgery, heat treatment, hydroxyapatite, loading condition, plasma spraying, porcelain

Y.C. Yang and B.Y. Chou, Institute of Mater. Sci. Eng., National Taipei University of Technology, Taipei, Taiwan. Cited: *Mater. Chem. Phys.*, 2007, Aug 15, **104**(2-3), p 312-319. ISSN 0254-0584.

Characteristics of hydroxyapatite coated titanium porous coatings on Ti-6Al-4V substrates by plasma sprayed method. A porous metal coating applied to solid substrate implants has been shown, in vivo, to anchor implants by bone ingrowth. Calcium phosphate ceramics, in particular hydroxyapatite [$Ca_{10}(PO_4)_6(OH)_2$, HA], are bioactive ceramics, which are known to be biocompatible and osteoconductive, and these ceramics deposited onto porous-coated devices may enhance bone ingrowth and implant fixation. In this study, bi-feedstock of the titanium powder and composite (Na_2CO_3/HA) powder were simultaneously deposited on a Ti-6Al-4V substrate by a plasma sprayed method. At high temperature of plasma torch, the solid state of Na_2CO_3 would decompose to release CO_2 gas and then eject the molten Ti powder to induce the interconnected pores in the coatings. After cleaning and soaking in deionized water, the residual Na_2CO_3 in the coating would dissolve to form the open pores, and the HA would exist at the surface of pores in the inner coatings. By varying the particle size of the composite powder, the porosity of porous coating could be varied from 25.0% to 34.0%, and the average pore size of the porous coating could be varied to range between 158.5 and 202.0 μm. Using a standard adhesive test (ASTM C 633), the bonding strength of the coating is between 27.3 and 38.2 MPa. By scanning electron microscopy (SEM), the HA was observed at the surface of inner pore in the porous coating. These results suggest that the method exhibits the potential to manufacture the bioactive ceramics onto porous-coated specimen to achieve bone ingrowth fixation for biomedical applications.

Keywords: bone, bone ingrowth, calcium phosphate, ceramic materials, coated materials, hydroxyapatite, implants (surgical), plasma spraying, porous materials, porous metal coating, porous-coated devices, substrates, titanium alloys

C.Y. Yang, C.R. Chen, E. Chang, and T.M. Lee, Institute of Oral Medicine, National Cheng Kung University, Tainan 701, Taiwan. Cited: *J. Biomed. Mater. Res.—Part B Appl. Biomater.*, 2007, July, **82**(2), p 450-459. ISSN 1552-4973.

Coating Removal

Surface preparation methods make it easier to be green. Various methods of surface preparation that aim to make coatings removal greener are discussed. The attraction of recyclable abrasive blasting with steel shot and grit has always been the ability to separate blasting waste from abrasive, which can then be reused a number of times. The technology reduces the overall amount of potentially hazardous waste generated during coatings removal operations compared with traditional, one-time-use abrasives. Blast rooms are an environmentally friendly alternative to open blasting and are used by the military to eliminate dangerous chemicals from paint stripping processes for worker safety and to reduce costs associated with the disposal of chemical residues. Shrouded power tools are appropriate for areas inaccessible to conventional abrasive blasting. The use of ultrahigh pressure (UHP) water jetting minimizes waste and prevents particulate or hazardous dust emissions. UHP water jetting is used extensively in shipyards and on water tanks.

Keywords: abrasive blasting, abrasives, blasting, dust emissions, environmental protection, jets, protective coatings, steel, surface preparation, surface treatment, water jetting

L.R. Huffman, JPCL. Cited: *J. Prot. Coat. Linings*, 2007, June, **24**(6), p 38-45. ISSN 8755-1985.

Corrosion

Corrosion—Are we bothered?. Corrosion science and technology can provide significant monetary gains to industries in the UK, which are motivated by the need to improve their capital productivity, operational reliability, efficiency, and performance of physical assets. The corrosion control technology not only increases the economic life cycle and performance of a material, but also reduces the overall cost of the technical system. Corrosion can be effectively controlled through intercepting with the material or environment by four methods, namely electrochemical modification, chemical modification of the environment, application of a protective coating, and appropriate selection and design of material. Most of the modern high-performance protective coatings are polymer systems with a carefully balanced selection of components developed to provide an essential range of functional properties. Various asset management approaches such as stress-corrosion cracking (SCC) can be applied to different industries thereby enhancing the useful life of materials.

Keywords: chemical modification, corrosion protection, cost reduction, electrochemical modification, industrial economics, materials science, operational reliability, protective coatings, stress-corrosion cracking, technical systems

S. Lyon, School of Materials, University of Manchester, United Kingdom. Cited: *Mater. World*, 2007, June, **15**(6), p 19-21. ISSN 0967-8638.

The corrosion protection of the future?. Eighty-nine delegates from 21 different countries met on June 14-15 in Berlin to discuss new ideas for anticorrosive coatings and corrosion protection testing. Particular topics included concepts for self-healing coatings; thin, high-density barrier films; conductive polymers; and fast new test methods.

Keywords: anticorrosive coatings, conductive plastics, corrosion protection, corrosion resistance, high-density barrier films, protective coatings, self-healing coatings

D. Meine. Cited: *Europ. Coat. J.*, 2007, (7-8), p 56-58. ISSN 0930-3847.

PHM and corrosion control on the joint strike fighter. The desire and need for automatic fault detection/isolation and prognostics capabilities have been around for as long as man has operated complex and expensive machinery. There has been a long history of trying to develop and implement various degrees of prognostics and health management (PHM) capability on new applications such as the joint strike fighter (JSF). A discussion of JSF's PHM system and its relationship to the autonomic logistics (AL) support concept are presented in this paper. Overall PHM Architecture are described with emphasis on its capabilities and its aims to enhance aircraft safety, improve sortie generation rate, decrease logistics footprint and reduce operation and support costs. To enable the benefits of AL support concepts, PHM will be used also for prevention, control, and monitoring of airframe and component corrosion. Corrosion control has, in the past, consisted of visual inspection, corrosion removal, and coating system repair on a regular, recurring basis. This cycle continues throughout the life of an aircraft, and it consumes a significant amount of man-hours, support costs, and material needs. Use of newer maintenance philosophies such as reliability-centered maintenance, as well as introduction of corrosion prevention compounds, upgraded coating systems, and PHM, leads to a reduction in operation and support costs and provides a benefit to the user in terms of reduced down time and repair requirements. Data collection, from location monitoring to tracking of inspection and repair trends, provides a key element for the continual update and refinement of a maintenance program. This paper describes some of the innovations in aircraft maintenance practices, task interval determination, and design strategies that can be applied to JSF and can have a positive impact to the aircraft and to the end user.

Keywords: aircraft parts and equipment, autonomic logistics, corrosion control, corrosion protection, fault detection, fighter aircraft, inspection, joint strike fighter, prognostics and health management, reliability theory, repair

G. Calvello, S. Olin, A. Hess, and P. Frith, Joint Strike Fighter Program Office, Arlington, VA 22202-4304. Cited: *Corros. Rev.*, 2007, **25**(1-2), p 51-80. ISSN 0334-6005.

The power of protection. Metal or thermal spraying with zinc or zinc alloys is an effective and long-term solution to protect steel-reinforced concrete from corrosion, thereby extending the life cycle of a variety of products in the most extreme environments. This zinc cathodic system works in galvanic or sacrificial mode, which more often operated in impressed current form. The use of sprayed zinc anodes provides various advantages as the zinc follows the surface to which it is applied and does not obscure architectural features. The metal-sprayed coatings are commercially viable to large concrete structures, especially to various unapproachable structures. An aluminum, zinc, and indium (Al-Zn-In) alloy can also used, which does not require impressed current to provide adequate levels of corrosion protection. The system is well adapted to treat corrosion in the viaduct panels and successful in various tests.

Keywords: cathodic protection, metal-sprayed coatings, reinforced concrete, sprayed coatings, steel, steel reinforced concrete, thermal spraying, zinc alloys, zinc cathodic systems

S. Milton, Metallisation, Dudley, UK. Cited: *Mater. World*, 2007, June, **15**(6), p 24-26. ISSN 0967-8638.

Functional

Europium-doped yttrium silicate nanophosphors prepared by flame synthesis. Europium-doped yttrium silicate ($Y_2SiO_5:Eu^{3+}$) nanophosphors were successfully synthesized by flame spray pyrolysis method. The effect of silicon concentration on the crystal structure and morphology of the $Y_2SiO_5:Eu^{3+}$ phosphors were investigated. As-prepared phosphor consists of spherical nanoparticles with filled morphology, high crystallinity, narrow size distribution, and intense photoluminescence. The crystal structure and photoluminescence intensity of $Y_2SiO_5:Eu^{3+}$ nanophosphors are strongly affected by the ratio of silicon to yttrium in the precursor solution, and the maximum photoluminescence intensity is obtained from particles prepared from the silicon to yttrium ratio of 1.25. A concentration quenching limit is observed at 30 mol.% Eu of yttrium. The photoluminescence intensity also increases with the increase of the concentration of precursor solution. This work demonstrates the advantages of flame spray pyrolysis method for the preparation of multicomponent nanophosphor, which can be found potential application in lamp and display industries.

Keywords: crystal structure, crystallinity, doping (additives), europium, flame synthesis, morphology, nanophosphors, nanostructures, narrow size distribution, phosphors, photoluminescence, pyrolysis, quenching, size distribution, yttrium

X. Qin, Y. Ju, S. Bernhard, and N. Yao, Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ 08544. Cited: *Mater. Res. Bull.*, 2007, Aug, **42**(8), p 1440-1449. ISSN 0025-5408.

Solid Oxide Fuel Cells

Synthesis and properties of nanostructured SOFC anode deposits. Nanostructured YSZ + Ni cermet anode functional layers for solid oxide fuel cells (SOFCs) were developed by plasma spraying. Spray processing was optimized by controlling plasma enthalpy and velocity to obtain well-distributed finely porous nanostructured deposits exhibiting high gas permeability, suitable high-temperature electronic conductivity, enhanced triple phase boundaries, and catalytic activity. The results were compared with conventional NiO + YSZ and Ni-C + YSZ anodes. YSZ electrolyte layer was deposited onto the anodes for electrochemical testing at 800 °C in static conditions. Impedance spectroscopy measurements were performed to collect data on polarization resistance and catalytic behavior of anode layers. It was established that enlarged reaction zone, provided by high specific surface area of nanostructured anodes, and finely porous microstructure, led to lower activation and concentration polarizations and enhanced cell performance by more than 60% compared with conventional cells.

Keywords: anodes, catalyst activity, electrochemical testing, electronic conductivity, enthalpy, impedance spectroscopy, nanostructured materials, optimization, plasma spraying, polarization, porous nanostructured deposits, solid oxide fuel cells, synthesis (chemical), velocity control

S.A. Ansar, Z. Ilhan, and W. Richter, German Aerospace Center (DLR), 70569 Stuttgart, Germany. Cited: *High Temp. Mater. Process.*, 2007, **11**(1), p 83-94. ISSN 1093-3611.

Thermal plasma spraying for SOFCs: Applications, potential advantages, and challenges. In this article, the applications, potential advantages, and challenges of thermal plasma spray (PS) processing for nanopowder production and cell fabrication of solid oxide fuel cells (SOFCs) are reviewed. PS processing creates sufficiently high temperatures to melt all materials fed into the plasma. The heated material can either be quenched into oxide powders or deposited as coatings. This technique has been applied to directly deposit functional layers as well as nanopowder for SOFCs application. In particular, low-melting point and highly active electrodes can be directly fabricated on zirconia-based electrolytes. This is a simple processing technique that does not require the use of organic solvents, offering the opportunity for flexible adjustment of process parameters and significant time saving in production of the cell and cost reduction compared with tape casting, screen printing, and sintering processing steps. Most importantly, PS processing shows strong potential to enable the deposition of metal-supported SOFCs through the integrated fabrication of membrane-electrode assemblies (MEA) on porous metallic substrates with consecutive deposition steps. On the other hand, the application of PS processing to produce SOFCs faces some challenges, such as insufficient porosity of the electrodes, the difficulty of obtaining a thin ($\leq$10 μm) and dense electrolyte layer. Fed with H_2 as the fuel gas and oxygen as the oxidant gas, the plasma sprayed cell reached high power densities of 770 mW/cm^2 at 900 °C and 430 mW/cm^2 at 800 °C at a cell voltage of 0.7 V.

Keywords: cell fabrication, electrodes, electrolytes, nanopowder production, organic solvents, oxide powders, plasmas, solid oxide fuel cells, thermal plasma spray, zirconia

R. Hui, Z. Wang, O. Kesler, L. Rose, J. Jankovic, S. Yick, R. Maric, and D. Ghosh, National Research Council Institute for Fuel Cell Innovation, Vancouver, BC V6T 1W5, Canada. Cited: *J. Power Sources*, 2007, July 10, **170**(2), p 308-323. ISSN 0378-7753.

Thermal Barrier Coatings

Development of intermixed zones of alumina/zirconia in thermal barrier coating systems. The mechanisms whereby intermixed zones of alumina and zirconia are formed at the interface between the metallic bond coat and the ceramic top coat (yttria-stabilized zirconia) in thermal barrier coating (TBC) systems have been investigated. The results lead to the following mechanism for the formation of the zones. The predominant mechanism for intermixed zone formation involves formation of a metastable alumina polymorph (θ or γ) during TBC deposition, with a significant amount of zirconia dissolved in it. The outward growth also begins to incorporate zirconia particles, which initiates the formation of the intermixed zone. Upon thermal exposure, the metastable thermally grown oxide (TGO) continues to grow outward, extending the intermixed zone, and eventually transforms to the equilibrium α-Al_2O_3. The transformation to α-Al_2O_3 results in an increase in the volume fraction of zirconia in the intermixed zone as it is rejected from solution. Once the α-Al_2O_3 appears, subsequent TGO growth produces a columnar zone of the TGO without a second phase. When α-alumina was preformed on the bond coat, prior to TBC deposition, no intermixed zone was formed for Pt-modified aluminide bond coats.

Keywords: alumina, deposition, metallic bond coat, metastable alumina polymorph, phase interfaces, thermal barrier coatings, volume fraction, yttria-stabilized zirconia, zirconia

M.J. Stiger, N.M. Yanar, R.W. Jackson, S.J. Laney, F.S. Pettit, G.H. Meier, A.S. Gandhi, and C.G. Levi, Department of Mater. Sci. Eng., University of Pittsburgh, Pittsburgh, PA 15261. Cited: *Metall. Mater. Trans. A: Phys. Metall. Mater. Sci.*, 2007, April, **38**(4), p 848-857. ISSN 1073-5623.

Interfacial fracture toughness of APS thermal barrier coating under high temperature. Thermal barrier coating (TBC) is an essential requirement of a modern gas turbine engine. The TBC failure is the delamination and spallation. The oxidation damage under high temperature results in the reduction of interfacial adhesion. The interfacial fracture toughness is an important property to analyze the TBC failure. The interfacial fracture toughness of ceramic-coating/bond-coating has been researched in the past. However, the facture toughness of the bond coating substrate due to the Al depletion was studied by very few. In this study, a NiCrAlY bond coating by air plasma spray (APS) was deposited. The substrate was directionally solidified superalloy (DZ40M). Isothermal oxidation was performed at 1050 °C for 100 h. Using the HXZ-1000 microhardness equipment, the five different times was chosen to test the hardness and the crack length, and then the fracture toughness was obtained, while the oxidation exposure time increased at 1050 °C, the hardness of the substrate close to the bond coating decreased with the increase of the bond coating' hardness. Meanwhile, the interfacial fracture toughness of the bond-coating/substrate decreased because of the Al depletion.

Keywords: thermal barrier coatings, fracture toughness, gas turbines, high-temperature effects, interfaces (materials), plasma spraying, superalloys, bond coating, spallation, oxidation damage

H. Qi, X. Yang, and R. Li, School of Jet Propulsion, Beihang University, Beijing 100083, China. Cited: *Key Eng. Mater.*, 2007, **348-349,** p 181-184. ISSN 1013-9826.

Morphology, microstructure, and residual stress in EBPVD erbia coatings. The electron-beam physical vapor deposition of erbium-oxide coatings onto sapphire wafers is investigated to evaluate processing effects on the residual stress state and microstructure. The erbium-oxide coatings are found to be in a compressive stress state. The crystallographic texture of the erbium-oxide coating is evaluated using x-ray diffraction along with an assessment of forming the cubic erbia phase as a function of substrate temperature. In addition to the cubic erbia phase, an orthorhombic phase is found at the lower

deposition temperatures. A transition is found from a two-phase erbium-oxide coating to a single phase at deposition temperatures above 948 K. The variation in morphology with deposition temperature observed in fracture cross sections is consistent with features of the classic zone growth models for vapor-deposited oxide coatings. For high-temperature applications, a deposition process temperature above 948 K is seen to produce a stoichiometric, fully dense, and equiaxed-polycrystalline coating of cubic erbia.

Keywords: deposition process temperature, erbium compounds, inorganic coatings, microstructure, morphology, orthorhombic phase, physical vapor deposition, residual stresses, sapphire, substrate temperature, vapor deposited oxide coatings, x-ray diffraction

A.F. Jankowski, C.K. Saw, J.L. Ferreira, J.S. Harper, J.P. Hayes, and B.A. Pint, Materials Science and Technology Division, Lawrence Livermore National Laboratory, Mail Stop L-352, Livermore, CA 94550. Cited: *J. Mater. Sci.*, 2007, July, **42**(14), p 5722-5727. ISSN 0022-2461.

Plasma spray synthesis of ultrafine YSZ powder. A plasma spray process has been developed for the mass production of nanopowders for solid oxide fuel cells (SOFCs) and significant technical developments have been achieved during the past 2 years. Ultrafine powders of 8 mol.% yttria-stabilized zirconia (YSZ) were produced directly from a precursor solution via plasma spray process. The powders were characterized by x-ray diffraction (XRD), nitrogen absorption technique (BET), transmission electron microscopy (TEM), particle size analysis (PSA), and thermogravimetric (TG) analyses. The as-sprayed YSZ powders with cubic phase were obtained without obvious impurity species. BET surface area of the sprayed powder reached as high as 27 m^2/g, indicating an equivalent particle size of 37 nm. The powder showed mostly spherical with mean size of about 100 to 200 nm by TEM results. Introduction of an organic additive resulted in a significantly increased specific surface area, accompanied by a slight decrease in grain size. This plasma spray process has the potential to be a less costly and time saving one for nanopowder production than the existing wet chemistry processes.

Keywords: grain size and shape, nitrogen absorption technique, particle size, plasma spraying, powder metals, precursor solutions, solid oxide fuel cells, sprayed powder, synthesis (chemical), thermogravimetric analysis, transmission electron microscopy, x-ray diffraction, yttria-stabilized zirconia

Z. Wang, R. Hui, N. Bogdanovic, Z. Tang, S. Yick, Y. Xie, I. Yaroslavski, A. Burgess, R. Maric, and D. Ghosh, Institute for Fuel Cell Innovation, National Research Council Canada, Vancouver, BC V6T 1W5, Canada. Cited: *J. Power Sources*, 2007, June 30, **170**(1), p 145-149. ISSN 0378-7753.

Vibration damping of superalloys and thermal barrier coatings at high temperatures. A high-temperature mechanical spectroscopy system, based on noncontact laser vibrometry, has been developed to investigate the temperature dependence of the flexural damping properties of materials and coatings up to 900 °C. Results for the damping coefficient and Young's modulus have been obtained for several high-temperature alloys (FeCrAlY and a single-crystal, Ni-based superalloy PWA 1484), ceramics (polycrystalline alumina and yttria-stabilized zirconia) and an electron-beam deposited thermal barrier coating. The results indicate that the thermally grown oxide, formed by high-temperature oxidation does not confer significant damping, whereas, coatings of the yttria-stabilized zirconia produce measurable damping over the entire temperature range with a peak centered at ~200 °C. The damping peak appears to be an intrinsic property of the YSZ material whether in the form of a bulk material or a metastable coating. Data on the temperature-dependent in-plane Young's modulus of the 7 wt.% yttria-stabilized zirconia thermal barrier coating between room temperature (22 GPa) and 900 °C (18 GPa) is also reported for the first time.

Keywords: damping, damping coefficient, dynamic mechanical analysis, elastic moduli, high-temperature mechanical spectroscopy, internal friction, oxidation, superalloys, thermal barrier coatings, vibration damping, vibrations (mechanical), yttria-stabilized zirconia

G. Gregori, L. Li, J.A. Nychka, and D.R. Clarke, California NanoSystems Institute, University of California, Santa Barbara, CA 93160-5050. Cited: *Mater. Sci. Eng. A*, 2007, Sept 25, **466**(1-2), p 256-264. ISSN 0921-5093.

Diagnostics and Control

Correlation of plasma sprayed coating deposition efficiency with volume flux measurements by phase-Doppler anemometry (PDA). The use of phase-Doppler anemometry (PDA) to characterize the details of in-flight plasma sprayed particle behavior has been demonstrated previously [Ma et al. *Plasma Chem. Plasma Process.*, 2004, **24**(1), p 85; 2005, **25**(1), p 56]. The present articles shows further that a direct relationship may exist between the PDA measured particle volume flux and the coating microstructure and deposition efficiency (DE). In the situation when the precise particle temperature information is not available, the PDA measured particle volume flux may provide an alternative to predict quantitatively the variation of the coating microstructure and the DE. By monitoring the in-flight particle volume flux variations, instead of the particle velocity, size, and temperature individually and simultaneously, the optimal settings of the plasma spraying parameters may also be determined conveniently. However, it is noted that the effective applications of such approach depend largely on the particle surface morphology and the predetermination of the particle size range.

Keywords: anemometers, correlation methods, deposition efficiency, phase Doppler anemometry, plasma deposition, plasma sprayed coating deposition, plasma spraying, sprayed coatings, volume flux, volume measurement

P. Wang, S.C.M. Yu, and H.W. Ng, Thermal and Fluids Engineering Division, School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798, Singapore. Cited: *Plasma Chem. Plasma Process.*, 2007, June, **27**(3), p 311-336. ISSN 0272-4324.

Studying a splat in the making. Researchers from the National Institute for Materials Science in Tsukuba and from Kinki University in Osaka have directly monitored plasma sprayed yttria-stabilized zirconia droplets as it impacts a quartz substrate at room temperature. The monitoring system consisted of a high-speed video camera, a long-distance microscope, and custom droplet-individualization techniques. The camera captures 312×260 pixel images at one million frames per second and a working distance of 11.4 m for the microscope. Monitoring the droplet impact during the coating formation can help produce more reliable information on controlling coating properties.

Keywords: coating properties, custom droplet-individualization techniques, high-speed cameras, monitoring, plasma spraying, quartz, yttria-stabilized zirconia

H. Hogan. Cited: *Photonics Spectra*, 2007, July, **41**(7), p 22+24. ISSN 0731-1230.

Measurement Methods

Calibration terms for thickness gages. Learning the language of coating measurement is critical. Definitions, explanations, limitations, and practical examples of metrology terminology as it relates to DeFelsko coating thickness measurement gages are presented. Electronic gage uses electronic circuitry to convert a reference signal into coating thickness and operates on one of the two different magnetic principles. A reference standard is a sample of known thickness against which users may verify the accuracy of their gages. A shim is a thin strip of nonmagnetic plastic, metal, or other material of known uniform thickness used to verify the operation and make adjustments to dry film thickness gages. When using a coating thickness gage, there are three basic procedures to ensure measurement accuracy such as calibration, verification, and adjustment. Coating thickness gages are necessarily sensitive to very small irregularities of the coating surface or of the steel surface directly below the probe center.

Keywords: calibration, coating measurement, coating techniques, DeFelsko coating thickness measurement gages, electronic circuitry, magnetic plastic, metrology terminology, thickness gages, thickness measurement

D. Beamish, DeFelsko Corp., Ogdensburg, NY. Cited: *Metal Finish.*, 2007, Jan, **105**(1), p 42-47. ISSN 0026-0576.

Design and numerical simulation of an optic fiber sensor for damage assessment of structures. The paper presents the design of a new optic fiber sensor that simultaneously measures normal deformation, cross-sectional deformation, and temperature with the minimum number of sensible elements. It is based on two assembled in phase quadrature traditional Fabry-Perot sensors. Lightness and the extreme compactness make the proposed sensor suitable to equip composite materials with low specific weight and various percentage in fiber volume, that it can be used for aeronautical and/or automotive applications without modifying mechanical characteristics. The example host material is Ti-6Al-4V/SiC composite characterized with the volume fraction of carbon fibers of 35%; it permits to insert the sensor at low temperature by means of cold-gas spray technology. Sensor construction is quite easy and does not require great economical effort in comparison with other types of optic fiber sensors reported in literature. The sensor has the capability of independently measuring the thermal and mechanical (bending and traction) loads. It has a great sensibility; indeed it allows evaluating urn displacements and bending angle of the order of one hundredth of degree, operating in a temperature range between −190 and 750 °C. The paper concludes with the description of the mathematical model of the proposed sensor and with the correspondent numerical characterization to estimate sensor capabilities. Numerical simulation points out the potentials of the new proposed sensor.

Keywords: cold gas spray technology, composite materials, damage detection, damage location, damage quantification, deformation, Fabry-Perot interferometers, fiber optic sensors, numerical methods, structural dynamics

C. Delprete and C. Rosso, Politecnico di Torino, Dipartimento di Meccanica, 10129 Torino, Italy. Cited: *Key Eng. Mater.*, 2007, **347**, p 393-398. ISSN 1013-9826.

Evaluation of adhesive strength of thermal sprayed hydroxyapatite coatings using the LAser Shock Adhesion Test (LASAT). The adhesive strength between a coating and a substrate is an important factor that characterizes the quality of thermally sprayed Hydroxyapatite (HA) coatings such as those for biomedical applications. In this study, adhesive strength was evaluated by the LAser Shock Adhesion Test (LASAT) technique. LASAT was

developed to be suitable for determining the coating-substrate adhesion. This study deals with hydroxyapatite coatings on Ti-base alloy substrate produced by atmospheric plasma spraying. To discuss the influence of the spray condition on adhesive strength, different types of specimens, i.e., from various powder feed rate spraying and different surface roughness, were LASATested. The results showed that the adhesive strength decreases with increasing number of impinging particles on a given area of surface in unit time. Furthermore, the adhesive strength tendency of low-roughness substrate specimens showed scatter. This tendency depends on the surface profile, i.e., skewness value. Consequently, not only the height direction roughness parameter, but also the wavelength of roughness, roughness morphological parameter and powder feed rate are important factors for the adhesion of the thermally sprayed HA coatings.

Keywords: adhesive strength, adhesives, hydroxyapatite, laser applications, laser shock, thermal spray coating, thermal spraying, wavelength

Y. Ichikawa, S. Barradas, F. Borit, V. Guipont, M. Jeandin, M. Nivard, L. Berthe, K. Ogawa, and T. Shoji, Fracture and Reliability Research Institute, Tohoku University, Sendai 980-8579, Japan. Cited: *Mater. Trans.*, 2007, April, **48**(4), p 793-798. ISSN 1345-9678.

Interfacial indentation test and adhesive fracture characteristics of plasma sprayed cermet Cr_3C_2/Ni-Cr coatings. Thermal spraying is often used to create coatings protecting parts against physicochemical aggressions or improving superficial mechanical properties. It involves several problems because of the high temperatures of the process: cracks, porosity, coating adhesion. The authors use Vickers interfacial indentation test to characterize adhesive fracture between substrates and coatings. From the Lawn's relation two curves: load/crack length ratio ($P/C^{3/2}$) vs crack length ($C^{1/2}$) and ln P vs. ln C are drawn for varying loads. They allow the determination of the type of residual stress, a coating fracture "toughness"/residual stress ratio (K_C/σ_r) characterizing interfacial behavior and may lead, in some cases, to residual stress σ_r. Influence of superficial remelting by CO_2 laser of cermet coating Cr_3C_2/Ni-Cr deposited on NiCrAlY covered steel and of annealing of Cr_3C_2/Ni-Cr coated cast iron are then studied. Possibility of reducing residual stress is shown at the same time as the interest of both approaches.

Keywords: adhesive fracture, annealing, cermets, coating techniques, cracks, interfacial indentation test, Lawn's relation, mechanical properties, plasma spraying, porosity, residual stresses, superficial remelting laser

P. Hivart and J. Crampon, Laboratoire d'Artois Mecanique, Thermique et Instrumentation, LAMTI, UPRES EA 2472, Universite d'Artois, 62400 Bethune, France. Cited: *Mech. Mater.*, 2007, Nov, **39**(11), p 998-1005. ISSN 0167-6636.

Measurement of the debonding resistance of strongly adherent thick coatings on metals via in-plane tensile straining. A method based on an in-plane tensile straining, for measuring the debonding resistance of strongly adherent thermally sprayed thick coatings is presented. The debonding characteristics are analyzed on the basis of an approximate model for the different sources of work dissipation, under the hypothesis of small scale yielding at the debonding crack tip. The microstructure of the coatings illustrated by SEM micrographs show that the deposition of a layer of Cu on the surface before cladding do not induce microstructural change in the coating and along the interface. The debonding stress is found to be nearly same as the flow stress measured at the same strain during purely uniaxial straining. The debonding resistance is of the thick coatings is characterized by the debonding toughness equal to the critical value reached by the strain energy release rate and during steady state debonding.

Keywords: coatings, crack tip, debonding, debonding resistance, microstructure, plastic flow, scanning electron microscopy, strain energy, tensile strain, thick coatings

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Residual strain measurements in thermal spray cermet coatings via neutron diffraction. The impact and fatigue resistance of overlay coatings is significantly influenced by the residual strain (or stress) field induced during coating deposition, post-treatment, and in-service loading. Optimization of the residual strain field is therefore critical to the life and performance of components. Nondestructive measurement of these strain fields in relatively thin (300-400 μm) thermal spray coatings, however, poses a challenge because conventional techniques, such as deep hole drilling, x-ray diffraction, synchrotron diffraction, and changes in beam curvature either make these techniques destructive and/or provides only a very near-surface strain measurement. This particularly complicates the strain analysis in cermet coatings, e.g., WC-Co deposited by the thermal spraying process, where the low penetration depth of x-ray and synchrotron-diffraction ray can only provide a through thickness measurement of stress or strain profile via the destructive layer removal technique. Recent investigations have therefore concentrated on the use of neutron diffraction technique for such analysis, and this paper reports some of the early findings of the comparison of through thickness strain measurements in relatively thin (400 μm) as-sprayed and post-treated WC-12 wt.% Co coatings via the neutron diffraction technique. Since neutrons are not charged, they do not interact with the electron cloud surrounding the atom (unlike x-ray); hence, diffraction results from the interaction with the atomic nucleus. Neutrons therefore have greater penetration depth in most engineering materials and therefore provide a nondestructive through thickness strain measurement. Results of strain measurement are discussed with the structure property relationships and contact fatigue performance, and indicate that post-treatment of these coatings results in harmonization of the strain field within the coating, and at the coating substrate interface. This significantly influences the contact fatigue performance by improving both the cohesive and adhesive strength of these coatings.

Keywords: cermets, cobalt, deposition, fatigue of materials, impact resistance, neutron diffraction, residual stresses, rolling contact fatigue, sprayed coatings, strain measurement, thermal spray coatings, thermal spraying, tungsten carbide

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Surface strain measurement of thermally sprayed ceramics coatings under static and cyclic loadings and its application to detection of delamination. Thermally sprayed ceramic coatings are commonly used as thermal barriers at high temperature. However, delamination of the coating from substrate (base metal) under various operation conditions, including high temperature and mechanical loads, always leads to serious degradation of the heat shielding effect. It is important to detect the delamination in situ and nondestructively for the maintenance and management of mechanical structures. However, until now, neither a clear definition of the delamination of the coating from the substrate nor an effective method to detect and evaluate the delamination process has been proposed. In this work, the surface strains of a substrate and a thermally sprayed coating were measured using an electronic speckle interferometry (ESPI) method. As a result, generation of delamination of the coating corresponded well to the critical strain ε_c on the ε-σ_s curve under a static load, where a large drop in the strain occurred for the coated specimen compared with the substrate-only specimen. Furthermore, generation of the delamination under a cyclic load also corresponded well to a large drop in strain for the coated specimen compared to the substrate only specimen.

Keywords: ceramic materials, cyclic loads, delamination, delamination generation, electronic speckle pattern interferometry, interferometry, static tensile load, strain measurement, surface strain, thermal barrier coatings, thermal spraying, thermally sprayed ceramic coating

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Microstructure

Deposition of HVAF sprayed Ni-base amorphous metallic coatings. $Ni_{53}Nb_{20}Ti_{10}Zr_8Co_6Cu_3$ (at.%) amorphous alloy with high glass-forming ability (GFA), capable of forming a wholly amorphous rod of ~3 mm diameter by casting, was adopted to deposit amorphous metallic coatings by high-velocity air fuel (HVAF) thermal spraying. The effects of powder feed rate and spraying distance on amorphous phase content and porosity of the coatings were investigated. It was indicated that an appropriate powder feed rate was desirable to produce a coating with high amorphous fraction, whereas a larger spraying distance led to a more dense coating. The corrosion resistance of the sprayed coatings was also examined in 1 M HCl aqueous solution.

Keywords: amorphous alloys, amorphous metallic coating, corrosion resistance, glass-forming ability, high-velocity air fuel, nickel, porosity, powders, thermal spraying

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Effect of heat treatment on properties of cold sprayed nanocrystalline copper alumina coatings. Cold gas dynamic spraying appears to be the most appropriate thermal spraying technique for depositing nanocrystalline powders given its low deposition temperature. Nanocrystalline copper alumina coatings were deposited on copper substrates and the effect of heat treatment temperature on porosity, grain size, microhardness, and conductivity of the coatings was studied and compared with that of cold sprayed copper. The role of alumina in inhibiting grain growth and in strengthening the copper matrix was investigated. An attempt has been made to assess the contribution of various mechanisms to the conductivity of nanocrystalline copper alumina coatings.

Keywords: alumina, cold gas dynamic spraying, cold spray, copper alumina coatings, electric conductivity, heat treatment, inorganic coatings, microhardness, nanocrystalline materials, porosity, thermal spraying

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Plasma sprayed basalt/chromium oxide coatings. Volcanic basalt and chromium oxide (Cr_2O_3) have been cosprayed in air with a direct current (dc) plasma to obtain composite coatings. Both powders were simultaneously injected by two separated injectors. The following spray parameters: arc current, hydrogen vol.%, and total plasma forming gas mass flow rate were optimized as well as injector positions. Different mass ratios of both components were used to achieve coatings. An uniform distribution of basalt among the Cr_2O_3 lamellae has been observed with SEM for all composite coatings. XRD showed that chromia became amorphous in the composite basalt/chromia coatings.

Keywords: amorphous materials, arc current, basalt, chromium compounds, chromium oxide, composite coatings, flow of gases, flow rate, mass flow, optimization, plasma spraying

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Ti and Ti-6Al-4V coatings by cold spraying and microstructure modification by heat treatment. The microstructure of cold sprayed Ti and Ti-6Al-4V coatings and the effect of heat treatment on coating microstructure modification was investigated. The results show that the cold sprayed Ti and Ti-6Al-4V coatings have porous structure with a high deposition efficiency. The porosities of cold sprayed Ti and Ti-6Al-4V coatings are found to be $5.4 \pm 2.4\%$ and $22.3 \pm 4.7\%$ under spray conditions. The results show that the reactions of spray particles with oxygen and the poor thermal conductivity of these materials result in a high particle interface temperature, resulting in localized melting and metallurgical bonding. Annealing at 859 °C for 4 h results in an increase in porosities of Ti and Ti-6Al-4V to coatings to $21.6 \pm 4.6\%$ and $29.7 \pm 5.1\%$, respectively, due to coalescence of incomplete interfaces and submicron pores.

Keywords: coalescence, coatings, cold spraying, deposition efficiency, heat treatment, interface temperature, metallurgical bonding, microstructure, porosity, spraying, thermal conductivity, titanium alloys

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Understanding grain growth and pore elimination in vacuum plasma sprayed titanium alloy. In the present study, grain growth, pore elimination, and densification of the vacuum plasma sprayed structure of Ti-6Al-4V alloy were investigated. The near-net-shaped formed components were deposited using a vacuum plasma spraying process. The as-sprayed specimens were heat treated at 1040 °C (50 °C above the β transus temperature) for up to 1440 min in an inert gas atmosphere. The apparent density of the as-sprayed and heat-treated samples was determined by the water displacement method. The theoretical density of the heat-treated samples was calculated from lattice parameters and phase compositions determined using x-ray diffraction (XRD). Densification of the heat-treated specimens at a given temperature and time was determined. Results revealed that the density initially increased sharply with isothermal heat treatment time and then reached a plateau. During short heat treatment times, the grains grow quickly within individual splats at a rate consistent with intrinsic boundary mobilities. For longer heat treatment times, the grain boundary mobility was limited by pore drag, and the grain growth rate was reduced. The pore and grain sizes increased with increasing isothermal heat treatment time up to about 17 and 100 μm, respectively.

Keywords: densification, grain boundaries, grain growth, grain growth rate, grain size and shape, heat treatment, isothermal heat treatment, lattice constants, phase composition, plasma spraying, pore size, titanium alloys, vacuum applications, vacuum plasma spraying process

H.R.S. Jazi, T.W. Coyle, and J. Mostaghimi, Center for Advanced Coating Technologies, University of Toronto, Toronto, ON M5S 3G8, Canada. Cited: *Metall. Mater. Trans. A: Phys. Metall. Mater. Sci.*, 2007, March, **38**(3), p 476-484. ISSN 1073-5623.

Modeling

Mechanical Modeling

Coating fragmentation by branching cracks at large biaxial strain. The fragmentation behavior of a thin brittle coating attached to a ductile substrate subjected to equibiaxial quasi-static in-plane tension is studied. The experimentally observed cracking patterns are related to repetitively branching coating cracks. The fragmentation process is modeled by the rate equation approach. It is established that fragmentation by branching cracks leads to a qualitatively different fragment distribution compared to binary fragmentation. The fragmentation model is applied to identify crack branching and coating/substrate stress transfer parameters.

Keywords: biaxial strain, coating fragmentation, coatings, computer simulation, crack initiation, cracking patterns, organic polymers, parameter estimation, silica, strain measurement, stress analysis, stress transfer parameters, Weibull distribution

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An elastohydrodynamic lubrication model for coated surfaces in point contacts. An elastohydrodynamic lubrication (EHL) model for coated surfaces in point contacts has been developed by combining the elastic deformation formulation for the coated surfaces with an EHL model. Inverse fast Fourier transform (IFFT) is employed first to obtain the influence coefficients (ICs) from the frequency response function (FRF). The subsequent calculation of elastic deformation is performed using the efficient algorithm of discrete convolution and fast Fourier transform (DC-FFT). The coating EHL model is verified by the comparison to available numerical results. The effects of coating on lubrication under various loads, speeds, rheological models, and pressure-viscosity behaviors are numerically investigated. Similar to the observations from dry contact, stiffer coatings in EHL tend to reduce the nominal contact radius but increase the maximum contact pressure, and vice versa for more compliant coatings. However, as coating thickness increases, the influence of coatings on film thickness, including the central and the minimum film thicknesses, does not follow a monotonic variation, and therefore cannot be predicted by any simple film thickness equation. The reason for that is the pressure viscosity effect, which tends to counterbalance the effect of coating. The average friction coefficient in lubricant film increases in stiff coating cases but decreases for compliant coating cases. Furthermore, two possible approaches to improving the minimum film thickness thus reducing friction and wear in mixed lubrication are indicated: a thin stiff coating for conventional EHL and a thick compliant coating for soft EHL.

Keywords: algorithms, coated surfaces, coating techniques, coatings, deformation, elastic deformation, elasticity, elastohydrodynamic lubrication, fast Fourier transforms, film thickness, inverse fast Fourier transform, lubricant film, mathematical models, mixed lubrication, point contacts, rheology, viscosity

Y. Liu, W.W. Chen, D. Zhu, S. Liu, and Q.J. Wang, Center for Surface Engineering and Tribology, Northwestern University, Evanston, IL 60208. Cited: *J. Tribol.*, 2007, July, **129**(3), p 509-516. ISSN 0742-4787.

Mathematical modeling of layered contact mechanics of cam-tappet conjunction. The paper briefly introduces a fast converging mathematical model to predict the peculiarities of the nonconforming contact between an infinitely long cylinder and a coated elastic substrate. The proposed method is then integrated into a multiphysics analysis of the valve train system of a racing type internal combustion (IC) engine. Due to relatively high loads and speeds experienced, particularly in the cam-tappet contacts, hard wear-resistant coatings are used, which greatly influence the contact mechanics performance. Results indicate that the layer thickness is the determining factor in contact characteristics, which alters during the cam cycle. Therefore, for optimal performance coatings of nonuniform thickness should ideally be applied to the circumference of the cam rather than the usual coating of the tappet surface with a given thickness.

Keywords: cam-tappet conjunction, coating techniques, coatings, convergence of numerical methods, fast converging mathematical model, internal combustion engines, layered contact mechanics, mathematical models, mechanics, multiphysics analysis, valve trains, wear resistance

M. Teodorescu and H. Rahnejat, Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough, Leics LE11 3TU, UK. Cited: *Appl. Math. Model.*, 2007, Nov, **31**(11), p 2610-2627. ISSN 0307-904X.

Optimization of thermomechanical loading by the inverse method. This study presents 2D experimental results and the numerical simulations of thermal loads to observe their influences on the life of mechanical systems. The experimental and thermal evolution was measured using several thermocouples and an infrared pyrometer. In fact, the thermal loading was determined by the resolution of an inverse process where the parameters of thermal laws were identified by minimizing the difference between the experimental results and the numerical simulations. After this optimization process, the mechanical modeling by the finite element method was carried out by applying the optimized thermal loading. The laws of elastoviscoplastic behavior are applied in the working temperature range of a continuous casting rollers tool. This modeling constitutes a technological means to choose a type of a coating material and its optimum thickness and to test different thermal loads in order to optimize the industrial process and to improve the tool's life.

Keywords: computer simulation, optimization, parameter estimation, process control, pyrometers, thermal evolution, thermal laws, thermal load, thermocouples, thermomechanical loading

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Microstructural Modeling

Constrained sintering of alumina thin films: Comparison between experiment and modeling. Alumina thin films deposited by dip coating on alumina substrates were sintered between 1150 and 1350 °C. A new measuring system using a rocking arm as a mechanical amplifier allows in situ measurement of the shrinkage of the film. Comparison of experimental densification behavior with the predictions of the isotropic continuum mechanics model (using values of constitutive parameters determined by sinter forging) highlights the inadequacy of the isotropic models. These results, together with other published evidence, provide justification to consider anisotropic models.

Keywords: alumina, alumina substrates, anisotropic models, continuum mechanics, densification, forging, sinter forging, sintering, substrates, thin films

O. Guillon, E. Aulbach, J. Rodel, and R.K. Bordia, Institute of Materials Science, Darmstadt University of Technology, 64287 Darmstadt, Germany. Cited: *J. Am. Ceram. Soc.*, 2007, June, **90**(6), p 1733-1737. ISSN 0002-7820.

Heat transfer and nonequilibrium phase change of lamellas under plasma spray conditions. The properties of a plasma sprayed coating are, to a great extent, controlled by the cooling and solidification of the droplets impinging on the part to be covered. Both processes condition the cooling rate, crystal growth, and formation of the crystalline phases. This paper presents a one-dimensional heat transfer model that predicts the cooling and solidification of a liquid lamella deposited on a flat surface. It is based on the solution of the time-dependent heat equation in the splat and the substrate coupled by an interface thermal resistance and takes into account the melt undercooling and crystal nucleation. The calculations are performed for alumina lamellas on steel and alumina substrates.

Keywords: alumina, coatings, crystal growth, crystal nucleation, crystalline phases, heat equations, liquid lamella, nucleation, one-dimensional, plasma spraying, rapid solidification, steel, undercooling

Y. Lahmar-Mebdoua, A. Vardelle, P. Fauchais, and D. Gobin, Centre de Developpement des Technologies Avancees, Algiers, Algeria. Cited: *High Temp. Mater. Process.*, 2007, **11**(2), p 191-204. ISSN 1093-3611.

Solidification in spray forming. Solidification in spray forming takes place in two distinct steps: typically half of the alloy latent heat is removed rapidly from the droplet spray created by gas atomization; the droplets are then constituted into a billet at deposition where the remaining liquid fraction solidifies relatively slowly. However, within the droplet spray, individual droplets have different thermal and solidification histories and depositing droplets may be solid, mushy, or liquid. Despite many studies of solidification behavior in spray forming, uncertainties and some misconceptions remain on how the solidification conditions in the spray and billet interact to give rise to the characteristic spray formed microstructure comprising refined, polygonal/equiaxed primary grains with low levels of microsegregation. This article presents a simple numerical model for the spray formed grain size arising from the deposition of the various droplets in the spray and combines insights provided by the model with previous investigations of the phenomena occurring during and immediately after deposition to propose a comprehensive description of the important solidification behavior during spray forming. Remelting, grain multiplication, thermal and elemental equilibration, and microstructural coarsening are proposed to play a critical role in the evolution of the spray formed microstructure.

Keywords: alloys, grain size and shape, mathematical models, metal forming, metallographic microstructure, microstructural coarsening, solidification, spray formed microstructure, spray forming

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Process Modeling

Modeling the spray forming of H13 steel tooling. On the basis of a numerical model, the temperature and liquid fraction of spray formed H13 tool steel are calculated as a function of time. Results show that a preheated substrate at the appropriate temperature can lead to very low porosity by increasing the liquid fraction in the deposited steel. The calculated cooling rate can lead to a microstructure consisting of martensite, lower bainite, retained austenite, and proeutectoid carbides in as-spray-formed material. In the temperature range between the solidus and liquidus temperatures, the calculated temperature of the spray formed material increases with increasing substrate preheat temperature, resulting in a very low porosity by increasing the liquid fraction of the deposited steel. In the temperature region where austenite decomposition occurs, the substrate preheat temperature has a negligible influence on the cooling rate of the spray formed material. On the basis of the calculated results, it is possible to generate sufficient liquid fraction during spray forming by using a high growth rate of the deposit without preheating the substrate, and the growth rate of the deposit has almost no influence on the cooling rate in the temperature region of austenite decomposition.

Keywords: cooling, cooling rate, liquid fraction, mathematical models, metal forming, metallographic microstructure, porosity, preheated substrate, preheating, spray forming, steel tooling, temperature measurement, tool steel

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Modeling of spraying with time-dependent material feed rate. This paper presents a mathematical model for predicting the thickness of coatings deposited by means of spraying onto rotating parts with circular symmetry, for the case of time-dependent material feed rate. A procedure for calculating the material feed rate control law providing production of coatings with uniform thickness or coatings with a predefined law of thickness variation is developed. The proposed procedure was used to analyze the process of spraying onto the surface of a rotating disc. A material feed rate variation law providing production of uniform coatings and coatings with linear thickness variation is calculated. It is demonstrated that for the first case the optimal law of material feed rate variation is described by a linear function and for the second case it can be successfully approximated by a quadratic function. The proposed calculation technique can be easily used for the case of coatings with a more complex law of thickness variation.

Keywords: deposition, linear function, material feed rate, mathematical techniques, mathematical models, quadratic function, spray deposition, sprayed coatings, spraying, thickness measurement, thickness variation, uniform coating

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Three-dimensional mathematical modeling and numerical simulation of billet shape in spray forming using a scanning gas atomizer. A three-dimensional shape model, tracing the coordinates of the moving surface of a growing billet spray formed by a scanning gas atomizer, has been developed in this study. New mesh generation and surface smoothing algorithms for the growing billet, as well as shading algorithms, are incorporated into the model for accurate prediction of the shape and dimensions of the billet during spray forming. Mass flux distribution profiles of the spray generated by the scanning atomizer under different spraying conditions have been revealed for the shape modeling. Geometrical evolution of the billet in spray forming has been investigated based on analysis of the scanning mechanism of the atomizer. The shape modeling has been validated by different numerical algorithms and experimental investigations. Finally, the influence of processing conditions on the shape and dimensions of spray formed deposits have been simulated and discussed. Near-net-shaped preforms with triangular or square cross section, other than the usual circular cross section, are expected to be produced under appropriate spray forming conditions.

Keywords: algorithms, atomizers, billets (metal bars), forming, mass flux distribution, mathematical models, shape modeling, spray forming, structural analysis, surface smoothing algorithms, three-dimensional

C. Cui, U. Fritsching, and A. Schulz, Institute for Materials Science, University of Bremen, Bremen, 28359, Germany. Cited: *Metall. Mater. Trans. B: Process Metall. Mater. Process Sci.*, 2007, April, **38**(2), p 333-346. ISSN 1073-5615.

Postprocessing

Heat treatment of nanostructured thermal barrier coating. A nanostructured thermal barrier coating has been prepared by air plasma spraying using YSZ (8 wt.% Y_2O_3 partially stabilized zirconia) nanopowder. The effect of annealing on the nanostructured zirconia coating has been investigated. The grain size of the nanostructured zirconia coating increased with increasing annealing time and temperature. Grains grew with preferential direction and into a columnar structure. The growth activation energy in the nanocrystalline grains is very low, which comes from existence of micropores in the coating and the grain-rotation-induced grain coalescence (GRIGC) mechanism.

Keywords: air plasma spraying, annealing time, coalescence, columnar structure, grain size and shape, heat treatment, nanostructured materials, nanostructured zirconia coating, plasma spraying, thermal barrier coatings, yttria-stabilized zirconia

N. Wang, C. Zhou, S. Gong, and H. Xu, Department of Mater. Sci. Eng., Beijing University of Aeronautics Astronautics, Beijing, 100083, China. Cited: *Ceram. Int.*, 2007, Aug, **33**(6), p 1075-1081. ISSN 0272-8842.

Processing

Influence of voltage fluctuations related to plasma torch working conditions on zirconia particle thermal treatment. The microstructure of plasma sprayed coatings is strongly linked to particle trajectories depending

among other parameters on arc root fluctuations. The latter depend on the torch anode-nozzle shape and internal diameter, the plasma forming gas composition and flow rate, and the anode erosion. Experiments were performed with yttria partially stabilized zirconia (8 wt.% yttria) particles with a size distribution between 5 to 25 m and either a PTF4 or a 3MB GE Sulzer-Metco torch. The PTF4 torch was fed with an Ar-Mb mixture and an arc current of 600 A, while the 3MB torch was fed with N2-H2 mixture with an arc current of 500 A. Particle mean temperatures and mean velocities were measured to evaluate the influence of voltage fluctuations on the treatment. This study shows that the torch working parameters, except the arc current, have nearly the same effects on the arc voltage fluctuations for the both torches. The 3MB torch voltage fluctuations are more important than those for a PTF4 torch, but they are less affected by the variations of spray parameters. Furthermore, the fluctuations of particle temperatures and velocities versus the voltage fluctuations are not the same.

Keywords: anodes, arc current, electric currents, electric potential, heat treatment, nozzles, parameter estimation, particle heat treatment, particle velocity, plasma spraying, plasma torches, voltage fluctuations, yttria-stabilized zirconia

E. Nogues, M. Vardelle, P. Fauchais, and P. Granger, SPCTS Laboratory, University of Limoges, 87060 Limoges Cedex, France. Cited: *High Temp. Mater. Process.*, 2007, **11**(2), p 161-174. ISSN 1093-3611.

Properties

Corrosion

Anticorrosion performance of Zn-Al thermal metal spraying method using steel structures. This study performs an electrochemical experiment to quantitatively evaluate the corrosion resistance performance in a Zn-Al thermal metal spraying method and produces corrosion current density according to the type of corrosion resistance methods. In the results of the calculation, the corrosion membrane produced in a Zn-Al thermal metal spraying method showed voltage differences more than 300 mV and that demonstrated enough corrosion performance with the corrosion resistance reaction of base materials and proper Zn:Al ratio, such as 50:50. Also, the results exhibited that the corrosion speed in a Zn-Al thermal metal spraying method was 0.66 time faster than that of the zinc galvanizing method in the estimation based on the standard of corrosion resistance service years in a zinc galvanizing method (JIS H 8641).

Keywords: base materials, corrosion membranes, corrosion protection, corrosion resistance, current density, electrochemical experiment, electrochemistry, galvanizing, metal spraying method, steel structures, thermal spraying

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Corrosion behavior of several thermal spray coatings used on boiler tubes at elevated temperatures. Purpose: Four thermal spray coatings were subjected to high-temperature corrosive environments of oil-fired boiler conditions to compare their corrosion protection under simulated conditions. The coatings included FeCrAl, Tafaloy 45CT, which were arc sprayed, 50Ni-50Cr and Cr_3C_2-NiCr, which were coated by high-velocity oxyfuel spray (HVOF) method. Design/methodology/approach: The coating substrates used were SA213TP 347H, SA213 T11, and SA213 T22 alloys that are widely used as boiler tube materials. Specimens were covered with a synthetic ash mixture of 70%V_2O_5-20%Na_2SO_4-10%NaCl and exposed to 550 °C and 65 °C. For 192 h (6 cycles). After high-temperature corrosion tests, weight change curves were obtained; specimens were examined by metallographical techniques, scanning electron microscopy and EDX analyses. Findings: Salt deposits attacked steels and coatings during the exposure. The corrosion rates were strongly affected by the composition of the scale formed adjacent to the steels and coatings surfaces. Austenitic steel was only bare material that experienced uniform corrosion in the tests. Ferritic steels were primarily attacked by grain-boundary corrosion. Thermally sprayed coatings were mainly attached through oxides and voids at splat boundaries. FeCrAl and 50Ni-50Cr were prone to spalling. Tafaloy 45CT is also a promising method for producing homogenous coatings. Cr_3C_2-NiCr 80/20 coating remained mostly intact. Originality/value: This paper provides useful information about corrosion behavior of four coatings used for common boiler tubes. It shows with a practical explanation how the bare material and coatings react in corrosion-simulated environments.

Keywords: boiler tubes, coated materials, computer simulation, corrosion rate, energy-dispersive spectroscopy, ferritic steels, grain-boundary corrosion, high-temperature effects, scanning electron microscopy, thermal spraying

D. Rezakhani, Niroo Research Institute (NRI), Tehran, Iran. Cited: *Anti-Corros. Meth. Mater.*, 2007, **54**(4), p 237-243. ISSN 0003-5599.

Study of molten salt corrosion of high-velocity oxyfuel sprayed cermet and nickel-base coatings at 900 °C. Samples of Cr_3C_2-NiCr cermet and NiCrBSi coatings formed by the high-velocity oxyfuel (HVOF) process on Superni 718 superalloy have been corroded in the Na_2SO_4-V_2O_5 molten salt environment at 900 °C under cyclic conditions. The hot corrosion behavior of the coatings has been investigated by means of thermogravimetric analysis, x-ray diffraction, scanning electron microscopy/energy dispersive spectroscopy, and electron probe microanalyzer techniques. Efforts have been made to formulate the mode of corrosion attack. Both the coatings protected the substrate superalloy Superni 718 completely. While protecting the superalloy, the Cr_3C_2-NiCr cermet coating partially oxidized along the splat boundaries up to the coating substrate interface, whereas only the upper part of the coating, to about 100 μm from the surface, oxidized in the case of the NiCrBSi coating. The hot corrosion resistance of both the coatings has been attributed to the formation of protective oxides of chromium/silicon at the surface and at the splat boundaries of the coatings.

Keywords: cermet coating, cermets, coatings, corrosion protection, corrosion resistance, high-velocity oxyfuel sprayed cermet, molten salt corrosion, nickel, nickel-base coatings, scanning electron microscopy, superalloys, thermogravimetric analysis, x-ray diffraction analysis

T.S. Sidhu, S. Prakash, and R.D. Agrawal, S.B.S. College of Engineering and Technology, Ferozepur 152004, Punjab, India. Cited: *Metall. Mater. Trans. A: Phys. Metall. Mater. Sci.*, 2007, Jan, **38**(1), p 77-85. ISSN 1073-5623.

Mechanical

Evaluation of grinding characteristics of thermal spraying ceramics film. This paper discusses the grindability of sprayed coatings of Al_2O_3(-TiO_2). The actual grinding action was investigated experimentally by surface grinding using a resinoid diamond wheel with different particle sizes and concentrations. The maximum height of the grinding surface was lower when the grain size of the wheel was larger and the degree of concentration of the wheel was higher. The abrasion of the grinding wheel was not due to the abrasion by the abrasive grain, but to a selective removal of the combining material during grinding and a reduction of the holding strength of the abrasive grain. This phenomenon was remarkable when the degree of concentration was low.

Keywords: abrasion, abrasives, alumina, ceramic materials, grain size and shape, grindability, grinding (machining), grinding surfaces, holding strength, sprayed coatings, surface grinding, thin films, wheels

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Failure mechanism of pure nickel (Ni 200/201) under thermomechanical loading. Cyclic loading of metallic engineering components at constant elevated or fluctuating temperature causes a complex evolution of damage that can hardly be described in a unique and straightforward manner. Often the thermal behavior of the base metals is to weak, so thermal barrier coatings were needed. Nickel is generally used for such thermal barrier coatings. Therefore it is necessary to study the thermomechanical fatigue (TMF) of this material. The lifetime of these coatings is very strong affected by the temperature loading in general, both described by nodal temperatures and their local gradient. The thermal cyclic loading takes place as thermomechanical and low cycle fatigue (LCF) damage regime. To classify the thermomechanical failure mechanism of pure nickel, OP (out of phase) and IP-TMF (in phase) test series were examined. The use of damage parameters like the unified energy approach make sense, a more detailed life time calculation for pure Nickel can be done by using the Neu-Sehitoglu model. Summary, thermomechanical loadings activate multiple damage mechanism. Surface embrittlement by oxidation is the major distinctive mechanism in addition to pure fatigue damage. Different lifetime approaches were tested and analyzed to fulfill the requirements for the fatigue analysis of nickel made components.

Keywords: cyclic loads, damage parameters, embrittlement, failure analysis, loads (forces), low-cycle fatigue, nickel compounds, thermal barrier coatings, thermal cycling, thermomechanical fatigue

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Nonlinear elastic properties of plasma sprayed zirconia coatings and associated relationships with processing conditions. Low-temperature thermal cycling of plasma sprayed zirconia coatings via curvature measurements revealed their in-plane nonlinear behavior. This feature arises from the unique layered, porous, and cracked morphology of thermal sprayed ceramic materials. The nonlinear aspect can be quantified by a novel data interpretation procedure consisting of modified beam bending analysis and inverse analysis. This versatile procedure requires minimum measurement preparation and computational effort, and its nonlinear model enables correct data interpretations otherwise not possible with the previous assumption of linear elastic models. Using this procedure, various specimens were tested to investigate the effects of processing conditions. Results are interpreted in the context of microstructural changes in the plasma sprayed coatings due to differences in particle state upon impact and coating buildup. The implications

of this study are significant for the thermomechanical design of strain-tolerant ceramic coatings in thermal barrier applications.

Keywords: ceramic coatings, ceramic materials, computational methods, curvature measurement, data reduction, elasticity, inverse analysis, linear elastic models, low-temperature operations, plasma spraying, sprayed coatings, thermal cycling, zirconia

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Preparation and properties of plasma spraying Cu-Al_2O_3 gradient coatings. To overcome the limitations of low adhesion strength and poor thermal-shock resistance of pure ceramic coatings, Cu-Al_2O_3 gradient coatings were fabricated by plasma spraying. The microstructure and distribution of Cu-Al_2O_3 gradient coatings were analyzed. The adhesion strength, thermal shock resistance and porosity of the coatings were tested. The results show that the composition of the gradient coatings has a gradient distribution along the thickness of coatings. As copper has a relatively low melting point and the molten copper has good wettability on the surface of Al_2O_3, it can be melted sufficiently and could fill the interstices and pores among the spraying particles effectively, thus improving the adhesion strength, thermal shock resistance and reducing the porosity. The adhesion strength of the gradient coating is 15.2 MPa, which is two times of that of the double-layer structure coating.

Keywords: adhesion, adhesion strength, bond strength (materials), ceramic coatings, coating porosity, gradient coating, melting point, microstructure, plasma spraying, porosity, thermal shock, thermal shock resistance, wetting

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Oxidation

High-temperature oxidation of Fe40Al coatings obtained by HVOF thermal spray. The objective of the present work is to provide insight into the high-temperature performance of iron aluminide intermetallic coatings, sprayed using high-velocity oxygen fuel. Isothermal oxidation experiments were completed at 900, 1000, and 1100 °C, and the cross sections and free surfaces of the coatings were characterized after 4, 36, and 72 h of exposure. The present results show differences in the oxidation behavior of the coatings at those temperatures, and they are especially remarkable when compared to bulk materials. For example, while at 1000 and 1100 °C where bulk FeAl presents a compact alumina layer, the coatings failed to reveal the presence of the stable α-Al_2O_3 phase, and an accelerated corrosion was observed leading to detachment from the substrate. On the basis of these results, the reasonable good performance exhibited at 900 °C indicates this could be the border line of the oxidation resistance for those coatings.

Keywords: bulk materials, compact alumina layers, corrosion, inorganic coatings, intermetallics, iron compounds, rapid solidification, thermal spraying, thermo-oxidation

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The influence of hybrid coatings on scaling-resistant properties of X33CrNiMn23-8 steel. The influence of two-layer hybrid coatings on the oxidation behavior of X33CrNiMn23-8 steel, utilized in valves of diesel engines, have been studied as a function of temperature (873 to 1273 K) and oxygen pressure (1 to 10^5 Pa), using modern microthermogravimetric techniques. Phase composition of the oxidation products (scale) was investigated by x-ray diffraction (XRD), and the morphology and chemical composition of reaction products by electron probe micro analysis (EPMA) and scanning electron microscopy (SEM) with energy disperse x-ray analyzer (EDX). It has been found that uncoated material shows very good oxidation resistance under isothermal conditions, comparable with that of chromia formers, due to the formation on its surface of Cr_2O_3 scale. However, beneath the scale, steel undergoes rapid degradation, as a result of crack formation; the deeper the penetration, the longer is the oxidation time. On the other hand, no cracks were observed in the coated steel and the oxidation rate was even slightly lower than that of uncoated material.

Keywords: diesel engines, electron probe microanalysis, hybrid coatings, inorganic coatings, oxidation, oxidation kinetics, phase composition, scaling resistant properties, scanning electron microscopy, steel, uncoated materials, x-ray diffraction

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Oxidation of Fe-22Cr coated with Co_3O_4: Microstructure evolution and the effect of growth stresses. The oxidation behavior of a commercially available Fe-22Cr alloy coated with a Co_3O_4 layer by metal organic-chemical vapor deposition was investigated in air with 1% H_2O at 1173 K and compared to the oxidation behavior of the uncoated alloy. The oxide morphology was examined with x-ray diffraction, electron microscopy, and energy-dispersive x-ray spectroscopy. Cr_2O_3 developed in between the Co_3O_4 coating and the alloy, while alloying elements of the substrate were incorporated into the coating. Particular attention was devoted to possible sources of growth stresses and the effect of the growth stresses on microstructure evolution in the scales that developed on the noncoated and the coated Fe-22Cr alloy. Microstructural features suggested that scale spallation on coated Fe-22Cr occurred as a result of superimposing thermal stresses during cooling onto the growth stresses, which had developed during oxidation.

Keywords: chromium, growth (materials), growth stresses, interdiffusion, iron alloys, microstructural evolution, oxidation, oxide morphology, protective coatings, stress analysis, wrinkling, x-ray diffraction analysis

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Oxidation-resistant aluminized MCrAlY coating prepared by spark plasma sintering (SPS). The oxidation-resistant aluminized NiCoCrAlYTa single-layered and multilayered coatings were prepared on a nickel-base superalloy substrate by the spark plasma sintering (SPS) process to improve high-temperature corrosion and oxidation behavior of materials with different compositions. The 8 mm diameter disk substrate with mechanically polished surface of 0.25 μm diamond grit was prepared from a single-crystal nickel-base superalloy. The SPS prepared layered coatings show a homogeneous microstructure with no porosity and a good adherence in the substrate. The layered coatings are found to be composed of three phases such as gamma, gamma prime, and beta. The interface between superalloy and coating shows an interdiffusion layer of 2 μm thick, and segregation of tantalum carbide TaC phase is observed at the outer side of the diffusion layer.

Keywords: coatings, diamond grit, interdiffusion layer, microstructure, multilayered coatings, single crystals, spark plasma sintering, superalloys, tantalum carbide

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Piezospectroscopic mapping of the thermally grown oxide in thermal barrier coatings. Mapping the effects of residual stress on the luminescence spectra from the thermally grown aluminum oxide (TGO) in thermal barrier coatings (TBCs) was conducted using a Raman microprobe in conjunction with a motorized stage. Maps of various spectral parameters such as peak shift, peak width ratio, peak height ratio, and peak separation were generated for different spot sizes and mapping pitches. The optimum lateral resolution was found to be ≤5 μm and is determined not only by the spot size, but also by the crystallite size in the TGO. Analysis of the spectral parameters reveals a preferential crystallographic orientation of the α-Al_2O_3 with the *c*-axis perpendicular to the substrate surface. Spectral parameters were found to deviate significantly from their "usual" values if the analyzed volume contains more than one significant stress level. In particular the width and height ratios of the R1 and R2 lines provide good indication of local damage.

Keywords: alumina, crystal orientation, crystallite size, luminescence spectroscopy, mapping, piezospectroscopic mapping, residual stresses, thermal barrier coatings, thermally grown oxide

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Use of plasma spray technology for deposition of high-temperature oxidation/corrosion-resistant coatings—A review. High-temperature oxidation is one of the main failure modes of the hot-section components in gas turbines, boilers, waste incinerations, diesel engines, coal gasification plants, chemical plants, and other energy-generation systems. In such applications the use of Fe-, Ni-, and Co-base alloys, especially of superalloys, is well known. The superior mechanical strength and good corrosion resistance of the superalloys at high temperature make them favorites for such applications. However, the presence of combustion gases constitutes an extreme environment, and hot corrosion is inevitable when superalloys are used at high temperatures for long durations of time. Therefore, these alloys need to be protected against this type of oxidation. Several countermeasures have been suggested in the literature to combat the same. One such countermeasure against hot corrosion and oxidation constitutes the deposition of protective coatings on these alloys. Among the various techniques used for deposition of coatings, plasma spraying is a versatile technology that has been successful as a reliable cost-effective solution for many industrial problems. It allows the spraying of a wide range of high-performance materials from superalloys and refractory intermetallic compounds to ceramics with continuously increasing commercial applications. Furthermore, it does not cause deterioration of the substrate alloys, and relatively thick coatings can be formed with high

deposition rates. In this paper, the technique of plasma spraying has been detailed, and the role of plasma sprayed coatings to arrest high-temperature oxidation has been discussed with the help of a comprehensive literature survey. The main focus of this investigation is the studies related to plasma sprayed NiCrAlY, Ni-Cr, nickel aluminide, and Co-based coatings.

Keywords: boilers, chemical plants, coal gasification plants, coating techniques, combustion gas, corrosion resistance, diesel engines, energy-generation systems, gas turbines, plasma spraying, refractory intermetallic compounds, thermo-oxidation, waste incineration

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Thermal

Thermal property evolution of metal-based thermal barrier coatings with heat treatments. Predicting "in-service" lifetime of ceramic thermal barrier coatings (TBCs) is difficult due to the inherent brittle nature of ceramics used. Therefore, the study of metal-based thermal barrier coatings (MBTBCs) has been initiated to challenge the current problems of ceramic-based TBCs (CBTBCs) and create a new generation of thermal barrier coatings (TBCs). In this work, nano/amorphous structured MBTBCs, for use in internal combustion engines, have been produced using high-frequency induction plasma spraying (IPS) of iron-base nanostructured alloy powders. Coatings were deposited by IPS using various spray parameters and heat treated up to 850 °C to study the thermal stability of the coating. The thermal diffusivity (α) properties of MBTBCs were measured using a laser flash method. Density (ρ) and specific heat (C_p) of the MBTBCs were also measured for calculating thermal conductivity ($k = \alpha\rho C_p$).

Keywords: ceramic materials, heat treatment, induction plasma spraying, laser flash method, metal-based thermal barrier coatings, plasma spraying, thermal barrier coatings, thermodynamic properties

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Synthesis

Solvent and plasma gas influence on the synthesis of Y_2O_3 nanoparticles by suspension plasma spraying. Suspension plasma spraying was used to synthesize Y_2O_3 nanoparticles. The Y_2O_3 starting material was first dispersed in a solvent to form a suspension and then injected axially into the plume of an inductive radio frequency plasma. It was found that the as-sprayed Y_2O_3 particles had a size distribution from nanoscale to micron scale and various morphological features, which varied with processing conditions as well as solvent and plasma gas type. In comparison with water, organic solvents led to a higher productivity and smaller particle size, whereas water introduced impurities such as $Y_2O_2C_2$, which is isotypic to $La_2O_2C_2$. Introduction of oxygen as an auxiliary plasma gas was an effective way to eliminate this impurity. In addition, complete combustion of the organic solvent and recombination of oxygen atoms above 4000 K also elevated the heat treatment degree of Y_2O_3. As a result, application of O_2 with an organic solvent resulted in an even smaller mean particle size and narrower size distribution.

Keywords: heat treatment, morphology, nanoparticles, organic solvents, particle size analysis, plasma gas, plasma spraying, suspension plasma spraying, synthesis (chemical), yttrium oxide

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Thermal and crystallization behavior of zirconia precursor used in the solution precursor plasma spray process. Yttria-stabilized zirconia (7YSZ) solution precursor has been successfully used in the deposition of high durability thermal barrier coatings. In this paper, the thermal and crystallization behaviors of 7YSZ precursor were investigated by thermogravimetric-differential thermal analysis (TG-DTA), Fourier transform infrared (FTIR) spectroscopy, and x-ray diffraction (XRD). The results show that the precursor decomposition and crystallization temperatures greatly depend on heating rate, e.g., 74 °C for the crystallization temperature when tripping the heating rate. With a 10 °C/min heating rate, the weight loss due to precursor pyrolysis occurs predominantly at temperatures below 500 °C. A small weight loss due to the oxidation of residual carbon is detected from 800 to 950 °C. The complete crystallization of the tetragonal phase was determined to be around 500 °C by DTA and XRD analyses with a 10 °C/min heating rate. The crystallization kinetics and the activation energy of amorphous 7YSZ precursor were investigated by variable heating rate DTA. The calculated activation energy is 66.2 kJ/mol. The Avrami parameter value was determined to be 2.68, which indicates that crystallization nucleation and growth is diffusion-controlled. The crystalline phase of 7YSZ coatings deposited by the solution precursor plasma spray process was identified by XRD and Raman spectrum. The average YSZ grain size in the SPPS coating was determined to be 61 nm.

Keywords: activation energy, Avrami parameter, crystallization, crystallization nucleation, Fourier transform infrared spectroscopy, heating, plasma spraying, solution precursor plasma spray, thermal barrier coatings, thermal effects, yttria-stabilized zirconia

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