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Selected Abstracts of Thermal Spray Literature

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Applications

Aerospace

Flying free. High-performance aluminum alloys used in aircraft are more prone to corrosion than pure aluminum and have traditionally been protected by systems containing toxic chromates. An overview is provided of the state-of-the-art in environmentally compliant pretreatment and coating systems for aircraft maintenance, in which the performance of the surface pretreatment and coating must be considered as a whole.

Keywords: aircraft, aluminum alloys, chromate coatings, coating systems, corrosion, environmental impact, protective coatings, surface pretreatment, surface treatment, toxicity

G. Bockmair, Wehrwissenschaftliches Institut fur Werk Explosiv-und Betriebsstoffe (WIWEB), 85435 Erding, Germany. Cited: *Eur. Coat. J.*, **9**, p 46, 48-50 [in English]. ISSN 0930-3847.

Biomaterials and Bioactive Materials

Alumina/zirconia micro/nanocomposites: A new material for biomedical applications with superior sliding wear resistance. In the present investigation, the sliding wear behavior is described for Al_2O_3/ZrO_2 micro/nanocomposites and monolithic alumina of similar grain size under defined conditions of a constant sliding speed and different loads (20-150 N). Nano ZrO_2 particles (1.7 vol%) were observed uniformly distributing throughout the composites, and most of them were located within the matrix alumina grains. The wear rate of the alumina and the micro/nanocomposites increased as the contact load increased, and a clear transition in friction and wear behavior was observed in both materials. However, the nanocomposite wear resistance at low contact loads was 1 order of magnitude higher than that of the alumina. In the severe regime, no difference was observed among the materials. The low wear rate (10^{-7} $mm^3 \cdot (N \cdot m)^{-1}$) along with low pullout indicates higher wear resistance of micro/nanocomposites in the mild regime compared with monolithic alumina. Based on the morphological observation of worn surfaces by scanning electron microscope and on residual stress analysis performed by neutron diffraction, some wear mechanisms of Al_2O_3-ZrO_2 micro/nanocomposites are proposed. The high wear resistance of the nanocomposites is discussed in terms of fracture resistance properties and residual stress. Improvements in mechanical and tribological properties of these composites make them promising candidates for biomedical applications.

Keywords: alumina, biomedical applications, fracture toughness, grain size and shape, medical applications, monolithic alumina, nanocomposites, residual stresses, scanning electron microscopy, stress analysis, superior sliding, wear resistance, zirconia

J.F. Bartolome, A.H. De Aza, A. Martin, J.Y. Pastor, J. Llorca, R. Torrecillas, and G. Bruno, Instituto de Ciencia de Materiales de Madrid, Consejo Superior de Investigaciones Cientificas (CSIC), Madrid 28049, Spain. Cited: *J. Am. Ceram. Soc.*, 2007, Oct, **90**(10), p 3177-3184 [in English]. ISSN 0002-7820.

Thermal Barrier Coatings

Design of 7 wt.%Y_2O_3-ZrO_2/mullite plasma sprayed composite coatings for increased creep resistance. Plasma sprayed standalone coatings of 7 wt.% Y_2O_3-ZrO_2 (YSZ), nominally 74 wt.%Al_2O_3-26 wt.%SiO_2 mullite, and a 46-to-54 volume ratio composite of YSZ to mullite were examined using x-ray diffraction, dilatometry, and compression creep. X-ray diffraction and dilatometer results showed that the as-sprayed predominantly amorphous mullite crystallized at 970 °C. Creep tests were conducted on all three coating types in the as-sprayed condition at stresses from 40 to 80 MPa and temperatures of 1000 to 1200 °C. The primary deformation mechanism in coatings made from all three materials was stress-assisted densification of the porous coating. While the creep behavior of YSZ/mullite composite specimens was between that of pure YSZ and pure mullite specimens for all combinations of temperature and stress tested, the creep response of the composite was more similar to that of pure mullite for all cases tested, consistent with mullite being the continuous phase in the composite.

Keywords: alumina, composite coatings, creep, creep response, crystallization, deformation, densification, mullite, plasma spraying, silica, stresses, volume ratio, yttrium oxide, zirconia

E. Withey, C. Petorak, R. Trice, G. Dickinson, and T. Taylor, School of Materials Engineering, Purdue University, West Lafayette, IN 47907-2044. Cited: *J. Eur. Ceram. Soc.*, **27**(16), p 4675-4683 [in English]. ISSN 0955-2219.

Effects of surface deposition, hole blockage, and thermal barrier coating spallation on vane end-wall film cooling. With the increase in usage of gas turbines for power generation and given that natural gas resources continue to be depleted, it has become increasingly important to search for alternate fuels. One source of alternate fuels is coal-derived synthetic fuels. Coal-derived fuels, however, contain traces of ash and other contaminants that can deposit on vane and turbine surfaces affecting their heat transfer through reduced film cooling. The end wall of a first-stage vane is one such region that can be susceptible to depositions from these contaminants. This study uses a large-scale turbine vane cascade in which the following effects on film cooling adiabatic effectiveness were investigated in the end-wall region: the effect of near-hole deposition, the effect of partial film cooling hole blockage, and the effect of spallation of a thermal barrier coating. The results indicated that deposits near the hole exit can sometimes improve the cooling effectiveness at the leading edge, but with increased deposition heights the cooling deteriorates. Partial hole blockage studies revealed that the cooling effectiveness deteriorates with increases in the number of blocked holes. Spallation studies showed that for a spalled end-wall surface downstream of the leading edge cooling row, cooling effectiveness worsened with an increase in blowing ratio.

Keywords: alternative fuels, coal ash, coal-fueled gas turbines, cooling, film cooling, heat transfer, hole blockage, near-hole deposition, spallation, thermal barrier coatings, turbine vane

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Novel composites constituted from hafnia and a polymer-derived ceramic as an interface: Phase for severe ultrahigh temperature applications. HfO_2-SiCN (polymer-derived silicon carbonitride) composites were prepared by two methods. In one case, equal volume fractions of HfO_2 and pyrolyzed powders of SiCN were cosintered to create a particulate composite. The second type, called interface composites, were prepared by coating HfO_2 particles with a thin film of the polymer precursor, followed by sintering so that densification and pyrolysis of the precursor occurred simultaneously; this process results in a ~5 nm thick grain-boundary film constituted from Hf, O, and Si. The fracture properties and environmental degradation (in a humid environment at a velocity of 17.6 to 35.0 cm/s at 1300 °C) of these two composites were measured. They were compared with the properties of a reference material made by sintering HfO_2 powders without any additives, under similar conditions (1450 °C for 2 h in air). The interface composite yielded the highest sintered density (0.90), exhibited negligible grain growth, and possessed the highest fracture strength (110 MPa). The strength remained immune to hydrothermal oxidation for several hundred hours. In contrast, the particulate composite suffered severe degradation in strength after hydrothermal exposure. The interface composites, with their highly refractory grain boundaries, represent a new class of ceramics for structural applications in harsh environments and at ultrahigh temperatures.

Keywords: ceramic materials, composite materials, densification, grain boundaries, hafnia, hafnium compounds, particulate composites, polymer-derived ceramics, silicon compounds, sintering, weathering

S. Brahmandam and R. Raj, Ultrahigh Temperature Materials Laboratory, Dept. Mechanical Engineering, University of Colorado, Boulder, CO 80309. Cited: *J. Am. Ceram. Soc.*, 2007, Oct, **90**(10), p 3171-3176 [in English]. ISSN 0002-7820.

Novel thermal barrier coatings that are resistant to high-temperature attack by glassy deposits. Airborne sand particles that deposit on thermal barrier coatings (TBCs) in gas-turbine engines melt and form calcium-magnesium-aluminosilicate (CMAS) glass, which attacks the TBCs. A new approach for mitigating CMAS attack on TBCs is presented, where up to 20 mol% Al_2O_3 and 5 mol% TiO_2 in the form of a solid solution is incorporated into Y_2O_3-stabilized ZrO_2 (YSZ) TBCs. The fabrication of such TBCs with engineered chemistries is made possible by the solution-precursor plasma spray (SPPS) process, which is uniquely suited for depositing coatings of metastable ceramics with extended solid solubilities. Here, the TBC serves as a reservoir of Al and Ti solutes, which are incorporated into the molten CMAS glass that is in contact with the TBC. This results in the crystallization of the CMAS glass and the attendant arrest of the penetrating CMAS front. This

approach could also be used to mitigate attack by other types of foreign deposits (salt, ash, and contaminants) on TBCs.

Keywords: CMAS glass, crystallization, depositing coatings, gas turbines, metallic glass, metastable ceramics, plasma spraying, solid solutions, solution-precursor plasma spray, thermal barrier coatings

A. Aygun, A.L. Vasiliev, N.P. Padture, and X. Ma, Dept. Materials Science and Engineering, The Ohio State University, Columbus, OH 43210. Cited: *Acta Mater.*, 2007, Dec, **55**(20), p 6734-6745 [in English]. ISSN 1359-6454.

Numerical analysis of FG and TBC systems based on thermoelastoplastic damage model. The model of thermoelastoplastic damage functionally graded material is developed, and the numerical simulation of the material behavior under complex thermomechanical loading conditions is performed. Sensitivity of the model response to variation of the basic mechanical moduli is examined for a graphite cast iron characterized by a changing volume fraction of graphite particles. The capability of the model to predict response of the complex (thermal barrier/functionally graded material/substrate material) system under thermal loading is checked by the use of two constituents: cast iron and ceramic, and the spatially changing temperature-dependent properties are governed by the appropriate rule of mixture. The response of the three-layer TBC/FGM/S system is compared with the reference metallic structure to show the benefits of the three-layer system.

Keywords: computer simulation, damage detection, elastoplastic-damage material, functionally graded materials, graphite, material behavior, mathematical models, mechanical moduli, residual stresses, sensitivity analysis, thermal barrier coatings, thermal stress, thermomechanical loading conditions

H. Egner, M. Juchno, M. Kula, and J. Skrzypek, Dept. Mechanical Engineering, Institute of Applied Mechanics, Cracow University of Technology, Krakow 31-864, Poland. Cited: *J. Thermal Stresses*, 2007, Sept, **30**(9-10), p 977-1001 [in English]. ISSN 0149-5739.

Thermal cycling of EB-PVD/NiCoCrAlYHf thermal barrier coatings. Microstructural evolution, interfacial toughness, and damage initiation of Y_2O_3 partially stabilized ZrO_2 thermal barrier coatings (TBCs), which have been deposited by electrobeam physical vapor deposition on NiCoCrAlYHf coated superalloy substrate, were studied as a function of thermal cycles at 1150 °C. Interfacial toughness of TBC systems was measured by indentation method. The results show that bond coat (BC) is composed of β-(Ni,Co)Al and γ solid solution at the initial cycles, β phase is completely transformed into γ at 185 cycles. The thermally grown oxide (TGO), which consists of an Al_2O_3 layer and a thin spinel layer, has a high growth rate and grows irregularly because of preferential oxidation of Hf-rich phases in the BC. This TBC system has a larger critical TGO thickness for failure. The thickness of TGO at planar place is approximately 10 μm when the TBCs spalled. Interfacial toughness decreases substantially at the initial stage of thermal cycling.

Keywords: alumina, electron beam physical vapor deposition, growth rate, interfacial toughness, microstructural evolution, oxidation, physical vapor deposition, thermal barrier coatings, thermal cyclic oxidation, thermal cycling, thermally grown oxide

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Thermal stability of air plasma spray and solution precursor plasma spray thermal barrier coatings. Yttria-stabilized zirconia (YSZ) thermal barrier coatings (TBCs) were produced by conventional air plasma spray (APS) and solution precursor plasma spray (SPPS) processes. Both TBCs were isothermally heat treated from 1200 to 1500 °C for 100 h. Changes in the phase content, microstructure, and hardness were investigated. The nontransformable tetragonal (t prime) phase is the predominant phase in both the as-sprayed APS and SPPS TBCs. APS and SPPS coatings exhibit similar thermal stability behavior such as densification rate, hardness increase, and grain coarsening rate. Both the as-received and heat treated APS and SPPS TBCs show a bimodal pore size distribution with nanosize and microsize pores. After 1400 °C/100 h heat treatment, equiaxed grains replace the columnar structure in APS TBCs and the splat structure disappears. Vertical cracks remain after the 1500 °C/100 h exposure in SPPS TBCs. The monoclinic phase appears in APS TBCs after a 1400 °C/100 h exposure and in SPPS coatings after a 1500 °C/100 h exposure.

Keywords: air plasma spray, densification, grain coarsening, hardness, heat treatment, isotherms, microstructure, phase content, plasma spraying, splat structure, thermal barrier coatings, thermodynamic stability, yttria stabilized zirconia

D. Chen, M. Gell, E.H. Jordan, E. Cao, and X. Ma, Materials Science and Engineering Program, Institute of Materials Science, University of Connecticut, Storrs, CT 06269. Cited: *J. Am. Ceram. Soc.*, 2007, Oct, **90**(10), p 3160-3166 [in English]. ISSN 0002-7820.

Diagnostics and Control

Particle injection in direct current air plasma spray: Salient observations and optimization strategies. External injection of high-melting-point low thermal conductivity ceramics orthogonal to a typical direct current thermal plasma jet plays a vital role in determining the in-flight state of the particles and the process downstream. The interactions between low-density ceramic particles and high-temperature plasma jet is quite complex, which influences the spray process and associated deposition. Detailed in-flight particle diagnostics as well as spray stream visualization have significantly enhanced our capability to diagnose and control the process. In this paper we present some salient observations on the role of key variables on particle injection. A number of experiments were conducted using a 7 MB torch (Sulzer Metco, Westbury, NY) with both Ar-H_2 and N_2-H_2 plasma gases, where the carrier gas flow to inject yttria-stabilized zirconia (YSZ) was varied systematically and the resulting in-flight particle state was captured using an array of particle and spray-stream sensors arranged in a 3D setup. A notable observation is the existence of a "sweet spot" in the plasma jet where the particle temperatures and velocities achieved a maximum. This sweet spot can be characterized by the plume position (location of centroid of the spray stream) rather than carrier gas flow rate and is independent of primary gas flows and other process/material conditions. This result suggests a possible approach to optimize particle injection independent of plasma forming torch parameters. Controlling particle injection at this sweet spot has shown to benefit the overall process efficiency (in terms of melting) and process reliability (both in-flight measurement and coating buildup) with concomitant application benefits.

Keywords: air plasma spray, deposition, electric currents, flow of gases, melting point, optimization, optimum injection, particle diagnostics, particle injectors, plasma spraying, process downstream, thermal conductivity, thermal effects

V. Srinivasan, M. Friis, A. Vaidya, T. Streibl, and S. Sampath, Center for Thermal Spray Research, Stony Brook University, 130 Heavy Engineering Building Stony Brook, NY 11794-2275. Cited: *Plasma Chem. Plasma Process.*, 2007, Oct, **27**(5), p 609-623 [in English]. ISSN 0272-4324.

Measurement Methods

On the determination of the Young's modulus of thin films using indentation tests. The main difficulty with the characterization of thin coatings using depth-sensing indentation tests is related to the determination of the contributions of the substrate and the film to the measured properties. In this study, three-dimensional numerical simulations of the Vickers hardness test are used to examine the influence of the elastic and plastic properties of the substrate and the film on the Young's modulus of the composite. The hardness of the film is equal to or higher than the substrate hardness. A study of the stress distributions and the indentation geometry of composites, film/substrate, was performed, taking into account the relative mechanical properties of the film and substrate. In addition, stress evolution during indentation was studied to quantify the critical indentation depth under which the substrate is not elastically deformed. The accurate evaluation of the Young's modulus of the films using weight functions is also examined: some of these have previously been proposed and one was introduced for this study. Two different fitting procedures were used to compare the results obtained from eight fictive film/substrate combinations using six weight functions. The first procedure, commonly used, considers the substrate's modulus as a known parameter in the fitting process. In the second, the film and the substrate's modulus are considered unknown variables that are calculated simultaneously during the fitting process. The validity of the conclusions obtained using the fictive materials was checked by applying the weight functions to four real composites.

Keywords: composite materials, elastic moduli, indentation, numerical methods, plastic properties, substrate hardness, thin coatings, thin films, three dimensional, Vickers hardness

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A numerical and experimental investigation into residual stress in thermally sprayed coatings. This paper is concerned with an investigation into the thermal spray process and is particularly concerned with the residual stresses that arise when a steel-alloy coating is sprayed onto a copper-alloy substrate. This material combination was used recently to enhance the thermal and mechanical efficiency of the pressure die casting process. A difficulty with the spraying of steel on copper is the attainment of appreciable thickness of the coating because of debonding during the thermal spraying process. Prominent among possible causes of debonding is residual stress, which is the focus of the research presented in the paper. An investigation into the thermal spray process is performed using experimentation, simplified numerical modeling, and finite element modeling. The development of residual stress for a range of process parameters, i.e. deposited layer thickness, interval of layer deposition, and the number of layers in a coating (i.e., block deposition versus multilayer deposition for a desired coating thickness) is recorded. The results from the three investigation methods agreeably indicate a progressive change

in average interfacial residual stress from compressive toward tensile with increase in thickness of deposited layer and a tensile interfacial stress in a two-layer coating, which increases with increase in interval of deposition between the two layers. On the whole, the observations from the results suggest an increase in potential for coating debonding with increase in both deposited layer thickness and layer deposition interval. The results further suggest higher potential for coating debonding with block deposition compared to multilayer deposition for a desired coating thickness.

Keywords: copper-alloy substrates, debonding, mechanical efficiency, mechanical properties, numerical methods, parameter estimation, process parameters, residual stresses, sprayed coatings, thermal spraying, thermally sprayed coatings

A.M. Kamara and K. Davey, School of Mechanical, Aerospace and Civil Engineering, University of Manchester, U.K. Cited: *Int. J. Solids Struct.*, 2007, Dec 15, **44**(25-26), p 8532-8555 [in English]. ISSN 0020-7683.

Microstructure

BAS, CMAS, and CZAS glass coatings deposited by plasma spraying. In this study, three different industrial frits $BaO\text{-}Al_2O_3\text{-}SiO_2$ (BAS), $CaO\text{-}MgO\text{-}Al_2O_3\text{-}SiO_2$ (CMAS), and $CaO\text{-}ZrO_2\text{-}Al_2O_3\text{-}SiO_2$ (CZAS) have been deposited on porcelainized stoneware tiles by plasma spraying. In the as-sprayed conditions, the microstructure of the coatings is defective because of pores, microcracks, and low intersplat cohesion. Hot-stage microscope and differential thermal analysis measurements made on the glass powders allowed to characterize the frits thermal behavior. Postprocess thermal treatments have been arranged, following these indications as well as preliminary tests, to achieve the lowest porosity and the highest resistance to abrasion. At the chosen temperatures, a microstructural improvement has been induced, but in the BAS specimens, an optimal sintering has not been accomplished because of the unavoidable full overlapping of the sintering and crystallization processes.

Keywords: ceramic coatings, crystal microstructure, crystallization, glass ceramics, glass coating, intersplat cohesion, plasma spraying, porosity, sintering, wear resistance

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Formation of $BaTiO_3$ nanoparticles from an aqueous precursor by flame-assisted spray pyrolysis. By manipulating process parameters, $BaTiO_3$ nanoparticles with tunable size were successfully prepared by flame-assisted spray pyrolysis (FASP) from an aqueous solution of barium acetate and titanium-tetra-isopropoxite. Particle size was controlled over a wide range (from about 23 to 71 nm) by varying the concentration of precursor and methane flow rate. Flame temperature was a key factor in producing particles with a narrow size distribution. The $BaTiO_3$ nanoparticles were cubic in crystal structure, dense, spherical, and softly agglomerated. The particles contained OH, carboxyl, and CO_2 bonding groups that could be completely removed by post heat treatment. At room temperature, $BaTiO_3$ pellets had relatively high dielectric constants (2578.8 to 3611.8) with loss factors ranging from 2.6% to 7.1% at the frequency of 1 kHz. The results of this study indicate that $BaTiO_3$ nanoparticles can be fabricated using continuous and industrially applicable FASP.

Keywords: agglomeration, barium acetate, barium titanate, ceramic capacitors, electric impedance, flame-assisted spray pyrolysis, methane, nanoparticles, permittivity, pyrolysis, titanium-tetra-isopropoxite

A. Purwanto, W.-N. Wang, I.W. Lenggoro, and K. Okuyama, Dept. Chemical Engineering, Graduate School of Engineering, Hiroshima University, Hiroshima, 739-8527, Japan. Cited: *J. Eur. Ceram. Soc.*, **27**(16), p 4489-4497 [in English]. ISSN 0955-2219.

Production and characterization of metastable $Al_2O_3\text{-}TiO_2$ ceramic materials. Producing nanostructured materials through metastable phases is interesting in the field of ceramic materials. Metastable phases can be obtained by the atmospheric plasma spray (APS) technique, which is a well-known technique to produce coatings. The initial powders are melted during the spraying, obtaining a homogenized phase due to their solubility in the liquid state. Afterward, the molten droplets are quenched in a cooled medium, producing the sought metastable phases. Finally, during material consolidation, the metastable structure evolves due to a dual structure. A suppression of the grain growth is produced as a consequence of the immiscibility of both phases in the solid state. Due to their small grain size and uniform structure, these nanostructured materials exhibit very interesting properties such as higher hardness and toughness. The aim of this research has been to produce nanostructured $Al_2O_3\text{-}TiO_2$ ceramic powders through APS + quenching route, starting from commercially available micron-sized powders. A complete characterization of the obtained structures using x-ray diffraction (XRD), scanning electron microscopy (SEM), field emission scanning electron microscopy (FESEM), and energy-dispersive spectroscopy (EDS) has been carried out in the Thermal Spray Center (CPT) of the University of Barcelona.

Keywords: alumina, atmospheric plasma spray, ceramic materials, dual structure, hardness, micron-sized powders, nanostructured materials, toughness, uniform structure, x-ray diffraction

I.G. Cano, S. Dosta, J.R. Miguel and J.M. Guilemany, University of Barcelona, Barcelona 08028, Spain. Cited: *J. Mater. Sci.*, November 2007, **42**(22), p 9331-9335 [in English]. ISSN 0022-2461.

Modeling

Mechanical Modeling

Characterization of NiCrAlY coatings for a high-strength, high-conductivity GRCop-84 copper alloy. NiCrAlY top coats are currently being considered as environmental protective coatings for copper alloy liners in rocket engine combustion chambers of reusable launch vehicles. The microstructure and mechanical properties of this top coat sprayed on GRCop-84 have been characterized as a function of thermal cycling between 298 and 873 K, and no obvious degradation was observed. Interfacial microsample tensile tests developed to measure coating adhesion to the substrate revealed that the interfaces were stronger than the substrate in both the as-received and thermal cycled conditions. Finite element modeling was used to analyze the stresses in the microsamples and verify the strength of the interfaces. The formation of depleted zones, devoid of Cr_2Nb particles, was associated with plasma arc cleaning in a minority of the samples prepared for this study, and the presence of these depleted zones has been found to significantly decrease the adhesion of the NiCrAlY coating and to change the failure mode in thermal cycled specimens.

Keywords: coating adhesion, combustion chambers, depleted zones, mechanical properties, microstructure, nickel compounds, NiCrAlY coatings, protective coatings, tensile strength, thermal conductivity

P. Jain, S.V. Raj, and K.J. Hemker, Dept. Mechanical Engineering, Johns Hopkins University, Baltimore, MD 21218. Cited: *Acta Mater.*, 2007, Sept, **55**(15), p 5103-5113 [in English]. ISSN 1359-6454.

Fretting contact with finite friction of a functionally graded coating with arbitrarily varying elastic modulus. Part 1: Normal loading. The two-dimensional normal contact of a functionally graded coated half-space by a rigid cylindrical punch under the action of a monotonically increasing normal load is considered. Friction with a finite coefficient is assumed between the contact surfaces. The whole contact region is composed of an inner stick region and two outer slip regions. The linear multilayered model is used to model functionally graded materials (FGMs) with arbitrarily varying shear modulus and constant Poisson's ratio under plane strain deformation; i.e., the FGM is divided into several sublayers and in each sublayer the shear modulus is assumed to be a linear function while Poisson's ratio is a constant. With the use of the transfer matrix method and Fourier integral transform technique, the problem is reduced to a set of Cauchy singular integral equations. An iterative method is developed to determine the stick-slip region. Normal and tangential tractions in the whole contact region are calculated. It is found that the stick region depends on the gradient of the functionally graded coating as well as on Poisson's ratio and the friction coefficient. The results also show that appropriate gradual variation in the shear modulus can significantly alter the contact traction. This may lead to suppression of Hertzian cracking at the edges of the contact region and thus modify the contact damage. Therefore, it is believed that FGM coatings would have potential applications in improving the resistance to contact damage at the contact surfaces.

Keywords: contact damages, contact mechanics, elastic moduli, friction, functionally graded coated half-space, functionally graded materials, load testing, mathematical models, protective coatings

L.L. Ke and Y.S. Wang, Institute of Engineering Mechanics, Beijing Jiaotong University, Beijing, 100044, China. Cited: *J. Strain Anal. Eng. Des.*, **42**(5), p 293-304 [in English]. ISSN 0309-3247.

Fretting contact with finite friction of a functionally graded coating with arbitrarily varying elastic modulus. Part 2: Tangential loading. Fretting is a major cause of surface damage, with fretting fatigue crack initiation at the contact surface subjected to a small-scale oscillatory tangential motion. In the present paper, which is part 2 of the series, the fretting contact between a functionally graded coated half-space and a rigid cylindrical punch is considered for the case where, first, a constant normal load is applied, and then a cyclically varying tangential load, which is less than that necessary to cause complete sliding, is applied. The functionally graded coated half-space is under conditions of plane strain deformation. The whole contact region is composed of an inner stick region and two outer slip regions in which Coulomb's friction law is assumed to apply. Owing to the mismatch in material constants of the punch and half-space, the problem is fully coupled and can be reduced to two coupled Cauchy singular integral equations. Based on the analyses of normal loading in part 1, contact tractions and in-plane stresses associated

with tangential loading are calculated in the whole contact region. The results show that appropriate gradual variation in the shear modulus can significantly alter the contact tractions and in-plane stresses. This may lead to suppression of crack initiation at the edges of the contact region and thus modify the fretting contact damage. Therefore, it is believed that functionally graded material coatings would have potential applications in improving the resistance to fretting contact damage at the contact surfaces.

Keywords: contact damage, contact mechanics, elastic moduli, fatigue crack propagation, fretting corrosion, friction, functionally graded materials, protective coatings

L.L. Ke and Y.S. Wang, Institute of Engineering Mechanics, Beijing Jiaotong University, Beijing, 100044, China. Cited: *J. Strain Anal. Eng. Des.*, **42**(5), p 305-313 [in English]. ISSN 0309-3247.

Residual stresses in high-velocity oxyfuel thermally sprayed coatings—Modeling the effect of particle velocity and temperature during the spraying process. The application of thick thermally sprayed coatings on metallic parts has been widely accepted as a solution to improve their corrosion and wear resistance. Key attributes of these coatings, such as adherence to the substrate, are strongly influenced by the residual stresses generated during the coating deposition process. In high-velocity oxyfuel (HVOF) thermal spraying, due to the relatively low temperature of the particle, significant peening stresses are generated during the impact of molten and semimolten particles on the substrate. While models exist for residual stress generation in plasma-based thermal spray processes, finite element (FE) prediction of residual stress generation for the HVOF process has not been possible due to the increased complexities associated with modeling the particle impact. A hybrid nonlinear explicit-implicit FE methodology is developed here to study the thermomechanical processes associated with particle impingement and layer deposition. Attention is focused on the prediction of residual stresses for an SS 316 HVOF sprayed coating on an SS 316 substrate.

Keywords: coatings, computer simulation, finite element method, high-velocity oxyfuel, metallic parts, residual stresses, semimolten particles, thermal spraying, velocity measurement, wear resistance

P. Bansal, P.H. Shipway, and S.B. Leen, School of Mechanical, Materials and Manufacturing Engineering, University of Nottingham, Nottingham, NG7 2RD, U.K. Cited: *Acta Mater.*, 2007, Sept, **55**(15), p 5089-5101 [in English]. ISSN 1359-6454.

Process Modeling

Dynamics of drop impact on a rectangular slot. Drop impact on substrates is of scientific importance and plays a central role in both microscale and large-scale applications, e.g., ink-jet printing and spray coating. For more than 100 years, researchers have studied situations where drops impact planar substrates, a beautiful free surface flow resulting in either drop deposition or splashing. By contrast, drop impact on nonplanar substrates, e.g., spheres, has become of interest only recently. Here, the impact of drops of several liquids with a slot of width comparable to the drop diameter that is dug into an otherwise planar substrate is studied experimentally as a function of impact velocity. Two different kinds of splashing arise in the new experiments: an internal splash similar to that observed on planar substrates and a new, external splash, where some of the drop liquid splashes out of the slot. Phase diagrams that delineate regimes of drop spreading and splashing are presented. Simple scaling arguments are also developed to rationalize the findings.

Keywords: drop liquid splashes, drops, ink, nonplanar substrates, phase diagrams, printing

H.J. Subramani, T. Al-Housseiny, A.U. Chen, M. Li, and O.A. Basaran, School of Chemical Engineering, Purdue University, West Lafayette, IN 47907. Cited: *Ind. Eng. Chem. Res.*, 2007, Sept 12, **46**(19), p 6105-6112 [in English]. ISSN 0888-5885.

Formation of pores in thermal spray coatings due to incomplete filling of crevices in patterned surfaces. Molten particles in a thermal spray land on a rough surface, coalesce with each other, and freeze to form a coating. Surface tension prevents liquid splats from completely filling crevices in the substrate, forming pores. An analytical model is developed to estimate the volume of such pores by calculating the equilibrium shape of a liquid meniscus pressing down on a surface asperity. Predictions from the model are compared with experimental results for the volume of voids formed under plasma sprayed yttria-stabilized zirconia (YSZ) particles (average diameter 18 μm) landing with an average velocity of 250 m/s on patterned silicon surfaces that had vertical posts on them. The model predicted, to within an order of magnitude, the volume of voids on a surface in which the posts were tall (3 μm high) and closely spaced (1 μm apart), where pores were principally formed by incomplete filling of gaps.

Keywords: filling, incomplete filling, parameter estimation, patterned surfaces, rough surface, surface tension, thermal spray coating, thermal spraying, void fraction, yttria-stabilized zirconia

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Numerical simulation on impact velocity of ceramic particles propelled by supersonic nitrogen gas flow in vacuum chamber. A low-pressure cold spray, which is conducted in a vacuum chamber, is under development in Japan. In this paper, the gas flow-field as well as the particle velocity of the low-pressure cold spray is numerically solved. A special attention is paid to the effect of the pressure in the vacuum chamber (back pressure) on the particle velocity. The working gas is nitrogen, and its stagnation temperature upstream of the nozzle is set at 573 K. The back pressure is set at constant values ranging from 3×10^2 to 1×10^5 Pa. The stagnation pressure upstream of the nozzle is kept constant at 30 times as much as the back pressure. The numerical results show that the decrease in the back pressure causes the decrease in the particle velocity in front of the normal shock wave. On the contrary, the decrease in the back pressure eases the particle deceleration through the normal shock wave. As a whole, due to the balance of the effects of the back pressure and the normal shock wave, the optimum value of the back pressure to obtain the maximum impact velocity varies depending on the particle diameter.

Keywords: ceramic materials, computer simulation, elementary particles, gas dynamics, low-density supersonic jets, nitrogen compounds, particle velocity, shock waves, vacuum chamber, velocity measurement

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Powder

Synthesis of thermal spray grade yttrium oxide powder and its application for plasma spray deposition. A process to transform the commercially available yttrium oxide powder (M/s. IRE) into thermal spray grade powder and development of plasma spray coating of it on graphite/metallic substrate are described. Experimental results show that the synthesized powder had very good flow characteristics and could be used for plasma spray deposition efficiently.

Keywords: coatings, corrosion, corrosion-resistant coating, deposition, plasma spray deposition, plasma spraying, spray grade ceramic powder, synthesis (chemical), yttrium oxide, yttrium oxide coating

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Properties

Adhesion

Grit blasting of Ti-6Al-4V alloy: Optimization and its effect on adhesion strength of plasma-sprayed hydroxyapatite coatings. The effect of grit-blasting parameters on the surface roughness of Ti-6Al-4V alloy as the substrate for plasma sprayed hydroxyapatite (HA) coatings was examined using the factorial and Taguchi designs of experiments. In this study, two grit materials (Al_2O_3 and SiO_2) each at two sizes, and two types of blasting systems (pressure and suction) were used. An equivalent surface roughness of 3.51 μm was obtained in three optimum conditions. The results of the Taguchi designed experiments were analyzed using signal-to-noise ratio. The tensile bonding strength of HA coatings deposited on the roughened substrates at the three different optimum conditions was measured by the standard adhesion test (ISO 13779-4). As the crystallinity of the coating at the interface, evaluated by the XRD analysis, reduced the bonding strength of the coatings was increased. These findings suggest that the substrate surface topography significantly influences the properties of the coating at the interface.

Keywords: blasting systems, bond strength (materials), grit blasting, hydroxyapatite, hydroxyapatite coatings, inorganic coatings, plasma spraying, surface roughness, Taguchi methods, titanium alloys, x-ray diffraction

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Corrosion

Corrosion resistance of thermally sprayed high-boron iron-base amorphous-metal coatings: $Fe_{49.7}Cr_{17.7}Mn_{1.9}Mo_{7.4}W_{1.6}B_{15.2}C_{3.8}S_{2.4}$. An iron-base amorphous metal, $Fe_{49.7}Cr_{17.7}Mn_{1.9}Mo_{7.4}W_{1.6}B_{15.2}C_{3.8}S_{2.4}$ (SAM2×5), with very good corrosion resistance has been developed. This material was

prepared as a melt-spun ribbon, as well as gas-atomized powder and a thermal spray coating. During electrochemical testing in several environments, including seawater at 90 °C, the passive film stability was found to be comparable to that of high-performance nickel-base alloys and superior to that of stainless steels, based on electrochemical measurements of the passive film breakdown potential and general corrosion rates. This material also performed very well in standard salt fog tests. Chromium (Cr), molybdenum (Mo), and tungsten (W) provided corrosion resistance, and boron (B) enabled glass formation. The high boron content of this particular amorphous metal made it an effective neutron absorber and suitable for criticality control applications. This material and its parent alloy maintained corrosion resistance up to the glass transition temperature and remained in the amorphous state during exposure to relatively high neutron doses.

Keywords: amorphous alloys, amorphous metal, breakdown potential, corrosion rate, corrosion resistance, electrochemistry, gas-atomized powder, glass transition, iron, temperature distribution, thermal spraying

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Investigations on role of plasma sprayed NiCrAlY and Ni-2oCr coatings to combat hot corrosion. Studies have been conducted to ascertain the role of plasma sprayed Ni-20Cr-10Al-1Y (NiCrAlY) and Ni-20Cr metallic coatings to combat hot corrosion of a Ni-base superalloy Superni 75 (Ni-3Fe-19.5Cr-0.3Ti-0.1C). The performance of the uncoated as well as coated superalloy has been evaluated in an aggressive environment of Na_2SO_4-60%V_2O_5 under cyclic conditions at an elevated temperature of 900 °C by the thermogravimetric technique for 50 cycles. X-ray diffraction (XRD), SEM/EDAX, and electroprobe microanalysis (EPMA) techniques were used to analyze the corrosion products. The uncoated superalloy suffered an accelerated oxidation in the form of spalling of its oxide scale, whereas NiCrAlY coated specimen showed marginal spalling toward the end of exposure. The Ni-20Cr coated superalloys did not suffer from spallation of its oxide scale. The Ni-20Cr coated specimen indicated a maximum weight gain among the cases studied, while NiCrAlY coated the least. Both the coatings were found to be useful in protecting the base superalloy against oxidation. Moreover, the coatings in general were successful in maintaining their continuous surface contact with the substrate superalloy during the whole tenure of cyclic exposure. The phases revealed for the oxidized coatings were mainly oxides of chromium/aluminum, and spinel containing nickel-chromium mixed oxides, which are reported to be protective against the hot corrosion.

Keywords: corrosion, hot corrosion, nickel alloys, plasma spray coatings, plasma spraying, protective coatings, scanning electron microscopy, superalloys, x-ray diffraction analysis

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Surface Finish

Surface roughness characterization of thermally sprayed and precision machined WC-Co and Alloy 625 coatings. Surface roughness characterization of thermally sprayed and precision machined WC-Co and Alloy-625 coatings was carried out. The objectives were to demonstrate that such difficult-to-machine coating surfaces could be machined with commercial machines and tools and to characterize the surface finish of the machined coatings. The coatings were obtained using two thermal spraying processes: arc spraying and high-velocity oxyfuel spraying. Different machining techniques were tried to optimize the surface finishing of the coatings based on surface finish and time required. Machined samples were then examined using stylus roughness testers. Surface roughness parameters R_a and R_q were measured using various cut-off lengths, sampling lengths, and numbers of sampling and cut-off lengths to characterize the scaling behavior of the surfaces. Diamond turning of WC-Co demonstrated the advantage of high material removal rates, and diamond grinding of WC-Co produced good surface finish with relatively high material removal rates. Precision-machined WC-Co and Alloy 625 surfaces could be identified as self-affine fractals in a statistical sense within the correlation length, i.e., within the length scales studied from 0.08 to 8 mm. The surface roughness heights of the machined surfaces were found to be dependent on the scale of cut-off length as a power law.

Keywords: cobalt alloys, commercial machines, cut-off length, diamond grinding, finishing, fractals, grinding (comminution), self-affine fractals, superalloys, surface roughness, turning

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