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Selected Abstracts of Thermal Spray Literature

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Applications

Automotive

Performance improvement of Al alloyed materials via plasma spray coating. *Purpose*: The aim of the research is to increase piston and engine performance by using ceramic coated pistons instead of pistons that are manufactured from aluminum alloys and having a coated flame chamber. *Design/methodology/approach*: Thermal torch and thermal shock tests were performed on the pistons, and some specimens of 1.5 mm thick were prepared according to ASTM standards; both have the same material characteristics. In the present work, plasma spray technique was used for ceramic coating. *Findings*: It was found that the ceramic coating, which, when performed properly, has compatible expansion coefficient with the aluminum alloy pistons, increasing performance of pistons and engines. *Research limitations/implications*: Coatings were limited with one type of bonding and two ceramics, and coated parts were subjected to thermal torch and thermal shock tests. *Practical implications*: For future work, instead of using other coating materials, stable yttria is used as the best coating material with optimum thermal resistance. By this process, working life of the machine parts can be extended and a number of economical advantages may also be obtained. *Originality/value*: This paper fulfills the identified information and offers practical help to the industrial firms working with ceramic coatings and also to the academicians working on wear of materials.

Keywords: aluminum alloys, ceramic coatings, flame chambers, heat resistance, pistons, plasma spraying, standards, thermal shock, thermal torches, wear resistance

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Short circuits cut down on friction. DaimlerChrysler's AMG subsidiary engineers have developed the new 6.3 L V8 engine, which comes in as the world's most powerful eight-cylinder engine. It has an output of 386 kW and 630 N · m of torque at the crankshaft, which is now used in various AMG models. It is composed of 32 valves, a cylinder bore of 102.2 mm, and a stroke of 94.6 mm. The electric arc wire spraying (EAS) is being used as the thermal coating to create a thin layer by spraying iron in the interior walls of the cylinder, which replaces the liners to bring in a robust cylinder-bore running surfaces. EAS coatings provide good tribological properties that reduces friction and wear while also improving fuel economy. EAS coatings also effectively transfers heat in the combustion chamber to provide efficient cooling of pistons and piston rings. These coatings are made up of nanolayers that can withstand higher pressure compared with other EAS coatings.

Keywords: crankshafts, electric arc wire spraying, engine pistons, friction, thermal spraying, torque, tribology, wear of materials

Cited: *Adv. Mater. Process.*, 2007, Feb, **165**(2), p 43-45 [in English]. ISSN 0882-7958.

Biomaterials and Bioactive Materials

Clinical applications of titanium dental implants coated with glass-reinforced hydroxyapatite composite (Bonelike). Commercially pure titanium dental implants were coated with glass-reinforced hydroxyapatite composites (Bonelike) using the plasma spraying technique. A total of 27 Bonelike coated 3.75 mm diameter and 10 mm length implants were placed in the maxilla and mandible of seven patients. Pre- and postoperative radiological examination was performed by orthopantomogram according to the standard follow-up protocols. After a 3 month healing period, one patient's implant from the mandible was surgically removed due to bad positioning and was then assessed by light and scanning electron microscopy for histological analysis. The reported Bonelike coated dental implants proved to be highly bioactive with extensive new bone formation and attachment.

Keywords: bioactivity, bone regeneration, dental prostheses, glass reinforced hydroxyapatite composites, histology, hydroxyapatite, orthopantomogram, plasma spraying, radiology, titanium

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Correlation of in vitro and in vivo results of vacuum plasma sprayed titanium implants with different surface topography. Research has proven that rough surfaces improve both biologic and biomechanical responses to titanium (Ti) implants. The purpose of this study was to evaluate the correlation between the expression of bone cell-associated proteins to vacuum plasma sprayed titanium implants (VPS-Ti) with different surface textures in vitro and the bone integration in vivo. The biological performances of the surfaces were evaluated over a period of 8 weeks using human bone marrow cell cultures and Gottinger mini pigs. Cells were cultured on VPS-Ti with two respectively different surface roughnesses (Ra). The level of osteoprotegerin (OPG), osteocalcin (OC), and alkaline phosphatase activity (ALP) were evaluated. The bone integration in vivo was evaluated by histomorphological analyses. A cancellous structured titanium (CS-Ti) construct was used as reference material in both study designs. Comparison of data was conducted using the Scheffe tests and the paired *t*-test with Bonferroni's correction. A comparative analysis was done to measure the degree of association between the in vitro and in vivo data. A total amount of OC was significantly increased for VPS-Ti for cells cultured on both VPS-Ti and CS-Ti, while OPG was only detectable after 8 weeks without any significant differences. The ALP activity on all surfaces was not statistically increased. For VPS-Ti with Ra ranging from 0.025 up to 0.059 mm, bone integration response was increased, but there was no statistical difference between the VPS-Ti. Expression of OPG, OC and ALP correlated with the histomorphological data over the 8-week period. The in vitro data suggest the superiority of VPS-Ti over CS-Ti, but more importantly, the biocompatibility of testing an in vitro model to predict the outcome and possible integration of implants in vivo.

Keywords: animal cell culture, biomechanics, bone, bone integration, implants (surgical), osteoprotegerin, proteins, surface roughness, surface textures, titanium dioxide, vacuum plasma sprayed titanium implants

S. Endres, M. Wilke, P. Knoll, H. Frank, M. Kratz, and A. Wilke, Department of Orthopaedic Surgery, Elisabeth-Klinik GmbH Bigge/Olsberg, 59939 Olsberg, Germany. Cited: *J. Mater. Sci.: Mater. Med.*, 2008; March, **19**(3), p 1117-1125 [in English]. ISSN 0957-4530.

The influence of residual stress on the shear strength between the bone and plasma sprayed hydroxyapatite coating. Plasma sprayed hydroxyapatite coating (HAC) 50 and 200 μm thick on Ti6Al4V cylinders was transcortically implanted in the femora of canines. Push-out testing of implant/bone interfaces showed that the HAC coating exhibited higher shear strength at with a 50 μm coating than with a 200 μm coating. The plasma sprayed HACs were exhibited compressive residual stresses, and the thicker HAC exhibited higher residual stress than that of the thinner HAC. Due to the structure for 50 and 200 μm implants were the same, meaning similar cohesive strength of the lamellar splats. Also, there was no difference in the physiological environment; hence the difference of the shear strength for the 50 and 200 μm HAC implants could best be attributed to the compressive residual stress that existed in the HA coating.

Keywords: bone, cohesive strength, hydroxyapatite, hydroxyapatite coating, lamellar splats, plasma spraying, residual stresses, shear strength

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Corrosion Protection

Thermal spray coatings protect steel structures from corrosion. Currently, thermal sprays are commonly used to protect steel structures from corrosion. The Metal Spray Suppliers Ltd., Metallisation Ltd.'s New Zealand distributor, has been supplying equipment and supplies to Edmonds Industrial Coatings Ltd. of Wanganui for applying a coating system for airport air bridges in New Zealand. The Metallisation Arc 170 push/pull system has been selected by Edmonds to provide the required spray rates, as well as the important reach for convenient positioning. It is fast and provides a high deposition rate and efficiency. Using this system, the processing time for all anticorrosion surface treatments has been cut by half to 2 days, and eliminated time-consuming manual sanding. Edmonds can complete the anticorrosion treatment of the air bridges in one process. Meanwhile, Resene Paints has developed and specified the post zinc arc spray paint system. The smoothness of the zinc coating eliminated the need for any prepaint preparation. By using this system, it can save time, labor and expense.

Keywords: airport air bridges, corrosion, deposition, protective coatings, steel structures, surface treatment, thermal spraying, zinc, zinc arc spray paint system

Cited: *Adv. Mater. Process.*, 2007, Nov, **165**(11), p 114-115 [in English]. ISSN 0882-7958.

Thermal spray coating provides saltwater corrosion protection. Metallisation Ltd. has been providing equipment for surface coating. The thermal spray coating provides protection and life extension to a wide variety of products in the most hostile environments and in situations where coatings are vital for safety and performance. Malmor in Gdansk, Poland, focusing initially on ships and ship repairs has also diversified into other industries such as food, agriculture, and energy. The company has applied aluminum-zinc (Al-Zn) metal spray coatings to various parts of the vessels using Metallization Arc 140 spray equipment. The metal spray is more durable than paint and independent European standards. The Arc 140 system offered flexibility, ease of use, and reliability. The company also uses metallization equipment and processes in protecting tanks, steel constructions, and artistic blacksmith items.

Keywords: aluminum alloys, corrosion protection, metallizing, reliability, saltwater corrosion protection, sprayed coatings, thermal spray coating, thermal spraying

Cited: *Adv. Mater. Process.*, 2008, Feb, **166**(2), p 68 [in English]. ISSN 0882-7958.

Energy

Influence of the surface roughness of plasma sprayed YSZ on LSM cathode polarization in solid oxide fuel cells. Under solid oxide fuel cells (SOFCs) operating condition, the cathode reaction rate is determined by triple phase boundary (TPB) areas, which are associated with the geometry of the interface between the cathode and the electrolyte. In this paper, yttria-stabilized zirconia (YSZ) electrolyte was deposited by atmospheric plasma spraying (APS). A nanoscaled lanthanum strontium manganate (LSM) cathode was prepared by sol-gel process on APS YSZ with different surface roughness to aim at increasing the TPB. The polarization curves of LSM cathode were characterized by potentiostat. The influence of the roughness of APS YSZ on the polarization of LSM cathode was investigated. It was found that the overpotential of the LSM cathode is significantly reduced with the increase of YSZ surface roughness.

Keywords: atmospheric plasma spraying, lanthanum compounds, lanthanum strontium manganate, phase boundaries, plasma spraying, polarization, solid oxide fuel cells, surface roughness, triple phase boundary, yttria-stabilized zirconia

M. Gao, C.-X. Li, M.-D. Wang, H.-L. Wang, and C.-J. Li, State Key Laboratory for Mechanical Behavior of Materials, School of Materials Science and Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China. Cited: *Key Eng. Mater.*, **373-374**, p 641-644 [in English]. ISSN 1013-9826.

Plasma spray coated rare-earth oxides on molybdenum disilicide—High-temperature stable emitters for thermophotovoltaics. Selective emitters for thermophotovoltaics consisting of intermetallic alloy $MoSi_2$ substrate with plasma spray coated rare-earth oxides ytterbium oxide Yb_2O_3, Yb-doped garnet $Yb_{1.5}Y_{1.5}Al_5O_{12}$, and erbium oxide Er_2O_3 have been successfully tested till 1650 °C. The emitters are fully operable in an oxygen-containing atmosphere, are highly thermal shock stable, and show good selective emitting properties. Shielding the high out-of-band emittance of the $MoSi_2$ substrate with a 4 μm thick Pt intermediate layer has resulted in reduced radiation power and emittance of the rare-earth oxide film due to multiple reflections at the interfaces. The novel technique of vacuum plasma spray coated rare-earth oxide films on $MoSi_2$ is a promising way for the production of effective and high-temperature stable selective thermophotovoltaic emitters.

Keywords: coated materials, high-temperature effects, photovoltaic cells, plasma spray coating, plasma spraying, selective emitter, thermal shock, thermophotovoltaics

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Plasma spray synthesis of $La_{10}(SiO_4)_6O_3$ as a new electrolyte for intermediate temperature solid oxide fuel cells. The apatite-type lanthanum silicate films were successfully synthesized by modified atmosphere plasma spraying using lanthanum oxide and silicon oxide mixed powders and precalcined hypereutectic powders in the size range 1-3 μm and 5-8 μm, respectively, as starting feedstock materials. The films differed not only in microstructural scale, but also in the characteristic of the degree of film densification. A detail describing the evolution of microstructure has been discussed. A considerable improvement in densification of the $La_{10}(SiO_4)_6O_3$ electrolyte films has been observed.

Keywords: electrolytes, feedstocks, film densification, hypereutectic powders, lanthanum compounds, plasma spraying, silicates, solid oxide fuel cells

W. Gao, H.-L. Liao, and C. Coddet, LERMPS, University of Technology of Belfort-Montbeliard, Belfort, 90010, France. Cited: *J. Power Sources*, 2008, May 1, **179**(2), p 739-744 [in English]. ISSN 0378-7753.

Study on the plasma sprayed molybdenum as plasma facing materials in fusion reactor. Molybdenum has many prominent properties, such as high melting point, good thermal properties, low erosion rate, and so on, which make it a promising candidate material for plasma facing materials in the next fusion reactor. In the present work, molybdenum coatings were deposited onto the oxygen-free copper substrates by atmospheric plasma spraying. Different interlayers were introduced between the coatings and substrates. SEM, EDS, and XRD were used to investigate the photographs and compositions of these coatings. The bonding strength of the coatings was tested to investigate the effect of interlayers on adhesion of the coatings at room temperature, and it was found that the coating without interlayers showed the highest bonding strength. Water quenching was used to evaluate the adhesion of the coatings under thermal cycling conditions, and the results showed that the molybdenum coating with two interlayers possessed of the highest resistance of thermal cycling wrack.

Keywords: adhesion, interlayers, molybdenum, plasma facing materials, plasma spray, plasma spraying, scanning electron microscopy, x-ray diffraction

W.Z. Yao, S.X. Song, Z.J. Zhou, W.W. Cong, Y. Ma, and C.C. Ge, Laboratory of Special Ceramics and Powder Metallurgy, University of Science and Technology Beijing, Beijing 100083, China. Cited: *Key Eng. Mater.*, **373-374,** p 81-84 [in English]. ISSN 1013-9826.

Thermal spraying provides corrosion protection to wind turbines. Descon Quimica has delivered a metal spraying system for wind turbine components to Granallados Molinero S.L. Descon has been chosen to supply automated metal spraying equipment. Throughout Spain, Descon has been supplying metal spraying equipment and materials that are used for the protection of wind turbine parts. The company provides anticorrosion protection for diverse industries. They use the spray equipment to spray components within the assembly that supports the turbine blades. Descon's products are found to be adaptable, flexible, and easy to use, which brought ease to Molinero in making the transition to metal spraying. Automating the spraying process brought many advantages within the process. Meanwhile, its arc spray process melts the raw material with an electric arc, which also promotes some major advantages.

Keywords: anticorrosion protection, corrosion protection, metal spraying, metal spraying equipment, thermal spraying, turbine blades, turbomachine blades, wind turbine parts, wind turbines

Cited: *Adv. Mater. Process.*, 2007, Aug, **165**(8), p 80 [in English]. ISSN 0882-7958.

Sensors and Electronic Materials

Gas sensing properties of nano SnO_2 based thick films prepared by dip coating method with effect of molarity of $PtCl_2$ solution. Synthesized nanophase SnO_2 powder was used as a functional material along with optimized 15 wt.% of glass, fired at 550 °C for better adhesion, to fabricate thick films using screen printing on alumina substrate. Their surface was modified by dip coating in platinum chloride solution ($PtCl_2$) of different molarities (0.05-0.2 M). A subsequent thermal treatment to these thick films was carried out at an optimized temperature of 750 °C in air atmosphere. The films were tested for 400 ppm concentration of H_2, CO and LPG. Sensors dip coated with 0.15 M solution of $PtCl_2$ show the highest sensitivity toward the test gases, which is 10 times higher than undoped SnO_2 sensors. XRD, EDX, and SEM measurements showed that the behavior could be associated with the spatial distribution of the platinum within the tin oxide film. The sensors have fast response time of 10 s to all the three gases with a minimum detection limit of 10 ppm.

Keywords: alumina, dip coating method, gas sensing electrodes, heat treatment, molarities, nanostructured materials, screen printing, substrates, thick films, tin dioxide

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Production and properties of a spray formed 70%Si-Al alloy for electronic packaging applications. The high silicon content Si-Al alloy is a typical heat-dissipation material that used in the electrical packaging field. A spray forming process is used to produce a 70%Si-Al alloy specimen as a heat-dissipation material with a diameter of 76.2 mm (3 in.) and a thickness of 6 mm. Then the spray formed Si-Al alloy specimens are hot pressed at 570 °C with different pressure ranged from 200 to 700 MPa to increase their density. The physical properties of the experimental alloy specimen are measured. Also, the microstructures are observed by using optical microscopy and scanning electronic microscopy. The results show that spray forming is suitable to produce a 70%Si-Al alloy. The size of primary Si phase in the spray formed 70%Si-Al alloy is refined only 20-30 μm. The relative density of 70%Si-Al alloy after spray forming is about 90%. With a following hot pressure of

700 MPa, the relative density value can obtain 98%. The typical physical properties such as the thermal conductivity, coefficient of thermal expansion and electrical conductivity of spray formed 70%Si-Al alloy are acceptable as a heat dissipation material for many electronic packaging applications.

Keywords: electric conductivity, electronics packaging, heat losses, hot pressing, relative density, silicon alloys, spray forming, thermal conductivity, thermal expansion

Y. Kun, L. Chao, W. Richu, and Y. Jun, School of Materials Science and Engineering, Central South University, Changsha 410083, China. Cited: *Mater. Trans*., 2008, March, **49**(3), p 685-687 [in English]. ISSN 1345-9678.

Wafer-level flame spray pyrolysis deposition of gas-sensitive layers on microsensors. This paper presents a CMOS-compatible wafer-level fabrication process for monolithic CMOS/MEMS sensor systems coated with sensitive layers directly deposited by means of flame spray pyrolysis (FSP). Micro hotplate (νHP)-based devices, featuring an FSP directly deposited SnO_2/Pt layer, have successfully been realized on a wafer level. The thermal characterization evidenced a thermal resistance of 10.6 °C/mW; moreover, gas test measurements with ethanol have been performed. Micro hotplate membrane deformations during device operation have been investigated and have been reduced by adjustment of the intrinsic stress of a deposited silicon nitride layer.

Keywords: CMOS integrated circuits, flame research, FSP directly, heat resistance, micro hotplate, microsensors, pyrolysis, thermal characterization

S. Kuhne, M. Graf, A. Tricoli, F. Mayer, S.E. Pratsinis, and A. Hierlemann, Micro and Nanosystems, ETH Zurich, CH-8092 Zurich, Switzerland. Cited: *J. Micromech. Microeng*., 2008, March 1, **18**(3), p [in English]. ISSN 0960-1317.

Thermal Barrier Coatings

Degradation of thermal barrier coated superalloy component during service. The time-dependent degradation of first-stage vanes for gas turbines was investigated. The specimens were prepared from the operating facilities in the Ulsan combined-cycle plant. A microstructural investigation of the thermal barrier coatings (TBCs) showed that spallation was occurring at inner root area of vanes during operation. Microstructural comparison of coating surfaces showed that exposure to the environment increased the thickness of thermally grown oxide (TGO) and that the β-depletion region also increased with operation time. After spallation of the top coat, mechanical thinning, and the development of fine grains by recrystallization at the bond coat also occurred. The substrates of welded and normal regions were compared and showed that the difference in aluminum diffusion rate and crack density resulted from chemical and mechanical differences in the two areas.

Keywords: aluminum diffusion rate, crack density, cracks, degradation, gas turbines, mechanical thinning, metallographic microstructure, microstructural investigation, spallation, superalloys, thermal barrier coatings, thermally grown oxide

H.-S. Lee, K.-B. Yoo, E.-H. Kim, S.C. Kim, and S. Ryou, Power Generation Lab, Korea Electric Power Research Institute, Daejeon 305-308, South Korea. Cited: *J. Fail. Analysis Prevent*., 2007, August, **7**(4), p 250-254 [in English]. ISSN 1547-7029.

Erosion, corrosion and erosion-corrosion of EB PVD thermal barrier coatings. Electron beam (EB) physical vapor deposited (PVD) thermal barrier coatings (TBCs) have been used in gas turbine engines for a number of years. The primary mode of failure is attributed to oxidation of the bond coat and growth of the thermally grown oxide (TGO), the alumina scale that forms on the bond coat and to which the ceramic top coat adheres. Once the TGO reaches a critical thickness, the TBC tends to spall and expose the underlying substrate to the hot gases. Erosion is commonly accepted as a secondary failure mechanism, which thins the TBC, thus reducing its insulation capability and increasing the TGO growth rate. In severe conditions, erosion can completely remove the TBC over time, again resulting in the exposure of the substrate, typically Ni-based superalloys. Since engine efficiency is related to turbine entry temperature (TET), there is a constant driving force to increase this temperature. With this drive for higher TETs comes corrosion problems for the yttria-stabilized zirconia (YSZ) ceramic topcoat. YSZ is susceptible to attack from molten calcium-magnesium-alumina-silicates (CMAS), which degrades the YSZ both chemically and microstructurally. CMAS has a melting point of around 1240 °C, and since it is common in atmospheric dust it is easily deposited onto gas turbine blades. If the CMAS then melts and penetrates into the ceramic, the life of the TBC can be significantly reduced. This paper discusses the various failure mechanisms associated with the erosion, corrosion, and erosion-corrosion of EB PVD TBCs. The concept of a dimensionless ratio D/d, where D is the contact footprint diameter and d is the column diameter, as a means of determining the erosion mechanism is introduced and discussed for EB PVD TBCs.

Keywords: ceramic coatings, column diameter, erosion, failure (mechanical), gas turbine engines, gas turbines, insulation, physical vapor deposition, thermal barrier coatings, thermally grown oxide

R.G. Wellman and J.R. Nicholls, School of Industrial and Manufacturing Science, Cranfield University, Bedford, MK 43 OAL, UK. Cited: *Tribol. Int*., 2008, July, **41**(7), p 657-662 [in English]. ISSN 0301-679X.

Failure of the plasma sprayed coating of lanthanum hexaluminate. Lanthanum magnesium hexaluminate ($LaMgAl_{11}O_{19}$, LMA) is an attractive material for thermal barrier coatings (TBCs), and the failure of its coating was studied in this work by thermal cycling, x-ray diffraction, dilatometric measurement, and thermal gravimetric differential thermal analysis. The dilatometric measurement indicates that even though the bulk material of LMA has a higher sintering resistance than the typical TBC material, i.e. yttria-stabilized zirconia (YSZ), the plasma sprayed coating of LMA has two serious contractions due to the recrystallization of LMA and phase transitions of alumina. LMA has similar thermal expansion behavior with alumina, leading to a good thermal expansion match between LMA and the thermally grown oxide layer. On the other hand, the platelike structure of LMA not only results in a low thermal conductivity and low Young's modulus, but also a high stress tolerance, and these are believed to be the reasons for the long thermal cycling life of LMA coating.

Keywords: elastic moduli, failure analysis, lanthanum alloys, lanthanum magnesium hexaluminate, phase transitions, plasma sprayed coating, plasma spraying, recrystallization (metallurgy), sprayed coatings, stresses, thermal barrier coatings, thermal conductivity, thermal cycling, thermal expansion, thermally grown oxide layer

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Influence of coatings on thermal characteristics and optimum sizes of fins. The influence of coatings on thermal characteristics of the fins having various shape (longitudinal and circular fins, cylindrical pins) has been investigated. Heat transfer in the simplified and two-dimensional statements of the problem is considered, and analytical solutions for the temperature distributions and thermal efficiency of the fins with coatings are obtained. The simplified and two-dimensional solutions for the composite fins are compared, and the errors that can appear in a simplified heat transfer model are obtained. The contribution of the top surface to the total heat flux from a composite fin is determined. The condition of the "advantage" for a composite fin is found. The optimum sizes of the longitudinal fins with uniform and nonuniform coatings are determined. It is shown that the optimum sizes of the fins with polluting or protective coating depend on the Biot number of the coating and can considerably differ from the optimum sizes of "clean" fins. The influence of nonuniform pollution on thermal efficiency and optimum sizes of the longitudinal fins is studied. The correction factors for fin efficiency and optimum fin sizes that take into account the nonuniformity of pollution have been calculated.

Keywords: coatings, cylindrical pins, fins (heat exchange), heat transfer, longitudinal and circular fins, problem solving, temperature distribution

V. Gorobets, Institute of Engineering Thermophysics, National Academy of Sciences of Ukraine, 03057, Kiev, Ukraine. Cited: *J. Enhanced Heat Transfer*, 2008, **15**(1), p 65-80 [in English]. ISSN 1065-5131.

A promising $LaSmZr_2O_7$ ceramic with pyrochlore structure for thermal barrier coatings. Based on $La_2Zr_2O_7$ ceramic for thermal barrier coatings, $LaSmZr_2O_7$ ceramic doped with samarium ion was successfully prepared using solid-state reaction method. The pellets were sintered at 1600 °C for 10 h in air. The phase structure, thermal conductivity, and thermal expansion coefficient of $LaSmZr_2O_7$ ceramic and $La_2Zr_2O_7$ ceramic were measured by XRD, laser-flash device, high-temperature dilatometry, respectively. The results show that the crystal structure of $LaSmZr_2O_7$ ceramic is not affected by the doped samarium ion in the zirconium lattice. The thermophysical results show that the thermal conductivity of the $LaSmZr_2O_7$ ceramic is lower than that of $La_2Zr_2O_7$ ceramic, while the thermal expansion coefficient is higher than that of $La_2Zr_2O_7$ ceramic, These results indicate that $LaSmZr_2O_7$ ceramic or $Ln_2Zr_2O_7$ ceramics doped with other rare earth ions could be candidate materials for future thermal barrier coatings.

Keywords: ceramic coatings, crystal structure, high-temperature dilatometry, lanthanum compounds, phase structure, samarium, samarium ions, solid-state reactions, thermal barrier coatings, thermal conductivity, thermal expansion, zirconium lattice

Q. Xu, W. Pan, C. Wan, L. Qi, H. Miao, and F. Wang, School of Materials Science and Engineering, Beijing Institute of Technology, Beijing 100081, China. Cited: *Key Eng. Mater*., **368-372**, Part 2, p 1328-1330 [in English]. ISSN 1013-9826.

Thermal barrier coatings: The basics. Thermal barrier coatings (TBCs) are widely used in gas turbine application because of its versatility. Typically, it consists of a top coat of Y_2O_3 air plasma sprayed partially stabilized ZrO_2 and a MCrAlY bond coat. The MCrAlY can be deposited using different thermal spray processes such as air plasma spray (APS), vacuum plasma spray (VPS), and high-velocity oxyfuel (HVOF). The HVOF coating demonstrate an acceptably low porosity level caused by high impact conditions during impingement, and it is less expensive compared to VPS process. Overall, TBCs exhibit good behavior regarding to thermal cycling tests and produce a high-performance coating with low sensitivity to variations in the process parameters.

Keywords: gas turbines, high-performance coating, high-velocity oxyfuel, plasma spraying, porosity, sensitivity analysis, thermal barrier coatings, vacuum plasma spray, zirconia

A. Scrivani and G. Rizzi, Turbocoating S.p.A, Parma, Italy. Cited: *Adv. Mater. Process.*, 2007, Nov, **165**(11), p 111-113 [in English]. ISSN 0882-7958.

Thermal failure of thermal barrier coating with thermal sprayed bond coating on titanium alloy. A thermal spray technology high-velocity oxygen fuel (HVOF) was used to deposit NiCoCrAlY as a bond coating between the titanium alloy substrate and top 8 wt.% yttria-stabilized zirconia thermal barrier coating (TBC) deposited by electron beam physical vapor deposition (EB-PVD). The thermal cycling and isothermal exposure tests were conducted to evaluate the durability of the TBC. Investigations using OM, SEM, EPMA, and XRD revealed that the thermal sprayed BC makes the TBC more durable in isothermal exposure tests, but more short-lived in thermal cycling tests, in comparison to our previous study in which the BC was prepared by EB-PVD. This is because the thermal sprayed imperfections, such as microcracks and voids, elevate the diffusion resistance and degrade the mechanical properties of the BC, simultaneously. To current TBC systems in which the BC is deposited by HVOF, thermal failure behaviors—such as the formation of the Ti/Al mixture oxides at some individual places in the BC, and the Ti_2Ni gaps formed around the BC/substrate interface—were also discussed.

Keywords: high-velocity oxygen fuel, isothermal exposure, scanning electron microscopy, thermal barrier coatings, thermal cycling, thermal failure, thermal spraying, titanium alloys, x-ray diffraction

B. He, F. Li, H. Zhou, Y. Dai, and B. Sun, State Key Laboratory of Metal Matrix Composites, School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China. Cited: *J. Coat. Technol. Res.*, 2008, Feb, **5**(1), p 99-106 [in English]. ISSN 1547-0091.

Diagnostics and Control

Controlling the properties of detonation-sprayed coatings: Major aspects. A system approach to controlling the quality of detonation-sprayed coatings is developed. It includes such stages as selecting powder characteristics and gas composition, forming a gas-powder mixture, adjusting the parameters of two-phase pulse flow, and ensuring contact interaction needed to form the coating that depends on the material and preset service properties of the layer sprayed.

Keywords: detonation, detonation-sprayed coatings, gas composition, gas-powder mixture, particle interactions, particle velocity, sprayed coatings, temperature measurement, two-phase flow, velocity control

E.A. Astakhov, Electric Welding Institute, National Academy of Sciences of Ukraine, Ukraine. Cited: *Powder Metall. Met. Ceram.*, 2008, Jan, **47**(1-2), p 70-79 [in English]. ISSN 1068-1302.

Development of precision spray forming for rapid tooling. The aim of the work is to improve the capability of the precision spray forming (PSF) rapid tooling process so that it can be extended to various applications. This work comprises the upgrading of the current spray forming machine from single atomizer to twin atomizers, so that the capability is much improved in terms of insert size and complexity. As a result, the insert size is increased from about 200-400 mm in diameter, and the process is more reliable to make complex structures. Know-how is accumulated for making large and/or complex inserts with controllable surface and internal soundness. A process of spray forming conformal cooling channels in die inserts or other components used at elevated temperatures is also developed, and various mold inserts are spray formed. In this paper, the plant modification is described. It is shown that the twin atomizers are more reliable in spray forming small inserts of about 200 mm in diameter and of high complexity than the single atomizer system. Spray forming of disc type inserts up to 400 mm diameter is demonstrated. Influence of deposition temperature and substrate moving speed, as well as the treatment of the ceramic mold surface is determined, and the technical measures to prevent surface defects related to large insert spray forming are specified.

Keywords: die casting inserts, forming, precision spray forming, rapid tooling, surface defects, temperature distribution, tool steel

Y. Yang and S.-P. Hannula, VTT Technical Research Centre of Finland, FI-02044 VTT, Finland. Cited: *Mater. Sci. Eng. A*, 2008, March 25, **477**(1-2), p 63-68 [in English]. ISSN 0921-5093.

Particle in-flight behavior and its influence on the microstructure and mechanical properties of plasma sprayed Al_2O_3 coatings. This paper aims to elaborate the particle characteristics during their flight into the spray and its significance in determining the microstructure and mechanical properties of resultant coatings. Study of plasma spraying of Al_2O_3 using three different grain fractions of feedstock was done by an online monitoring system (SprayWatch 2i). The as-sprayed coatings were characterized in terms of the microstructure and composition, microhardness, adhesion strength, and porosity. In addition, a statistic study of Weibull analysis was employed to further examine the microstructural homogeneity of coatings. It was found that particle in-flight behaviors are strongly influenced by feedstock particle size. Improved particle velocity and temperature as well as melting extent can be obtained for the finer feedstock. This contributes to produce increasingly bonded splats, resulting in coating with compact microstructure, where low porosity and increased microhardness and adhesion strength were realized.

Keywords: alumina, bond strength (materials), ceramic coatings, crystal microstructure, grain fraction, microhardness, particle in-flight behavior, particle size, plasma spraying, porosity, structure (composition), temperature distribution, velocity, Weibull distribution

Z. Yin, S. Tao, X. Zhou, and C. Ding, The Key Laboratory of Inorganic Coating Materials, Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai, 200050, China. Cited: *J. Eur. Ceram. Soc.*, 2008, **28**(6), p 1143-1148 [in English]. ISSN 0955-2219.

Measurement Methods

Bonding adhesive strength for plasma spray with cathode spots of low-pressure arc after grit blasting and removal of oxide layer on metal surface. Cathode spots of a low-pressure arc can remove oxide layers and evaporate impurities on metal surfaces. Removal of the oxide layer using cathode spots is expected to solve recent obstacles due to chemical and mechanical cleaning methods. Various phenomena of cathode spots have been investigated for pretreatment of atmospheric pressure plasma spray (APPS). This study treated the surface shapes of oxide and nonoxide samples using a composite pretreating method: cathode spots after grit blasting. In addition, the samples are compared with conventionally treated cathode spots and mechanical blasted surfaces. Results show that roughness on the sample surfaces becomes higher in concomitance with the initial oxide layer thickness. This fact reveals the factors those dominant bonding strength on the pretreated surface using cathode spots of a low-pressure arc. Bonding strength becomes higher in relation to the arithmetical mean height of the surface roughness caused by the initial oxide layer thickness. Bonding strength is higher when the mean spacing of profile irregularities is narrower. The bonding adhesive strength after treatment using cathode spots after grit blasting is greater than 90 MPa. However, cathode spot treatment must be limited not to destroy the projection formed by melting after grit blasting in an arc time up to 5 s. Also, basically the removal characteristics of oxide layer using the cathode spots were discussed on the trace, roughness, number of cathode spots in time and pressure, moving speed on the metal surface.

Keywords: adhesive strength, adhesives, atmospheric pressure, blasting, bond strength (chemical), cathode spot, cathodes, grit blasting, low-pressure arc, plasma spraying, surface roughness, thickness measurement

M. Hara, S. Yamakawa, M. Saito, S. Tobe, and T. Inaba, Chuo University, Tokyo, 112-8551, Japan. Cited: *Prog. Organic Coat.*, 2008, Feb, **61**(2-4), p 205-210 [in English]. ISSN 0300-9440.

An FIB study of sharp indentation testing on plasma sprayed TiO_2. Instrumented sharp indentation is often employed for micromechanical investigation of thermal spray coatings. However, rather complex dependencies of measured values on indentation load have been reported. To verify the possible influence of subsurface cracking, Vickers and Berkovich indentations on plasma spray TiO_2 were sectioned by FIB. Remarkable subsurface cracking was found for indentations performed on the coating cross section, even for rather low loads (1 N). Much less subsurface cracking occurs when indenting the top surface, indicating material anisotropy. This preliminary investigation highlights the need for thorough studies of subsurface cracking during instrumented sharp indentation.

Keywords: ceramic materials, coatings, focused ion beams, indentation, indentation load, indentation testing, material anisotropy, plasma spraying, titanium oxides

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In-line inspection with high-resolution EMAT technology: Crack detection and coating disbondment. The various and complex cracking processes that can occur on a pipeline have made accurate and reliable crack detection a great challenge. Different conditions give rise to different cracking mechanisms, which result in different crack types. In many cases, coating disbondment occurs as a precursor to cracking, as with stress-corrosion cracking (SCC). The associated challenges for a pipeline operator in the complex and dynamic oil and gas industry are continuous and require thorough, short- and long-term solutions. An in-line inspection tool for the detection of cracks, in particular SCC, and coating disbondment has been developed. The system is equipped with electromagnetic acoustic transducers, following a high-resolution approach. After successfully testing this 16-in. EMAT crack detection ($RoCD^2$) tool thoroughly in sample pipes containing real SCC and various types of artificial defect, the first operational runs—one in a gas

pipeline and another one in an oil pipeline—were performed that proved the performance of the approach under operational conditions. This article introduces parts of the data evaluation process and presents results obtained from these two field tests.

Keywords: crack detection, cracking (chemical), data evaluation, gas pipelines, stress-corrosion cracking

H. Al-Qahtani, T. Beuker, and J. Damaschke, Saudi Aramco Pipelines Department, Dhahran, Saudi Arabia. Cited: *Global Pipeline Monthly*, 2008, March, **4**(3) [in English].

Nondestructive testing of open microscopic cracks in plasma sprayed coatings using ultrasound excited vibrothermography. While other nondestructive testing methods hardly reveal microscopic open cracks, vibrothermography stimulated by ultrasound provides very promising results by converting mechanical waves into local heat by friction. This phenomenon enhances thermal gradients in temperature maps as compared to conventional techniques. To detect temperature gradients caused by hidden cracks, high thermal and spatial resolution infrared cameras are usually used. The aim of this work is to investigate the ability of the vibrothermography stimulated by ultrasound to detect such cracks and measure the gap between adjacent cracks. To do so, we investigated tungsten carbide coatings where cracks were artificially generated using a controlled bending test. Several samples were investigated during this study, but only typical results from one sample are presented and discussed.

Keywords: carbide coatings, crack detection, infrared devices, microscopic open cracks, sampling, spatial resolution, sprayed coatings, thermal gradients, ultrasonic testing, ultrasound excited vibrothermography

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A novel technique for viewing stress distribution with mechanoluminescence materials. We have successfully demonstrated that the stress distribution of a metal substrate can be directly displayed by coating $SrAl_2O_4$:Eu (SAO), a representative of strong mechanoluminescent materials, on the surface of test objects. An aluminum plate with SAO sensing film had been applied to experimental analysis of stress concentrations, and a numerical calculation via a finite element method confirmed that the observed real time mechanoluminescence images displayed the stress distribution. As a result, visualization of stress distribution on metal surface has been realized by ML images using SAO sensing film, and this novel visualization technique can be applied for viewing the stress concentration in various fields such as modeling, manufacturing, and demonstration of an industrial product.

Keywords: aluminum, chemical sensors, finite element method, image analysis, mechanoluminescence images, sensing films, stress concentration, strontium compounds, triboluminescence

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Microstructure

Microstructure and properties of TiB_2-containing coatings prepared by arc spraying. Low-cost arc spraying and cored wires were used to deposit composite coatings consisting of TiB_2 and TiB_2/Al_2O_3 hard particles in a Ni(Cr) and stainless steel 304L matrix. Four coatings were prepared namely Ni(Cr)-TiB_2, Ni(Cr)-TiB_2/Al_2O_3, 304L-TiB_2, and 304L-TiB_2/Al_2O_3. The microstructural characteristics of powders and coatings were observed by scanning electron microscopy (SEM). Phase compositions of powders were analyzed by x-ray diffraction (XRD). Although all the analyzed coatings exhibited similar lamella structure, remarkable differences not only in the morphology of hard phase and matrix but also in the size and distribution of hard phases were observed from one coating to another. Tribological behavior of the coatings was analyzed in room-temperature dry sliding wear tests (block-on-ring configuration), under 75 N at low velocity (0.5 m/s). The coatings showed far high wear resistance than low-carbon steel substrate under same conditions examined. Wear loss of 304L-TiB_2 and Ni(Cr)-TiB_2 coatings were lower nearly 15 times than that of steel substrate. TiB_2 hard phases in coatings bonded well with metal matrix contributed to high wear resistance.

Keywords: arc spraying, coating techniques, microstructure, phase composition, room temperature, stainless steel, steel substrate, titanium compounds, tribological behavior, wear resistance

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Microstructure and wear behavior of arc sprayed WC-Co FeCrB and WC-Ni FeCrB composite coatings. Two types of ceramic composite coatings of Fe-Cr-B alloy reinforced with cobalt-coated tungsten carbide (WC-Co) particles or nickel-coated tungsten carbide (WC-Ni) particles were deposited on a mild steel substrate by arc spraying, respectively. The microstructure of the coating was investigated by optical microscopy. X-ray diffraction analysis was used to study the phase composition in the coating. The microhardness of the coating was determined. The wear behavior of the coating was evaluated. The results showed that the WC-Co/FeCrB coating has the excellent abrasive wear resistance which is about 11 times higher than that of Q235 mild steel. The main wear mechanism of both coatings was silica scratching and microcutting of the matrix and the resultant pulling out of WC particles.

Keywords: abrasion, abrasive wear resistance, arc spraying, ceramic materials, composite materials, sprayed coatings, tungsten carbide, wear behavior

B.-Y. Fu, D.-Y. He, J.-M. Jiang, and X.-Y. Li, College of Materials Science and Engineering, Beijing University of Technology, Beijing, 100022, China. Cited: *Key Eng. Mater.*, **373-374,** p 468-471 [in English]. ISSN 1013-9826.

Nanostructured YSZ thermal barrier coatings engineered to counteract sintering effects. Thermal spray zirconia-8 wt.% yttria (YSZ) deposits have been employed as thermal barrier coatings (TBCs) in the hot sections of gas turbines. The use of nanostructured YSZ represents an alternative for improving the performance of these coatings. Despite some initial positive research results, there are still fundamental questions to be answered on the applicability of nanostructured YSZ coatings as TBCs. These questions are related to sintering effects, which could significantly increase the thermal diffusivity/conductivity and elastic modulus values of these types of coatings in high-temperature environments. In this study, nanostructured and conventional YSZ coatings were heat treated at 1400 °C for 1, 5, and 20 h. It was observed that the nanostructured coatings counteract sintering effects, due to the presence of a bimodal microstructure exhibiting regions with different sintering rates: (i) matrix (low rate) and (ii) nanozones (high rate). Important sintering-affected properties, such as thermal diffusivity and elastic modulus, were studied. The thermal diffusivity and elastic modulus values of the nanostructured YSZ coatings were significantly lower than those of conventional YSZ coatings, even after an exposure to a temperature of 1400 °C for 20 h. This study demonstrates that nanostructured YSZ coatings can be engineered to counteract sintering effects and exhibit significantly lower increases in thermal diffusivity and elastic modulus values in high-temperature environments when compared to those of conventional YSZ coatings.

Keywords: differential sintering, elastic moduli, nanostructured coatings, nanostructured materials, sintering, sintering effects, thermal barrier coatings, thermal diffusivity, thermal spraying, yttria-stabilized zirconia

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Preparation and properties of HVOF NiAl nanostructured coatings. Nanostructured NiAl powder has been prepared by mechanical alloying. A high-velocity, oxyfuel (HVOF) thermal spray process has been used to deposit the agglomerated NiAl nanopowders. The coatings were characterized by means of x-ray diffraction and scanning electron microscopy (SEM) coupled with energy dispersive spectrometry analysis (EDS). The results showed that it was possible to deposit high-quality NiAl nanostructured intermetallic compound coatings. Properties of the coating regarding hardness, elastic modulus, dynamic hardness, high-temperature hardness, and wear behavior were also reported.

Keywords: elastic moduli, hardness, high-velocity oxyfuel thermal spray, intermetallics, mechanical alloying, nanostructured materials, nanostructured powder, powder coatings, thermal spraying, wear of materials

W. Hu, M. Li, and M. Fukumoto, Department of Applied Physics, Hunan University, Changsha, 410082, China. Cited: *Mater. Sci. Eng. A*, 2008, April 15, **478**(1-2), p 1-8 [in English]. ISSN 0921-5093.

Sintering of nanoceramics. There are two challenges in nanoceramic sintering: fully densifying the sintered body and maintaining the sintered grains at less than or equal 100 nm size. This review examines the fundamental factors underlying nanoceramic sintering and the approaches to effectively utilize the sintering factors to advantage. Nanoceramic sintering techniques are divided into four categories: pressureless sintering, pressure sintering, electrically assisted sintering, and other sintering-related techniques. Pressureless sintering has mainly evolved around modifying sintering schedules, improving nanoparticle packing characteristics, and using additives to tailor the diffusion rates, Pressure sintering, which includes hot pressing, hot isostatic pressing, and sinter forging, can effectively achieve full densification for nanostructured ceramics, but microstructural inhomogeneity and sintered shape limitation are difficult to overcome. For electrically assisted sintering, many nanoceramics have been sintered to full density with spark plasma even though the atomic diffusion process is not well understood; microwave sintering can achieve fast heating but has limited ability in reaching full density or controlling grain growth, Plasma spray forming and dynamic compaction are drastically different from the mainstream sintering concepts and so are briefly reviewed. Finally, the remaining issues in nanoceramic sintering are summarized and future directions are projected.

Keywords: ceramic materials, densification, grain growth, hot isostatic pressing, microstructure, microwaves, nanoceramic sintering, nanoparticles, nanostructured ceramics, nanostructured materials, pressure sintering, sinter forging, sintered body, spark plasma sintering

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Structure and properties of ZrO_2 ceramic coatings on AZ91D Mg alloy by plasma electrolytic oxidation. ZrO_2 ceramic coatings were prepared in situ on an AZ91D Mg alloy by plasma electrolytic oxidation in a K_2ZrF_6 solution. The phase composition and the surface morphology of the coatings were examined with x-ray diffraction and scanning electron microscopy. The thermal shock resistance of the coatings was evaluated by a thermal shock test. The corrosion resistance of the coated samples was examined by the polarizing curve method in a 3.5% NaCl solution. The prepared coating was composed of t-ZrO_2 and a small amount of c-ZrO_2. There were many residual discharging channels on the coating surface. The coated samples showed excellent thermal shock resistance under 500 °C, which improved with increasing frequency or decreasing current density or PEO time. Besides, the coating improved the corrosion resistance of AZ91D Mg alloy considerably. In the experiments, the corrosion current density of the coated samples prepared under 1000 Hz was the least, which also decreased with the current density during the PEO process.

Keywords: ceramic coatings, corrosion resistance, discharging channels, electrolytic oxidation, electrooxidation, magnesium alloys, polarizing curves, scanning electron microscopy, surface morphology, x-ray diffraction analysis, zirconia

Z. Yao, H. Gao, Z. Jiang, and F. Wang, Department of Applied Chemistry, Harbin Institute of Technology, 15000, China. Cited: *J. Am. Ceram. Soc.*, 2008, Feb, **91**(2), p 555-558 [in English]. ISSN 0002-7820.

Modeling

Mechanical Modeling

Axisymmetric frictionless contact of functionally graded materials. The main interest of this study is a new method to solve the axisymmetric frictionless contact problem of functionally graded materials (FGMs). Based on the fact that an arbitrary curve can be approached by a series of continuous but piecewise linear curves, the FGM is divided into a series of sublayers with shear modulus varying linearly in each sublayer and continuous at the subinterfaces. With this model, the axisymmetric frictionless contact problem of a functionally graded coated half-space is investigated. By using the transfer matrix method and Hankel integral transform technique, the problem is reduced to a Cauchy singular integral equation. The contact pressure, contact region, and indentation are calculated for various indenters by solving the equations numerically.

Keywords: axisymmetric problems, coating techniques, contact mechanics, functionally graded materials, integral equations, problem solving, singular integral equation, transfer matrix method

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Modeling of gas permeation through ceramic coatings produced by thermal spraying. An analytical model has been developed for simulation of gas permeation through thermal spray coatings and for prediction of the permeability. The model is based on a geometrical representation of the coating microstructure. This involves thin splats, with limited intersplat bridging, and microcracks within the splats. Important variables include the thickness (smallest dimension) of the intersplat pores and intrasplat microcracks. Uniform values of these parameters are used in the model. Predicted permeabilities are compared with experimental data obtained using plasma sprayed zirconia coatings, both in the as-sprayed state and after heat treatments sufficient to generate significant microstructural changes via sintering effects. In general, good agreement is obtained, and it is concluded that the model constitutes a useful tool for exploration of gas permeation characteristics in coatings or layers produced by thermal spraying.

Keywords: analytical modeling, ceramic coatings, computer simulation, gas permeability, gas permeation, geometrical representation, mathematical models, microstructure, porous materials, thermal spraying

I.O. Golosnoy, S. Paul, and T.W. Clyne, Department of Materials Science and Metallurgy, Cambridge University, Cambridge, CB2 3QZ, U.K. Cited: *Acta Mater.*, 2008, Feb, **56**(4), p 874-883 [in English]. ISSN 1359-6454.

Thermal stress intensity factors for a normal surface crack in a functionally graded coating structure. The thermal fracture behavior for a functionally graded coating structure (FGCS) with a normal surface crack is studied. The thermomechanical properties are continuous across the interface. The surface crack may intersect the interface. In the analytical procedure, integral transforms and residue theory are used. Some samples with some representative thermomechanical parameters are analyzed, and the corresponding thermal stress intensity factors (TSIFs) are calculated. It is found that the TSIF is greatly affected by the temperature conditions and thermomechanical properties. Moreover, the possibility for a surface crack to expand across the interface is discussed.

Keywords: cracks, functionally graded coating structure, functionally graded materials, integral equations, interfaces (materials), normal surface cracks, parameter estimation, stress intensity factors, thermal stress intensity factor, thermomechanical treatment

L.-C. Guo, N. Noda, and M. Ishihara, Center for Composite Materials, Harbin Institute of Technology, Harbin 150001, China. Cited: *J. Therm. Stresses*, 2008, Feb, **31**(2), p 149-164 [in English]. ISSN 0149-5739.

Thermomechanical model for moving layered rough surface contacts. A numerical model designed to simulate a moving line contact of two rough layered bodies is presented. Fourier transforms are used to obtain fundamental solutions to relevant differential equations, and then these solutions are used as kernel functions in a numerical scheme designed to provide a full thermomechanical solution for real layered contacts. The model assumes steady-state heat transfer and predicts contact pressures and deformations, contact temperature rise, and resulting thermal stresses. The heat division between the contacting components is fully accounted for, as are the interactions between the mechanical and thermal displacements. Some results are presented to illustrate the potential importance of a full thermomechanical analysis compared to a purely mechanical one as well as to demonstrate the influence of coating properties and surface roughness structure on the contact temperatures.

Keywords: contact angle, deformation, differential equations, Fourier transforms, kernel function, mathematical models, surface roughness, temperature distribution, thermal stress, thermomechanical analysis

A. Kadiric, R.S. Sayles, and E. Ioannides, Tribology Group, Imperial College, London SW7 2BX, UK. Cited: *J. Tribol.*, 2008, Jan, **130**(1), p [in English]. ISSN 0742-4787.

Process Modeling

Modeling the shape and thermal dynamics of Ni superalloy rings during spray forming Part 1: Shape modeling—Droplet deposition, splashing and redeposition. A numerical model has been developed to simulate the dynamic shape evolution of Ni superalloy rings during spray forming. The model comprises: (1) a droplet primary deposition model, simulating droplet primary deposition at a deposition surface; (2) a droplet splashing model, simulating the droplet splashing/scattering behavior; and (3) a droplet redeposition model, simulating the redeposition of the scattered droplets onto the deposition surface. The model has been validated against experiments of spray forming large-diameter IN718 alloy rings, and for the first time, the effects of droplet splashing and redeposition on the dynamic shape evolution of spray forming IN718 alloy rings and the deposition yields have been investigated and quantified. The model serves as the basis for a thermal dynamic model that is described in Part 2 of this publication.

Keywords: computer simulation, deposition, droplet deposition, drops, mathematical models, nickel alloys, nickel superalloys, redeposition, spraying, superalloys, thermal dynamics

J. Mi and P.S. Grant, Department of Materials, University of Oxford, Oxford, OX1 3PH, UK. Cited: *Acta Mater.*, 2008, April, **56**(7), p 1588-1596 [in English]. ISSN 1359-6454.

Modeling the shape and thermal dynamics of Ni superalloy rings during spray forming. Part 2: Thermal modeling—Heat flow and solidification. In Part 1 of this paper, a model was described to simulate the dynamic shape evolution of Ni superalloy rings during spray forming, concentrating on the effects of droplet splashing and redeposition. In this part, a companion model is presented that simulates the heat flow and solidification of the Ni superalloy rings during spray forming. In this model, generic algorithms of (1) coupling of droplet mass and enthalpy at a deposition surface, and (2) data mapping between time-evolving computational domains were developed and implemented. The effects of (1) droplet redeposition and (2) changes in the convective heat transfer coefficients and their distributions on the resulting ring preform heat flow and solidification were studied, and simulations were again compared with experiments. The model was applied to investigate the effects of key processing parameters on the internal heat flow and solidification of large diameter IN718 alloy rings.

Keywords: algorithms, enthalpy, nickel alloys, nickel superalloys, solidification, spray forming, superalloys, thermal effects

J. Mi and P.S. Grant, Department of Materials, University of Oxford, Oxford, OX1 3PH, UK. Cited: *Acta Mater.*, 2008, April, **56**(7), p 1597-1608 [in English]. ISSN 1359-6454.

Planarization during spray coating: Numerical study. Spin coating has been mainly used to produce photoresist-coated layers on wafers in the semiconductor fabrication process due to its simplicity of operation, and uniformity and thinness of coated layers. To improve productivity, the wafer size

has increased to 300 mm recently, and it keeps increasing. The spray coating system, which uses a spray nozzle transversing over a wafer while dispensing the photoresist solution, was developed to tackle the coating defect problem and limit of the current spin coating system in handling the 450 mm wafers, which will come in use from the year 2010. A new simulation model to predict the mean thickness and the uniformity of the photoresist film coated by the spray coating system was developed and validated with experimental data. The new model takes advantage of the simplicity of a one-dimensional model to estimate the uniformity of the final film thickness. The new model captures the effects of various operation parameters including the wafer-spinning speed, the amount of photoresist solution applied, the initial viscosity of the solution and the dispensing phase duration on the mean film thickness and uniformity. The evaporation control was found to be most important to obtain a uniform film profile, so that it was recommended to shorten the dispensing phase by increasing the dispensing rate.

Keywords: coated materials, evaporation, evaporation control, mathematical models, nozzles, numerical methods, photoresistors, spin coating system, spray coating, WSI circuits

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Simulation of a turbulent spray flame using coupled PDF gas phase and spray flamelet modeling. A joint mixture fraction-enthalpy probability density function (PDF) is proposed for the simulation of turbulent spray flames. The PDF transport equation is deduced and modeled. The interaction-by-exchange-with-the-mean (IEM) model that has been developed for gas-phase flows is extended to describe molecular mixing in nonreactive and reactive spray flows. The joint PDF transport equation is solved by a hybrid finite-volume and Lagrangian Monte Carlo method. Standard spray and turbulence models are used to describe the gas phase and the liquid phase. A turbulent methanol/air spray flame is simulated using the present method. Detailed chemistry is implemented through the spray flamelet model. The precalculated spray flamelet library for methanol/air combustion comprises 23 species and 168 elementary reactions. Thus, the model is capable of predicting the formation of radicals and of pollutants. Different values for the model constant C_ϕ in the IEM model are tested. The numerical results for the gas velocity, the gas temperature, and the mass fraction of methanol vapor are compared with experimental data in the literature. Good agreement with experiment is obtained when $C_\phi = 2.0$. Marginal PDFs of mixture fraction, enthalpy, and gas temperature are presented. The computed PDFs of mixture fraction are compared with the presumed standard β function and modified β function. The results show that the standard β function fails to reproduce bimodal shapes observed in transported PDF computation, while the modified β function, fits the computed PDFs very well. Moreover, joint PDFs of mixture fraction and enthalpy are presented and analyzed. The enthalpy and mixture fraction are strongly correlated. The samples that deviate from the linear correlation are due to the energy consumption of local spray evaporation.

Keywords: computer simulation, detailed chemistry, energy utilization, enthalpy, finite volume method, flame spraying, methanol, Monte Carlo methods, probability density function, spray combustion, spray flamelet model, turbulent flow

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A three-dimensional model of the wire arc spray process and its experimental validation. A CFD study of the twin wire arc spray process is presented in this paper. A three-dimensional model was used to compute the flow inside and outside the spray gun and gas-particles interactions were computed on the basis of one-way and two-way coupling methods, the latter allowing taking the loading effect into account. The considered particle size distributions were measured experimentally on particles collected at the spray distance, so that no atomizing model was required. In a second step, the model validation was performed on the basis of comparisons between predictions and particle velocity measurements.

Keywords: computational fluid dynamics, gas-particles, mathematical models, particle interactions, process modeling, thermal spraying, three-dimensional, three-dimensional model, velocity measurement, wire arc process, wire-arc spray

R. Bolot, M.-P. Planche, H. Liao, and C. Coddet, LERMPS, Universite de Technologie de Belfort-Montbeliard, 90010 Belfort, France. Cited: *J. Mater. Process. Technol.*, 2008, May 8, **200**(1-3), p 94-105 [in English]. ISSN 0924-0136.

Three-dimensional simulation of plasma jet and particle groups in plasma spraying. The temperature field, velocity field, as well as species distribution in three-dimensional space are successfully calculated by establishing three-dimensional geometry model and solving plasma-jet/substrate interaction equations, optimized particle trajectory models, as well as particle-particle heat transfer equations in three-dimensional space. Under typical working conditions, the flying trajectories and distribution of ZrO_2 ceramic particles and Ni metal particles are also simulated. Results show that, the plasma jet becomes wider near the substrate, and the stochastic trajectory model is preferable to simulate the turbulent diffusion effect of particles. In addition, Ni metal particles penetrate relatively more deeply than ZrO_2 ceramic particles due to larger density.

Keywords: ceramic particles, diffusion, geometry, geometry model, heat transfer, mathematical models, Ni metal particles, nickel, particle groups, particle heat transfer equations, particle trajectory model, particles (particulate matter), plasma jet substrate interaction equations, plasma jets, plasma spraying, stochastic trajectory model, temperature field, three-dimensional, three-dimensional space, turbulent diffusion effect, velocity field, zirconium

Q.-B. Fan, L. Wang, and F.-C. Wang, School of Material Science and Engineering, Beijing Institute of Technology, Beijing 100081, China. Cited: *J. Beijing Inst. Technol. (English Edition)*, 2008, March, **17**(1), p 115-121 [in English]. ISSN 1004-0579.

Thermal Modeling

Scattering of thermal waves and nonsteady effective thermal conductivity of composites with coated fibers. In this study, thermal wave method is applied to predict the nonsteady effective thermal conductivity of composites with coated fibers, and the analytical solution of the problem is obtained. The Fourier heat conduction law is applied to analyze the propagation of thermal waves in the fibrous composite. The scattering and refraction of thermal waves by a cylindrical fiber with coating in the matrix are analyzed, and the results of the single scattering problem are applied to the composite medium. The wave fields in different material layers are expressed by using the wave function expansion method, and the expanded mode coefficients are determined by satisfying the boundary conditions of the layer. The theory of Waterman and Truell is employed to obtain the effective propagating wave number and nonsteady effective thermal conductivity of composites. As an example, the effects of the material properties of the coating on the effective thermal conductivity of composites are graphically illustrated and analyzed. Analysis shows that the nonsteady effective thermal conductivity under higher frequencies is quite different from the steady thermal conductivity. In the region of lower frequency, the effect of the properties of the coating on the effective thermal conductivity is greater. Comparisons with the steady thermal conductivity obtained from other methods are also presented.

Keywords: coated fiber, coated materials, composite materials, fiber reinforced composite materials, heat conduction, nonsteady effective thermal conductivity, scattering, thermal conductivity, thermal waves

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Postprocessing

Femtosecond laser micromachining of dielectric materials for biomedical applications. Techniques for microfluidic channel fabrication in soda-lime glass and fused quartz using femtosecond laser ablation and ablation in conjunction with polymer coating for surface roughness improvement were tested. Systematic experiments were done to characterize how process variables (laser fluence, scanning speed and focus spot overlap, and material properties) affect the machining feature size and quality. Laser fluence and focus spot overlap showed the strongest influence on channel depth and roughness. At high fluence, the surface roughness was measured to be between 395 and 731 nm RMS. At low fluence, roughness decreased to 100-350 nm RMS and showed a greater dependence on overlap. The surface roughness of laser ablation was also dependent on the material properties. For the same laser ablation parameters, soda-lime glass surfaces were smoother than fused quartz. For some applications, especially those using quartz, smoother channels are desired. A hydroxyethyl methacrylate (HEMA) polymer coating was applied and the roughness of the coated channels was improved to 10-50 nm RMS.

Keywords: biomedical engineering, coated channels, dielectric materials, femtosecond laser micromachining, fused quartz, laser ablation, micromachining, polymer coating, quartz applications, surface roughness, ultrashort pulses

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Femtosecond pulsed laser damage characteristics of 7% Y_2O_3-ZrO_2 thermal barrier coating. Ablation characteristics of 7% yttria stabilized zirconia thermal barrier coating, deposited by the electron beam physical vapor deposition method, was studied using a femtosecond pulsed laser. The

single-pulse damage threshold fluence for the coating was determined to be 1.64 J is a member of the set of cm^{-2}. The threshold fluence was not appreciably dependent on the initial roughness of the coating surface. An incubation effect, that is, a decrease in the damage threshold fluence with an increase in number of pulses incident at a given location, was observed for this coating. Based on the damage morphology generated by single and multipulse interactions, a mechanism for the incubation effect was proposed.

Keywords: damage threshold, incubation, laser damage, morphology, physical vapor deposition, pulsed laser applications, pulsed laser damage, surface roughness, thermal barrier coatings, ultrashort pulses, yttria-stabilized zirconia

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Recombination of silica and zirconia into zircon by means of laser treatment of plasma sprayed coatings. Self-supported zircon ($ZrSiO_4$) coatings have been deposited by means of atmospheric pressure plasma spraying, a high growth rate deposition method. However, it is well known that when $ZrSiO_4$ dissociates into ZrO_2 and SiO_2 in the high-temperature plasma torch during plasma spraying, the rapid quenching preventing reverse combination of both components into $ZrSiO_4$. Usually, high-temperature annealing (1600-1900 K) is applied to recombine SiO_2 and ZrO_2 into $ZrSiO_4$. In this contribution, we investigate an attractive technological alternative to recombine SiO_2 and ZrO_2 into $ZrSiO_4$ by laser treatment with a scanning continuous wave CO_2 laser. By carefully adjusting the CO_2 laser treatment parameters (laser power density and scanning velocity), we show that the SiO_2 and ZrO_2 phases indeed recombine into $ZrSiO_4$, however, with a very low recombination rate. Thus, we have investigated the addition of SiO_2-rich glassy particles to the plasma spray powders to facilitate the recombination of ZrO_2, and SiO_2 into $ZrSiO_4$ during the laser treatment. Furthermore, the beneficial role of the glassy particles addition to substantially lower the annealing temperature during classical heat treatments has been studied. Available evidence indicates that the glassy particles melt during heat treatment and thus favor the mobility and availability of silica at the ZrO_2 grains, which results in a lowering of the reaction temperature and an enhancement of the reaction kinetics.

Keywords: atmospheric pressure, coatings, deposition, glassy particles, growth rate, growth rate deposition, heat treatment, laser treatment, plasma spraying, rapid quenching, silica, zirconia

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Powder

Characterization and comparison between APS coatings prepared from ball-milled and plasma processed nickel-aluminum powders. Plasma spraying has wide range of applications that include corrosion, thermal, and abrasion resistant coatings. In the present work, nickel and aluminum powders were ball milled, and the same were thermal plasma processed to produce spherical nickel aluminides particles. Both ball milled and plasma processed powders were spray deposited on stainless steel (SS 304) substrate using atmospheric plasma spray technique (APS). The experiments were carried out for different plasma input power levels, torch to base distances, and coating thicknesses. Microstructure, microhardness, adhesive strength, and porosity of the coatings are reported and discussed. Effect of plasma processing parameters and plasma spheroidization of powders on coating properties has been evaluated and reported. High plasma power, low torch to base distance lead to high temperature supplied to in-flight particles that correspond to high hardness, low porosity, and high adhesion. Spherical morphology and formation of nickel aluminide intermetallic were achieved by plasma spheroidization. Coatings prepared from plasma processed powders enhance the coating properties positively.

Keywords: ball milling, bond strength (materials), corrosion resistance, heat resistance, microhardness, morphology, nickel aluminide, plasma applications, plasma spheroidization, plasma spraying, porosity, powder coatings, sprayed coatings, wear resistance

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Effect of sintering on thermally sprayed carbon nanotube reinforced aluminum nanocomposite. Reconsolidation of thermally spray formed (plasma and high-velocity oxyfuel spraying) hypereutectic Al-Si nanocomposites with multiwalled carbon nanotube (MWCNT) reinforcement was carried out by inert atmosphere sintering for prolonged time periods. The sintering treatment resulted in the removal of porosity and residual stress, and increase in size and volume fraction of primary Si particles in the Al-Si matrix. The morphology of multiwalled carbon nanotubes in sintered nanocomposites remained unchanged after sintering. The interfacial ultrathin product layer of silicon carbide between MWCNT reinforcement and Al-Si matrix was unaltered. Microhardness and elastic modulus of the sintered nanocomposites were influenced by combined effect of multiple factors, i.e. reduction in porosity, residual stress removal, and MWCNT distribution. Overall improvement of microhardness and elastic modulus of the sintered nanocomposites was observed. The experimentally measured elastic modulus values were compared with theoretically estimated values using micromechanics models.

Keywords: aluminum alloys, elastic moduli, fiber reinforced metals, hypereutectic nanocomposites, metallic matrix composites, microhardness, micromechanics model, morphology, multiwalled carbon nanotubes, particle size, porosity, residual stresses, sintering, thermal spraying, volume fraction

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An on-line measurement and control system for submerged arc spray synthesis of TiO_2 nanoparticles. This article presents the development of an on-line measurement and control system for process characterization and optimization of the nanoparticle manufacturing process, called the submerged arc spray nanoparticle synthesis system (SANSS). To achieve optimized control of particle uniformity, this research investigates the feasibility of employing optical fiber probe and the dynamic light scattering (DLS) technique to monitor and control particle sizes. According to the theory of DLS, an on-line nanoparticle sampling and measurement system was developed and integrated with the SANSS as an important step to verify the measurement performance of the proposed method. To examine the measurement accuracy of the developed system, calibrated polystyrene latex particles with known accurate sizes were employed to verify the particle sizing accuracy of the proposed system. The data conformity between the measurement results of TiO_2 nanoparticles obtained by various methods, including TEM, a calibrated commercial particle sizing system and the on-line measurement system, has indicated that the developed method was feasible and effective.

Keywords: arc spray synthesis, dynamic light scattering, latexes, nanoparticle measurement, nanoparticles, optimization, particle size, process characterization, submerged arc spray nanoparticle synthesis system, synthesis (chemical), titanium dioxide

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Submerged arc spray synthesis of TiO_2 nanoparticles with desired form sphericity using process characterization and optimization. This article presents a study on process characterization and optimization of the metal nanoparticle fabrication process known as the submerged arc spray nanoparticle synthesis system (SANSS) for obtaining desired geometric sphericity of nanoparticles. The geometric shape characteristics of nanoparticles pose significant impact on innovative product and process design. The sphericity and surface roughness of prepared TiO_2 nanoparticles can vary widely and are influenced by the process parameters being employed in the SANSS. To improve this, an in situ nanofluid sampling and measurement approach was developed to analyze the particle shape characteristics and characterize the nanoparticle synthesis process. The particle shape contours obtained from FE-SEM and TEM were employed to quantify the TiO_2 nanoparticle sphericity and analyze the effect of process parameters on particle roundness. The optimized process parameters were identified using the Taguchi method. Our results proved that the average sphericity of TiO_2 particles prepared using the optimized process parameters was effectively improved up to three folds.

Keywords: characterization, nanofluidics, nanoparticle measurement, nanoparticles, optimization, parameter estimation, sphericity, submerged arc spray nanoparticle synthesis system, submerged arc spray synthesis, synthesis (chemical), titanium dioxide

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Processing

An automatic high-velocity arc spraying system. A new automatic high-velocity arc spraying system was developed. The system was consisted of five units, that is, central control unit, operating machine, positioner, touching screen, and high-velocity arc spraying equipment. The central control unit is controlled by a program, controlling the other four units. Spraying parameters could be input and modified on the touching screen during spraying. The moving of spraying gun was carried out by motion arm of the operating machine. The rotational velocity and angle of components to be sprayed was

controlled by positioner. The spraying process for a cylinder body of automobile engine with the system was introduced in detail. The auto and manual arc spraying have been used to fabricate coating. The microstructure of the coatings prepared by the two spraying processing was analyzed. The result shows that the auto sprayed coating has a more uniform and compact structure than that of the manual sprayed coating.

Keywords: high-velocity arc spraying, maintenance, microstructure, parameter estimation, remanufacture, spraying, velocity measurement

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Dense alumina-zirconia coatings using the solution precursor plasma spray process. For the first time, dense coatings have been made by the solution precursor plasma spray (SPPS) process. The conditions are described for the deposition of dense Al_2O_3-40 wt.%7YSZ (yttria-stabilized zirconia) coatings; the coatings are characterized and their thermal stability is evaluated. X-ray diffraction analysis shows that the as-sprayed coating is composed of α-Al_2O_3 and tetragonal ZrO_2 phases with grain sizes of 72 and 56 nm, respectively. The as-sprayed coating has a 95.6% density and consists of ultrafine splats (1-5 μm) and unmelted spherical particles ($\leq$0.5 μm). The lamellar structure, typical of conventional plasma sprayed coatings, is absent at the same scale in the SPPS coating. The formation of a dense Al_2O_3-40 wt.%7YSZ coating is favored by the lower melting point of the eutectic composition, and resultant superheating of the molten particles. Phase and microstructural thermal stabilities were investigated by heat treatment of the as-sprayed coating at temperatures of 1000-1500 °C. No phase transformation occurs, and the grain size is still in the nanometer range after the 1500 °C exposure for 2 h. The coating hardness increases from 11.8 GPa in the as-coated condition to 15.8 GPa following 1500 °C exposure due to a decrease in coating porosity.

Keywords: alumina, coating porosity, grain size and shape, lamellar structures, plasma spraying, thermodynamic stability, ultrafine splats, x-ray diffraction analysis, zirconia

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Dense TiO_2 coating using the solution precursor plasma spray process. A dense titania (TiO_2) coating was deposited from an ethanol solution containing titanium isopropoxide using the solution precursor plasma spray process. Thermal and crystallization behaviors of the solution precursor were investigated by thermal gravimetric analysis-differential thermal analysis, Fourier-transform infrared spectrum, and x-ray diffraction (XRD). XRD and Raman spectrum analyses confirmed that the coating is exclusively composed of rutile TiO_2. Scanning electron micrographs show the as-sprayed coating is dense with uniform thickness, and there are no coarse splat boundaries. The individual ultrafine splats (1-5 μm diameter) are composed of columnar grains. X-ray photoelectron spectroscopy analysis indicates that some Ti-OH groups exist in the as-sprayed coating surface. Deposition mechanisms are described based on model experiments.

Keywords: coating techniques, dense titania coatings, differential thermal analysis, ethanol, ethanol solutions, Fourier transform infrared spectroscopy, grain boundaries, plasma spraying, solution precursors, thermogravimetric analysis, titanium isopropoxide, titanium oxides, ultrafine splats

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Fabrication and mechanical properties of composite structure by warm spraying of Zr-base metallic glass. Metallic glasses are highly attractive because of their superior strength, relatively low Young's modulus and superb corrosion resistance [S1], and so forth. By combining a metallic glass with different materials, a synergy effect can be expected in the mechanical properties and corrosion resistance, for example. Fabricating a thick metallic glass layer on a substrate material by thermal spray process is one way to bond these materials. In such practice, however, the temperature of the sprayed metallic glass and that of the substrate must be kept relatively low to avoid crystallization and/or oxidation of the amorphous deposits, Warm Spray is a modified version of HVOF spraying developed by National Institute for Materials Science (NIMS) suited for spraying of heat-sensitive feedstock materials. In the process, high-velocity solid particles heated to the temperatures below its melting point are projected on to the substrate. A Zr-base metallic glass powder was warm sprayed onto cylindrical substrates of 316L stainless steel to various thicknesses. Negligible crystallization and oxidation were observed in the deposited layer of the glass alloy. The linear relationship between the thickness of the glass alloy layer and the Young's modulus of the composite bar demonstrated that the mechanical property of such composite structures can be controlled.Keywords: amorphous deposits, composite structures, corrosion resistance, crystallization, elastic moduli, metallic glass, thermal spraying, warm spraying

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Porosity, mechanical properties, residual stresses of supersonic plasma sprayed Ni-base alloy coatings prepared at different powder feed rates. The aim of this paper was to investigate the effect of powder feed rate (PFR) on the microstructure and mechanical properties of the supersonic plasma sprayed Ni-Cr-B-Si-C coatings. The microstructure, porosity, and mechanical properties of the coatings and the residual stresses at the coating surfaces were experimentally determined. Results showed that the variations of porosity, elastic moduli and microhardness of the coatings followed Weibull distribution. From the statistical trend, the porosity of the coating increased with increasing PFR. However, the elastic modulus and the microhardness of the coating decreased and reached local minima and then increased with increasing PFR. Elastic modulus could be generally considered to be an increasing function of microhardness. The mean value of the elastic modulus of the coating calculated from Weibull plot was almost proportional to the square root of the mean value of the microhardness of the coating. Moreover, with increasing PFR, the residual stress at the coating surface, which was mainly governed by the elastic modulus of the coating, decreased to a local minimum and then increased.

Keywords: coatings, elastic moduli, Ni-base alloy coating, nickel alloys, porosity, powder feed rate, residual stresses

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Preparation and characterization of plasma sprayed Al/Al_2O_3 composite coating. Al/Al_2O_3 composite coating was prepared by plasma spraying and characterized by XRD and SEM. Some thermal-mechanical properties of the composite coating including thermal diffusivity, microhardness, fracture toughness, and sliding wear rate were measured. The results showed that the Al/Al_2O_3 composite coating, compared with Al_2O_3 coating, exhibits denser structure and developed splat interface. The coexistence of Al metal phase and Al_2O_3 ceramic phase effectively increased the fracture toughness and thermal diffusivity of composite coating, in spite of the slight decrease in microhardness. Furthermore, the wear resistance of Al/Al_2O_3 composite coating is superior to that of Al_2O_3 coating.

Keywords: ceramic matrix composites, characterization, composite coatings, fracture toughness, microhardness, plasma spraying, sliding wear rate, thermal diffusivity, wear resistance

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Room-temperature deposition of nano-TiO_2 coating by vacuum cold spraying using $TiCl_4$-agglomerated nano-TiO_2 powder for flexible dye-sensitized solar cell. $TiCl_4$ treatment was used to chemically agglomerate TiO_2 primary nanoparticles to form a nanostructured powder in size of submicrometer. Nanocrystalline TiO_2 coatings were fabricated by vacuum cold spraying at room temperature using the powder and were employed to assemble dye-sensitized solar cells. TiO_2 coating of 10-20 μm in thickness was deposited successfully on both F-doped tin oxide (FTO) conducting glass and plastic conducting substrate. The assembled solar cell with an FTO conducting glass yielded a short-circuit current density of 9.7 mA/cm^2 and an energy conversion efficiency of 3.3%. Using the plastic substrate, the cell efficiency was 1.9%. These results suggest that $TiCl_4$-treated nanocrystalline TiO_2 agglomerates can be used to deposit TiO_2 coating by vacuum cold spraying at low temperature for flexible dye-sensitized solar cells.

Keywords: dyes, dye-sensitized solar cell, low-temperature fabrication, low-temperature effects, nanostructured materials, solar cells, titanium dioxide, vacuum cold spraying

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Self-propagating high-temperature synthesis for the deposition of thermal sprayed coatings. The paper reviews the relevant literature and results of the author's research into self-propagating high-temperature synthesis (SHS) used to deposit protective thermal sprayed coatings. The compositions of different SHS-produced powders, which are used to deposit thermal sprayed coatings, are indicated. The combination of spraying and synthesis of the material to form coatings by the interaction of composite powder particles is considered.

Keywords: composite powder particles, powders, sprayed coatings, synthesis (chemical), thermal spraying, thermal sprayed coatings, wear resistance

A.L. Borisova and Y.S. Borisov, Electric Welding Institute, National Academy of Sciences of Ukraine, Kiev. Cited: *Powder Metall. Met. Ceram.*, 2008, Jan, **47**(1-2), p 80-94 [in English]. ISSN 1068-1302.

Spray deposition of cerium oxide-based conversion coatings on Al 2024-T3. Cerium oxide conversion coatings were deposited on aluminum alloy 2024-T3 panels from an aqueous solution using a spray process. Substrate cleaning temperature was varied to evaluate its effect on deposition. Coating thickness did not increase linearly with the number of spray cycles. Deposition rate increased after five spray cycles for panels cleaned at 55 or 65 °C. After 15 spray cycles, coatings were ≤100 nm thick on panels cleaned at 45 °C, but were more than 300 nm thick on panels cleaned at 55 or 65 °C. Based on corrosion testing, the best coatings formed on panels cleaned at 55 °C.

Keywords: aluminum alloys, cerium compounds, cerium oxide, coating thickness, conversion coatings, deposition, protective coatings, sprayed coatings, substrate cleaning temperature

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Spreading and solidification of a highly undercooled $Y_3Al_5O_{12}$ droplet impinging on a substrate. Because of the containerless state, an in-flight droplet in thermal spray coating (TSC) has been presumed to experience a large undercooling prior to impact on a substrate. In the present investigation, using a $Y_3Al_5O_{12}$ (YAG) droplet as a model material for TSC, the spreading and solidification of the droplet impacted on a substrate were investigated over a wide range of undercoolings by means of both levitation and high-speed imaging techniques. The maximum spread of the droplets upon impact decreased with increasing undercoolings. The rebound of the droplets observed at high temperature also disappeared with increasing undercoolings. These results suggest that the spreading behavior and the final splat shape are strongly influenced by undercoolings because of their increase in viscosity.

Keywords: drops, high-speed imaging techniques, interfacial energy, model material, substrates, thermal spray coating, viscosity, yttrium compounds

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Properties

Adhesion

Effect of bond coat diffusion on adhesion behavior of hard alloy powder NiCrBCSi (Fe) coatings thermally sprayed on 60CrMn4 steel. The object of the present work is to study the spraying of poly-powders nickel bases containing Cr, Si, C, and B elements addition with variable percentage of iron, deposited on a steel substrate by oxyfuel thermal spraying. The substrate surface was previously treated by Al-Ni bond coat and postannealing at 650 °C. The spraying powder and coating microstructure were investigated by combination of x-ray diffraction, electron microprobe and scanning electron microscope coupled to an analyzer energy dispersive x-ray. The adherence to substrate was determined by using shear test for adhesion. The result of this study was to investigate to compare potentials of HVOF sprayed NiCrBCSi and satellite 6 coating for a possible to replacement of hard chromium plating. A good adherence of coating NiCrBCSi (Fe) on steel substrate is explained by formation of large diffusion zone in interface after annealing and by the nature of the structure deposit duplexes.

Keywords: adhesion, bond coat diffusion, electron probe microanalysis, nickel alloys, nickel-base alloys, oxyfuel thermal spraying, powder coatings, steel, substrate surface, thermal spraying, x-ray diffraction

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Effect of platinum on the oxide-to-metal adhesion in thermal barrier coating systems. An investigation was conducted to determine the role of Pt in a thermal barrier coating system deposited on a nickel-base superalloy. Three coating systems were included in the study using a layer of yttria-stabilized zirconia as a model top coat, and simple aluminide, Pt-aluminide, and Pt bond coats. Thermal exposure tests at 1150 °C with a 24-h cycling period to room temperature were used to compare the coating performance. Additional exposure tests at 1000, 1050, and 1100 °C were conducted to study the kinetics of interdiffusion. Microstructural features were characterized by scanning electron microscopy and transmission electron microscopy combined with energy dispersive x-ray spectroscopy as well as x-ray diffraction. Wavelength dispersive spectroscopy was also used to qualitatively distinguish among various refractory transition metals. Particular emphasis was placed on: (i) thermal stability of the bond coats, (ii) thickening rate of the thermally grown oxide, and (iii) failure mechanism of the coating. Experimental results indicated that Pt acts as a "cleanser" of the oxide/bondcoat interface by decelerating the kinetics of interdiffusion between the bond coat and superalloy substrate. This was found to promote selective oxidation of Al resulting in a purer Al_2O_3 scale of a slower growth rate, increasing its effectiveness as "glue" holding the ceramic top coat to the underlying metallic substrate. However, the exact effect of Pt was found to be a function of the state of its presence within the outermost coating layer. Among the bond coats included in the study, a surface layer of Pt-rich γ-phase ($L1_2$ superlattice) was found to provide longer coating life in comparison with a mixture of $PtAl_2$ and β phase.

Keywords: metallic substrate, oxides, oxide-to-metal adhesion, platinum, scanning electron microscopy, superalloys, thermal barrier coatings, yttria-stabilized zirconia

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Corrosion

Corrosion protection of magnesium alloys by cold spray. Corrosion protection by cold spray is a method by which thick aluminum coatings can be directly and locally applied to magnesium alloys to reduce or eliminate general or galvanic corrosion. Cold spray technology is based on the fact that every metal displays a temperature-dependent critical particle velocity above which the particles bond to the substrate. The method is capable of producing thick coatings that exhibit extremely low porosity while avoiding oxidation, phase transformations, and tensile residual stresses for a wide selection of materials. The presence of aluminum on the surface has been shown to reduce the general and galvanic corrosion tendency of magnesium components. However, more research is required to understand optimize the cold spray process.

Keywords: magnesium alloys, coatings, corrosion protection, oxidation, phase transitions, porosity, residual stresses, spraying, tensile stress, cold spray, aluminum coatings, galvanic corrosion

J. Villafuerte and W. Zheng, CenterLine (Windsor) Ltd., Windsor, ON N9J 3T8, Canada. Cited: *Adv. Mater. Process.*, 2007, Sept, **165**(9), p 53-54 [in English]. ISSN 0882-7958.

A survey of the literature on the use of high-velocity oxyfuel spray technology for high-temperature corrosion and erosion-corrosion resistant coatings. *Purpose*: This paper seeks to summarize the results of available research on the use of high-velocity oxyfuel (HVOF) thermal spray technique to provide protection against high-temperature corrosion and erosion-corrosion of materials. *Design/methodology/approach*: This paper describes one of the recent thermal spray processes, namely HVOF thermal spray technology and presents a survey of the studies on the use of this technique to provide protection against corrosion and erosion-corrosion of high-temperature alloys, with a special emphasis on boiler steels. *Findings*: High-temperature corrosion and erosion-corrosion are serious problems observed in steam-powered electricity generation plants, gas turbines, internal combustion engines, fluidized bed combustors, industrial waste incinerators and recovery boilers in paper and pulp industries. These problems can be prevented by changing the material or altering the environment, or by separating the component surface from the environment. Corrosion prevention by the use of coatings for separating materials from the environment is gaining importance in surface engineering. Among various surface modifying techniques, thermal spraying has developed relatively rapidly due to the use of advanced coating formulations and improvements in coating application technology. One of the variants of thermal spraying, namely HVOF has gained popularity in recent times due to its flexibility for in situ applications and superior coating properties. *Research limitations/implications*: This review covers mainly information that has been reported previously in the open literature, international journals, and some well-known textbooks. *Practical implications*: The paper presents a concise summary of information for scientists and academics, planning to start their research work in the area of surface engineering. *Originality/value*: This paper fulfills an identified information/resources need and offers practical help to an individual starting out on a career in the area of surface engineering for erosion-corrosion and wear.

Keywords: coatings, corrosion resistance, corrosion-resistant coatings, erosion, fluidized beds, gas turbines, internal combustion engines, spray technology, thermal protection, thermal spraying, waste incineration

M. Kaur, H. Singh, and S. Prakash, Baba Banda Singh Bahadur Engineering College, Fatehgarh Sahib, India. Cited: *Anti-Corros. Meth. Mater.*, 2008, **55**(2), p 86-96 [in English]. ISSN 0003-5599.

WC-CoCr coatings sprayed by high-velocity oxygen fuel (HVOF) flame on AA7050 aluminum alloy: Electrochemical behavior in 3.5% NaCl solution. In the present work, the electrochemical behavior of WC-CoCr coatings with 10 (W10), 15 (W15), and 20 (W20) torch passes sprayed by high-velocity oxygen fuel (HVOF) flame on AA7050 aluminum alloy substrate,

evaluated in 3.5% NaCl solution, were compared using open-circuit potential (E_{OC}) measurements, electrochemical impedance spectroscopy (EIS), and polarization curves. The coating surfaces and their cross sections were characterized by x-ray diffraction and the Rockwell C hardness test, and also by optical (OM) and scanning electron microscopy (SEM) before and after the corrosion tests. The electrochemical data showed that sample W10 presented higher corrosion resistance than the others in chloride solutions. In some tests, aluminum salts on the coating surface were identified by EDS, indicating the corrosion of the substrate. Also, using aluminon, aluminum ions were detected and analyzing the surface via stereomicroscopy, hydrogen bubbles were observed, both showing that the electrolyte reached the substrate and galvanic corrosion possibly occurred. The physical characterization showed that sample W10 presented a lower number of cracks and pores, justifying its higher corrosion resistance.

Keywords: aluminum alloys, corrosion resistance, electrochemical impedance spectroscopy, electrolytes, flame spraying, hardness testing, high-velocity oxygen fuel, optical microscopy, scanning electron microscopy, sprayed coatings, stereomicroscopy

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Mechanical

Characterizations of cold sprayed TiN particle reinforced Al2319 composite coating. In this study, a dense Al2319/TiN composite coating was successfully prepared using cold spraying with mechanically blended powders. TiN particles were uniformly dispersed in the coating matrix with a volume fraction of 38.7 vol.%, which is higher than that of 32.7 vol.% in the powder blend. Compared with the pure Al2319 coating, the Al2319/TiN composite coating exhibits a significantly increased adhesive strength. The incorporation of the TiN particles increases the coating hardness from 106 $\pm$ 7.8 to 154.5 $\pm$ 18.9 $HV_{0.2}$. In addition, compared with the pure Al2319 coating, the composite coating exhibits a significantly improved tribological performance. The results obtained in this work indicated that cold spraying is a promising process to fabricate Al alloy-based composite coatings.

Keywords: aluminum alloys, bond strength (materials), coating matrix, cold spraying, composite coatings, microhardness, powder metals, protective coatings, titanium nitride, tribological performance

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The effects of ceria on the mechanical properties and thermal shock resistance of thermal sprayed NiAl intermetallic coatings. The effects of ceria addition to thermal sprayed NiAl intermetallic coatings were investigated through microindentation, thermal shock testing, and microstructural analysis techniques (scanning electron microscopy with energy-dispersive x-ray spectrometry and x-ray diffraction analysis). It has been found that the addition of CeO_2 to NiAl coatings reduces the tendency of brittle peeling during thermal spraying. This reduction in peeling is presumably caused by the improved wetting of the substrate by the molten coating material, which leads to better coating adhesion. The addition of CeO_2 resulted in higher coating hardness and elastic modulus. The coatings containing CeO_2 also exhibited significant increases in thermal shock resistance compared with that of the pure NiAl coating. The NiAl coating containing 2 wt.% CeO_2 had the highest hardness, elastic modulus and thermal shock resistance of the four NiAl-based coatings tested. The possible mechanisms responsible for the improvement of the properties upon addition of CeO_2 are addressed.

Keywords: CeO_2, cerium compounds, coatings, heat resistance, intermetallic coatings, intermetallics, mechanical testing, nickel aluminides, nickel compounds, shock resistance, thermal spraying, thermodynamic stability

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Effect of coating microstructure on the fatigue properties of steel thermally sprayed with Ni-base self-fluxing alloy. To investigate the factors that most strongly influence fatigue properties of steel thermally sprayed with Ni-base self-fluxing alloy, we prepared three types of thermally sprayed specimens which differed in heating time in the fusing process. Rotational bending fatigue tests were carried out, and coating microstructures were observed. The results show that fatigue properties of steel thermally sprayed with Ni-based self-fluxing alloy were affected by two factors. The first factor is the size and population of porosities in the coating. This factor was changed by fusing time with longer fusing times producing larger and more porosities. Because the fatigue crack initiates at the porosities, specimens fused for longer time exhibit lower fatigue strength. The second factor is lowered hardness of Ni matrix accompanying chromium segregation. The sprayed specimens fused for longer time exhibit lower fatigue strength, because the longer fusing process induces segregation of the chromium compound in the coated microstructures. Therefore, performing the fusion for a shorter time is effective for producing sprayed materials of enhanced fatigue properties.

Keywords: chromium segregation, coated microstructures, fatigue of materials, fusing time, microstructure, nickel alloys, pore size, sprayed materials, steel, strength of materials, thermal spraying

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Fatigue resistance of plasma sprayed CrC-NiCr cermet coatings in rolling contact. The aim of this paper was to address the fatigue behavior and failure modes of plasma sprayed CrC-NiCr cermet coatings in rolling contact under the identical tribological conditions of contact stress at room temperature. For all tests, the thicknesses of the coatings were controlled to be about 100 μm. Thirteen rolling contact tests were performed to obtain the statistical result. The Weibull distribution plot of fatigue-life data of the coating specimens was obtained. The failure modes and mechanisms of the coatings were studied on the basis of the worn surface observations of the failed coatings. Experiment results showed that the RCF life data of the coatings exhibited high scattering, since the bimodal distribution of the fatigue-life data of the coatings was observed in the Weibull plot. Different failure modes named as spalling and delamination were observed during this investigation. However, the failure modes might be associated with the microstructure and the bonding strength of the coating, and the distribution of shear stress at the subsurface. The coatings failed in the spalling generally exhibited the relatively high fatigue lives and the coatings failed in the delamination exhibited low lives, resulting in the bimodal distribution of the fatigue-life data in the Weibull plot.

Keywords: bimodal distribution, cermets, coatings, CrC-NiCr cermet coating, failure analysis, fatigue of materials, plasma spraying, rolling contact fatigue, rolling mills, tribology, Weibull distribution, Weibull plot

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Lanthanum zirconate ceramic toughened by $BaTiO_3$ secondary phase. $La_2Zr_2O_7$ (LZ) is a promising thermal barrier coating material for the high-temperature applications, which could be significantly toughened by the $BaTiO_3$ piezoelectric phase incorporated into the matrix. The composites of $x BaTiO_3/(1-x)LZ$ ($x = 5$, 10, 15, 20 vol.%, LZ-x-$BaTiO_3$) were densified by means of high-pressure sintering (HPS) under a pressure of 4.5 GPa at 1450 °C for 10 min, by which a high relative density above 93% could be obtained. The morphologies of the fractured surfaces were investigated by the scanning electron microscope, and the fracture toughness and Vicker's hardness of the composites were evaluated by the microindentation. The grain size of the LZ matrix drops significantly with the addition of $BaTiO_3$ piezoelectric phase, and the fracture type changes from the intergranular to a mixture type of the transgranular and intergranular in the composites. The LZ-10-$BaTiO_3$ composite has a fracture toughness of 1.98 MPa $m^{1/2}$, which is obviously higher than that of the pure LZ (1.60 MPa $m^{1/2}$), and the toughening mechanism might be attributed to the ferroelastic domain switching of ferroelectric phase $BaTiO_3$.

Keywords: ceramic matrix composites, coating materials, coating techniques, ferroelastic domain switching, high-temperature applications, lanthanum compounds, piezoelectric phases, piezoelectricity, scanning electron microscopy, sintering, Vickers hardness, zirconium compounds

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Microdamage evolution and residual stress in thermally grown oxides of detonation gun sprayed thermal barrier coatings. Thermal barrier coatings (TBCs) were prepared by the recently developed detonation gun spray process. The oxide scale formation and microdamage evolution of these coatings during oxidation in air at 1100 °C were investigated. It was found that duplex oxide scales, the upper oxide mixture scale, and α-Al_2O_3 subscale, form at the interface between bond coat (BC) and top coat (TC) during the oxidation. Microcracks usually nucleate within the porous oxide mixture layer. With the increase of oxidation time, some microcracks coalesce to form a long crack. Residual stress in the thermally grown oxides (TGO) was measured using photostimulated luminescence spectroscopy. It was found that compressive residual stress exhibits a fast increase at the beginning of oxidation up to maximum value for about 10 h. Then, the compressive stress begins to decline up to 100 h. Local stress distribution showed that the microdamage in the TGO causes a remarkable decrease in the magnitude of compressive residual stress.

Keywords: detonation gun spray, interfaces (materials), oxidation, residual stresses, spectroscopic analysis, thermal barrier coatings, thermally grown oxides

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Microstructure and fracture morphology of thermally sprayed refractory metals and ceramics. The microstructural characteristics such as porosity, splat morphology, and grain size of thermally sprayed coatings made of both ceramic and refractory metals are investigated. Al_2O_3 and Cr_2O_3 coatings represent ceramic materials while pure W and Mo coatings represent the refractory metals. The used deposition technology (RF plasma, gas-stabilized or water-stabilized DC plasma) was found to influence the coatings microstructure to a great extent by providing different particle impact velocities and temperatures. At the same time the substrate temperature plays an important role as is shown for refractory metal coatings deposited at different substrate temperatures. Generally, all investigated coatings contained intrasplat cracks, intersplat pores and voids, individual splats of different degree of deformation, and different degree of intersplat sintering, crystal grains formed inside individual splats or extending through many of them. It is shown that the size and abundance of the aforementioned microstructural features predetermine the fracture morphology of the coating as well as mechanical properties.

Keywords: ceramic materials, deformation, deposition, elastic moduli, fractography, mechanical properties, microstructure, particle impact velocities, refractory materials, thermal spraying

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Study of microstructure, phases, and microhardness of metallic coatings deposited by flame thermal spray. The recharging technique by thermal spraying offers the opportunity of renovating the worn surface parts of a machine element to give it again a new technical life despite its previous degradation in service. This process has consequently interesting economic impacts. To improve the adherence between 100Cr6 steel deposits and the substrate material (left worn crankshafts), company SNC ATRA of Bejaia uses at present a composite formed by (100Cr6 steel/molybdenum bond coat of 0.2 mm thick/crankshaft substrate). As a matter of fact, it is shown in the present work that the molybdenum bond coat is not appropriate since, for the 0.2 mm thickness, lateral cracks are observed in the middle of the bond coat. On the other hand, our experiment is that a deposit of 100Cr6 steel projected directly on the substrate seems more promising since no gaps or cracks were detected at the ''deposit/substrate'' interface of this two-material composite. Lastly, phase analysis using x-ray diffraction confirmed that during spraying process, a stable α-phase (bcc) of 100Cr6 wire was transformed to a new phase of γ-phase (fcc). The coatings exhibited the higher microhardness which would contribute to increase wear resistance.

Keywords: coating microstructures, coatings, flame spraying, metallic coatings, microhardness, microstructure, molybdenum, x-ray diffraction analysis

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Wear and corrosion properties of nanocrystalline coatings on stainless steel produced by plasma electrolytic nitrocarburizing. Plasma nitrocarburizing was applied to AISI 316L stainless steel substrates using an electrolytic plasma technique, based on a dielectric barrier discharge created during cathodic saturation in an aqueous electrolyte. The samples were biased cathodically with a direct-current high voltage. The wear resistance of the treated samples was evaluated using a pin-on-disk wear testing method. Results indicate that the resultant hardened nitrocarburized layers exhibited excellent abrasive wear resistance. Investigation of the wear characteristics showed that the magnitude of weight loss and the wear mechanisms strongly followed from the treatment experimental parameters. Additionally, to evaluate the corrosion properties of the layers a potentiodynamic polarization test was performed on the hardened samples. Results indicated that short time as well as high treatment temperature provided a slight increase in corrosion resistance while in the case of long treatment time the corrosion resistance decreased. These changes in the properties could be attributed to the different nanocrystalline morphologies of the nitrocarburized layers.

Keywords: abrasion, carbonitriding, coatings, corrosion resistance, dielectric barrier discharge, nanocrystalline materials, nanocrystals, plasma, plasma electrolytic nitrocarburizing, stainless steels

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Oxidation

Oxidation behavior of HVOF sprayed Ni-5Al coatings deposited on Ni- and Fe-based superalloys under cyclic condition. Ni-5Al coating was obtained on three superalloy substrates, namely, Superni 76, Superni 750, and Superfer 800 using high-velocity oxyfuel (HVOF) spray process. Oxidation studies were carried out on both bare and coated superalloy substrates in air at 900 °C for 100 cycles. The weight change was measured at the end of each cycle and observed that the weight gain was high in Superni 750 alloy when compared to Superni 76 and Superfer 800. A nearly parabolic oxidation behavior was observed for Ni-5Al coated Superni 750 and Superfer 800 alloys but a Ni-5Al coated Superni 76 substrate showed a slight deviation. The scale was analyzed using x-ray diffraction (XRD), scanning electron microscopy (SEM), and energy dispersive x-ray analysis (EDAX) and electron probe microanalysis (EPMA). The coating increased the oxidation resistance for all the alloy substrates at 900 °C. Among the three-coated superalloys, Superfer 800 substrate has shown the best resistance to oxidation. The protective nature of the Ni-5Al coated superalloys was due to the formation of protective oxide scales such as NiO, Al_2O_3 and Cr_2O_3.

Keywords: coated superalloy substrates, deposition, electron probe microanalysis, energy dispersive x-ray analysis, high-velocity oxyfuel, iron alloys, nickel compounds, oxidation resistance, protective coatings, scanning electron microscopy, sprayed coatings, superalloys, x-ray diffraction analysis

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Thermal

Thermal conductivity of plasma sprayed aluminum oxide—Multiwalled carbon nanotube composites. Aluminum oxide nanocomposites reinforced with multiwalled carbon nanotubes (MWNT) were prepared by atmospheric plasma spraying of blended and spray dried powders. Thermal conductivity was measured using the laser flash technique for temperatures between 25 and 300 °C. An aluminum oxide-4 wt.% MWNT nanocomposite prepared from the blended powder showed the highest conductivity, followed by aluminum oxide without nanotubes, 8 and 4 wt.% MWNT composite prepared from spray dried powder in that order. The thermal conductivity values obtained are rationalized taking into account the crystallite size, porosity, MWNT content, microstructure, and the interfaces and metastable γ-Al_2O_3 content present in the nanocomposite.

Keywords: alumina, atmospheric plasma spraying, blended powder, crystallite size, laser flash technique, multiwalled carbon nanotubes, nanocomposites, plasma spraying, porosity, spray drying, thermal conductivity

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Safety

Tips on using plural-component spray technology safely in confined spaces. Definitions of confined spaces and some basic tips on safe use of plural-component equipment and coatings are provided to help contractors who are to use plural-component spray in permit-required confined spaces. Confined space work is regulated by 29 Code of Federal Regulations (CFR) 1910.146. The standard defines confined space as one that is large enough and so configured that an employee can bodily enter and perform assigned work, has limited means for entry and exit, and is not designed for continuous occupancy. High-pressure plural component spray system that allows to reduce or totally remove solvents from coating systems, making application in confined spaces safer and more efficient than with conventional coatings, also poses some hazards related to equipment. Careful planning, effective evaluation of hazards, development of sound safety plans, and communication with personnel and emergency services can help to mitigate risk in applications involving confined spaces.

Keywords: confined spaces, conventional coatings, protective coatings, risk analysis, safety plans, solvents, spray drying

S. Wierzchowski, RLS. Cited: *J. Prot. Coat. Linings*, 2008, Feb, **25**(2), p 59-63 [in English]. ISSN 8755-1985.