Selected Abstracts of Thermal Spray Literature

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Application

Automotive and Aircraft Parts

Technology and Materials for Applying the Wear-Resistant Anticorrosion Plasma Coatings on Parts of Automobile and Aviation Technique. The powders on the base of Fe, Ni, alloyed with B, Cr, and Mo, are created, and coating technology of plasma wear- and corrosion-resistant coatings is elaborated in place of the ecologically hazardous electrodeposition of Cr and Cd. Corrosion rate in seawater and fatigue strength under condition of sliding and reversible friction are by 1.6 to 2 times higher compared with the electrodeposited coatings. In addition, the induced inner compressing stresses in the amorphized coatings result in the rise of fatigue strength by 10 to 35% for sprayed coatings.

V.F. Gol'nik and Yu.S. Borisov. Cited: *Avtom. Svarka*, Vol 12, Dec 1997, p 49 [in Russian]. ISSN 0005-111X. PHOTOCOPY ORDER NUMBER: 199806-57-0832.

FGM Hydroxyapatite Materials

Thermal Spraying of Functionally Graded Calcium Phosphate Coatings for Biomedical Implants. Biomedical requirements in a prosthesis are often complex and diverse in nature. Biomaterials for implants have to display a wide range of adaptability to suit the various stages of the biointegration process of any foreign material into the human body. Often, a combination of materials is needed. The preparation of a functionally graded bioceramic coating composed of essentially calcium phosphate compounds is explored. The coating is graded in accordance to adhesive strength, bioactivity, and bioresorbability. The bond coat on the Ti-6Al-4V stub is deposited with a particle range of the hydroxyapatite (HA) that will provide a high adhesive strength and bioactivity, but have poor bioresorption properties. The top coat, however, is composed of predominantly α-tricalcium phosphate (α-TCP) that is highly bioresorbable. This arrangement has the propensity of allowing accelerated biointegration of the coating by the body tissues as the top layer is rapidly resorbed, leaving the more bioactive intermediate layer to facilitate the much needed bioactive properties for proper osteoconduction. The processing steps and problems are highlighted, along with the results of postspray heat treatment.

Y. Wang, P. Cheang, and K.A. Khor. Cited: *J. Therm. Spray Technol.*, Vol 7 (No. 1), March 1998, p 50-57 [in English]. ISSN 1059-9630. PHOTOCOPY ORDER NUMBER: 199806-57-0844.

Hydroxyapatite

Thermal Spraying of Ti-6Al-4V/Hydroxyapatite Composites Coatings: Powder Processing and Postspray Treatment. Hydroxyapatite (HA) is known for its attractive bioactive properties. Thermal spray techniques (plasma spray and high-velocity oxyfuel) are employed to deposit HA on titanium implants because of their high thermal efficiency and relative economy. However, some of the bioactive properties of HA are lost during thermal spraying. Generally, HA has poor mechanical properties. Titanium is a light metal that has been applied to biomedical engineering because of its nontoxicity and low density. A composite that can elicit the combined bioactive property of HA and the mechanical properties of Ti-6Al-4V to provide an implant that is both biocompatible and mechanically strong would certainly be desirable. Thermal spray techniques are employed in the present study to process Ti-6Al-4V/HA composite coatings. The Ti-6Al-4V/HA coatings can be sprayed onto existing implants to improve postoperation healing. This paper reports the thermal spraying of Ti-6Al-4V/HA composite coatings using powder feedstock prepared by two powder processing techniques: (1) mechanical alloying and (2) the ceramic slurry mixing method. The effects of postspray treatment by hot isostatic pressing (HIP) on the microstructure and other physical properties are investigated also. The surface morphology and microstructure of the as-sprayed coatings and hot isostatically pressed coatings are examined by scanning electron microscopy. The investigation shows that the as-sprayed coating microstructure is comprised, predominantly, of HA lamella sandwiched between the Ti-6Al-4V lamellae. The coatings, in particular the HA-rich regions, suffer from high porosity levels. A mercury intrusion porosimeter is used to study the pore-size distribution of the as-sprayed and hot isostatically pressed samples, the results indicating that the majority of the micropores are drastically reduced. The improvement in the physical properties of the composite was attributed to this reduction. Overall, the results showed that HIP can effectively enhance the mechanical properties of the as-sprayed coatings and improve the porosity levels.

K.A. Khor, P. Cheang, N.L. Loh, and C.S. Yip. Cited: *J. Mater. Process. Technol.*, Vol 65 (No. 1-3), March 1997, p 73-79 [in English]. ISSN 0924-0136. PHOTOCOPY ORDER NUMBER: 199806-58-0660.

Thermal Barrier Coating Failure

Modifications of Thermal Barrier Coatings (TBCs). To develop highly efficient gas turbines, thermal barrier coating systems with a high reliability and a long lifetime under severe operating conditions are required. The failure of TBC systems is caused by thermal cycling conditions, oxidation attack, and insufficient adhesion at the interface of the ceramic coating and the bond coat. Coating failure occurs mostly near the interface top coat-bond coat. Two modifications of a conventional duplex TBC system consisting of a Ni-base alloy substrate/MCrAlY-bond coat/ZrO_2 7 wt% Y_2O_3 top coat, which is used as the reference system, are presented as follows. (1) By contouring the MCrAlY-bond coat with a laser, the stress distribution at the ZrO_2 bond coat interface can be modified by forming folds within the laminate structure of the ceramic top coat and increasing the bonding area. TBC systems containing a contoured bond coat show better thermal cycling behavior. FEM simulation of thermally induced stress shows an alternating stress distribution that is caused by the contoured bond coat interface. (2) High-velocity oxygen fuel (HVOF) sprayed MCrAlY layers are a new possibility to create homogeneous bond coats. Thermal barrier coatings with LPPS (low-pressure plasma sprayed) or HVOF CoNiCrAlY bond coats are compared by investigating their porosity, roughness, and oxidation behavior. The porosity is proportional to the roughness of the HVOF bond coats. The oxide content was examined by TEM and EDX analysis. HVOF-CoNiCrAlY bond coats show oxidation behavior similar to coatings produced by LPPS.

K.G. Schmitt-Thomas, D. Fu, and H. Haindl. Cited: 24th International Conference on Metallurgical Coatings and Thin Films (*Proc. Conf.*), San Diego, CA, 21-25 April 1997, *Surf. Coat. Technol.*, Vol 94-95 (No. 1-3), Oct 1997, p 149-154 [in English]. ISSN 0257-8972. PHOTOCOPY ORDER NUMBER: 199805-57-0646.

Composite Coating

Aluminum-Silicon Materials

Developments in the Processing and Properties of Particulate Al-Si Composites. In the past ten years, materials R&D has shifted from monolithic to composite materials, adjusting to the global need for reduced weight, low cost, quality, and high performance in structural materials. This article reviews developments in the molten processing of particulate Al-Si alloy composites and their respective properties. Existing and emerging processing innovations are discussed, and the reinforcement phases in prominent R&D activities are identified. The vortex (or mixing) method continues to be the most popular processing method in use because of its ease of operation, total production cost, and suitability, while the infiltration, compocasting (or rheocasting), in situ, and spray atomization and codeposition techniques receive less attention. Composites discussed include Al_2O_3, SiC, graphite, $ZrSiO_4$, and carbon reinforced Al-Si alloys.

J.U. Ejiofor and R.G. Reddy. Cited: *JOM*, Vol 49 (No. 11), Nov 1997, p 31-37 [in English]. ISSN 1047-4838. PHOTOCOPY ORDER NUMBER: 199806-62-1132.

Aluminum-Silicon Carbide Materials

Aluminum-Silicon Carbide Coatings by Plasma Spraying. An aluminum-base composite (Al-SiC) powder has been developed for producing plasma sprayed coatings on Al and other metallic substrates. The composite powders were prepared by mechanical alloying of 6061 Al alloy with SiC particles. The concentration of SiC was varied between 20 and 75 vol%, and the size of the reinforcement was varied from 8 to 37 μm in the Al-50 vol% SiC composites. The 44 to 140 μm composite powders were sprayed using an axial feed plasma torch. Adhesion strength of the coatings to their substrates were found to decrease with increasing SiC content and with decreasing SiC particle sizes. The increase in the SiC content and decrease in particle size improved the erosive wear resistance of the coatings. The abrasive wear resistance was found to improve with the increase in SiC particle size and with the SiC content in the composite coatings.

K. Ghosh, A.C.D. Chaklader, and T. Troczynski. Cited: *J. Therm. Spray Technol.*, Vol 7 (No. 1), March 1998, p 78-86 [in English]. ISSN 1059-9630. PHOTOCOPY ORDER NUMBER: 199806-58-0638.

Carbon Long Fibers

Development and Application of Carbon Long Fiber Reinforced Metal-Matrix Composites. The paper deals with the preparation and properties of long fiber reinforced aluminum-matrix composites. Carbon fibers in coated or uncoated form were applied as reinforcements in metal-matrix composites. The fibers of the fiber bundle were separated mechanically and in the sequence, the prepregs were prepared by metallization using thermal spraying methods. In a following step the prepregs were compressed to a solid composite by a hot pressing process. Results obtained from tensile and bending tests of the compact composites are compared to those obtained by metallographical examinations. The state of the interface between fiber and matrix and its chemical and mechanical behavior was investigated by SEM and TEM. In the process of hot pressing the thermal load of the components is higher, causing damage of fibers and the formation of aluminum carbide at the interface. The carbide acts as a brittle phase and causes the strength of the composite to decrease. To reduce those reactions, the coating of the fibers with a pyrolytic carbon/SiC layer is successfully applied. The layer acts as a diffusion and reaction barrier. Summarizing the results obtained, the application of a SiC layer causes an improvement of the mechanical properties of the carbon fiber reinforced aluminum composites. Application possibilities of carbon fiber reinforced aluminum MMC exist in the automobile industry especially in state-coach body and engines. These materials are well qualified for light structures with high strength and stiffness and low thermal expansion coefficients at temperatures to 300 °C.

B. Wielage and J. Rahm. Cited: *High Technology Composites in Modern Applications* (Proc. Conf.), Corfu, Greece, 18-22 Sept 1995, University of Patras, 1995, p 334-337 [in English]. ISBN 960-85676-0-2. PHOTOCOPY ORDER NUMBER: 199806-62-1018.

Composites

Functionally Graded Materials of Thermal Barrier Coating Systems

Microstructure and Mechanical Properties of Functionally Graded NiCrAlY/ZrO 2%N Thermal Barrier Coating Layers Fabricated by Plasma Spraying Technique. Functionally graded thermal barrier coating (TBC) consisting of NiCrAlY and 8 wt% Y_2O_3-ZrO_2(YSZ) was produced on a Co-base superalloy (HAYNES 188) substrate using the Ar-shielded air plasma spraying method. Functional grading was obtained by the stepwise change of metal/ceramic composition: 1, 2, and 4 layers with different compositional combinations were inserted between metal and ceramic layers. Microstructure of the functionally graded thermal barrier coating was examined to check proper grading of metal/ceramic compositions and features of defects. No particular defect that may affect the properties of TBS significantly was found at interface and through thickness of the graded layers, even though some unavoidable oxides and pores were observed. Microstructural observation revealed fabrication of functionally graded TBC by plasma spraying technique. Adhesion strength of TBC with four layers was measured with the highest value. In other words, the strength increased with more smooth change of metal/ceramic composition within TBC. Thus, functional grading tends to improve the strength removing the sharp interface and relieving the internal stress level due to the thermal mismatch between metal and ceramic.

C.-H. Park, K.-M. Cho, M.-G. Jung, and I.-M. Park. Cited: *J. Korean Inst. Met. Mater.*, Vol 35 (No. 11), Nov 1997, p 1540-1546 [in Korean]. ISSN 0253-3847. PHOTOCOPY ORDER NUMBER: 199804-57-0577.

Functionally Graded ZrO_2-NiCrAlY Coatings Prepared by Plasma Spraying Using Premixed, Spheroidized Powders. Functionally graded ZrO_2-NiCrAlY coatings were prepared by plasma spraying. Premixed, plasma spheroidized powders were used as the feedstock. The advantage of using premixed, spheroidized powders was to ensure chemical homogeneity and promote uniform density along the graded layers, and these premixed powders are used to form the different interlayers of functionally graded coatings in the present study. The microstructure, density, and microhardness changed gradiently in the ZrO_2-NiCrAlY FGM (functionally graded materials) coatings. The bond strength of ZrO_2-NiCrAlY FGM coatings with different graded layers was measured. Results showed that for as-sprayed coatings with the same thickness, the bond strength increased with the number of graded layers. The bond strength of the FGM coatings with five graded layers was about twice as high as that of the duplex coatings because of the significant reduction of the residual stress in the coatings. Experimental results also showed that the bond strength of as-sprayed FGM coating increased significantly after hot isostatic pressing (HIP), and the reason can be attributed to the densification of the microstructure, the decrease of defects in the coatings, interdiffusion between layers, and reduction in the residual thermal stresses. Nickel stubs and aluminum plates were the substrates.

K.A. Khor, Y.Q. Fu, Y.W. Gu, and Y. Wang. Cited: *Surf. Coat. Technol.*, Vol 96 (No. 2-3), 25 Nov 1997, p 305-312 [in English]. ISSN 0257-8972. PHOTOCOPY ORDER NUMBER: 199804-57-0548.

Structural Reaction Injection Molded Process

Assessment of Thermal Spray SRIM Composites. Material and mechanical properties of structural reaction injection molded (SRIM) composites manufactured with the thermal spray (TS) preforming process are investigated analytically and experimentally. Flexure, compressive, and tensile coupon tests are conducted to obtain respective moduli and strength. In addition to classical flat coupons, hat beams are tested to assess structural response. The elastic constants obtained from the coupon tests were used in the finite element models of the hat beam flexure tests that provided good agreement with the experimental load-deflection response.

O.O. Ochoa, J.H. Barron, and B.W. Hill. Cited: *American Society for Composites: Twelfth Technical Conference* (Proc. Conf.), Dearborn, MI, 6-8 Oct 1997, Technomic Publishing, 1997, p 817-825 [in English]. ISBN 1-56676-606-0. PHOTOCOPY ORDER NUMBER: 199804-E1-D-0089.

Corrosion

Al-5Mg Coatings for Thermal Insulation Corrosion

Corrosion Protection under Thermal Insulation—The Use of Coatings to Mitigate Corrosion. An experimental study to determine how effective coatings are at mitigating corrosion under situations relevant for thermally insulated pipelines has been performed. The emphasis has been to study stainless steel materials (austenitic UNS S 31603 and the duplex, UNS S 31803). At a steel surface temperature or 70 °C and higher, the austenitic AISI 316L was very susceptible to stress-corrosion cracking. Blistered or damaged organic coatings will not mitigate corrosion of the 316L. The duplex stainless steel did not develop chloride stress-corrosion cracking over a four-month exposure, at 120 °C. Thermally sprayed Al5Mg can mitigate general corrosion, pitting, and cracking on 316L in areas with coating damage.

K.P. Fischer, L.D. Brown, and J. Murali. Cited: *EUROCORR '97,* Vol I (Proc. Conf.), Trondheim, Norway, 22-25 Sept 1997, Norwegian University of Science and Technology, 1997, p 357-362 [in English]. PHOTOCOPY ORDER NUMBER: 199805-35-0756.

High-Temperature Oxidation of Zirconium-Containing Iron Aluminide

Microstructure of Alumina Scales and Coatings on Zirconium-Containing Iron Aluminide Alloys. In the present study, thermally grown oxide scales on Zr-doped, Fe_3Al-base alloys are compared with those formed after oxidation of plasma-deposited alumina coatings on the same alloy. The oxide scales on both the coated and on the uncoated Zr-containing alloy were well adherent. After 96 h at 1273 K, both scales were entirely α-Al_2O_3. The presence of the coating, which is primarily amorphous in the as-deposited state, resulted in thicker oxide scales with long oxide needles at the scale/gas interface, indicating primarily outward growth. The oxidation also roughened the metal/oxide interface, indicating some oxide growth at this interface. Zirconium was found to be segregated at oxide grain boundaries as well as at the scale/metal interface of both the coated and the uncoated material, in addition, Zr-rich metallic precipitates were found at the scale/metal interface of the coated alloy after oxidation. Zirconium-rich oxide particles were found in regions of the oxide scale that correspond to the crystallized coating. It is proposed that the primarily amorphous coating promotes the nucleation and growth of metastable alumina phases, resulting in slightly enhanced oxidation and thicker scales. Due to crystallization and phase transformation of the coating to α-Al_2O_3, the transport properties of the scale change during the oxidation process and oxygen inward diffusion would occur after crystallization of the coating.

K.B. Alexander, P.Y. Hou, K. Prüssner, and P.F. Tortorelli. Cited: *Microscopy of Oxidation* (Proc. Conf.), Cambridge, UK, 16-18 Sept 1996, Institute of Materials, 1997, p 246-255 [in English]. ISBN 1-86125-034-7. PHOTOCOPY ORDER NUMBER: 199805-34-0403.

Protection by Silicon and Chromium-Base Materials

Protection of Carbon Steel against Hot Corrosion Using Thermal Spray Silicon- and Chromium-Base Coatings. A Fe75Si thermal spray coating was applied on the surface of a plain carbon steel baffle plate. Beneath this coating, a Ni20Cr coating was applied to give better adherence to the silicon coating. The baffle was installed in the high-temperature, fireside, corrosion zone of a steam generator. At the same time, an uncoated 304 stainless steel baffle was installed nearby for comparison. For 13 months the boiler burned heavy fuel oil with high contents of vanadium. The samples were studied employing scanning electron microscopy, x-ray microanalysis, and x-ray diffraction techniques. After that, it was possible to inspect the structural state of the components, and it was found that the stainless steel baffle plates were destroyed almost completely by corrosion, whereas the carbon steel coated baffle plate did not suffer a significant attack, showing that the performance of the thermal spray coating was outstanding and that the coating was not attacked by V salts of the molten slag.

J. Porcayo-Calderon, J.G. Gonzalez-Rodriguez, and L. Martinez. Cited: *J. Mater. Eng. Perform.*, Vol 7 (No. 1), Feb 1998, p 79-87 [in English]. ISSN 1059-9495. PHOTOCOPY ORDER NUMBER: 199804-35-0648.

Steel Structures and Infrastructure

Corrosion of Steel Structures of China's Coastal Ships and Arc Spray Protection Measures. Steel structures on ships operate in sea environment and can be subject to severe corrosion. Current practice in China for corrosion protection for large steel structures is traditional organic coating. The protection in service is effective only for one to two years. Composite coatings consisting of aluminum are sprayed and organic layers can effectively increase the service life of such structures. The composite layers developed consist of an electric arc sprayed aluminum layer followed by a layer of organic paint to seal the aluminum coating, followed by a layer of conventional ship's paint.

M. Dan, X. Binshi, W. Jianjun, and M. Shining. Cited: *EUROCORR '97*, Vol I (Proc. Conf.), Trondheim, Norway, 22-25 Sept 1997, Norwegian University of Science and Technology, 1997, p 387-393 [in English]. PHOTOCOPY ORDER NUMBER: 199805-35-0761.

Diagnostics

In-Flight Particle Measurements of the Two Wire Arc Process

In-Flight Particle Measurements of Twin Wire Electric Arc Sprayed Aluminum. A real-time, nonintrusive measurement technique was successfully applied to a Tafa Model 9000 (TAFA Inc., Concord, NH) twin wire electric arc thermal spray system to simultaneously measure particle size, velocity, and temperature within the spray plume. Aluminum wire was sprayed with the current varied from 100 to 300 amp, and the gun pressure (air flow rate) varied from 40 to 75 psia. For all cases, the average sizes of the molten Al particles along the spray centerline range from 33 to 53 μm. The particles accelerate to peak velocities between 130 and 190 m/s, then decelerate slightly as they travel downstream. The average centerline particle temperature ranges from 2004 to 2056 °C, and the temperature profile remains fairly flat throughout transport to the substrate. A stagnation pressure probe was used to quantify the gas flow regime in the unladen jet. The wires were found to have a pronounced effect on the flow, resulting in a complex three-dimensional flowfield with mixed regions of subsonic and supersonic flow.

D.L. Hale, D.C. Haggard, and W.D. Swank. Cited: *J. Therm. Spray Technol.*, Vol 7 (No. 1), March 1998, p 58-63 [in English]. ISSN 1059-9630. PHOTOCOPY ORDER NUMBER: 199806-58-0636.

Equipment

Hybrid High-Velocity Oxgen Fuel Process

Hybrid HVOF: The System and its Applications. In the thermal spray industry, new surfacing techniques and equipment tend to be developed as a way of solving an industrial problem. The high-velocity oxyfuel process is one example of this. Applications discussed include the U.S. Navy's use of such technology to apply SM5803, a tungsten carbide and nickel alloy, for applications to be subjected to saltwater corrosion.

T. Reeve. Cited: *Prod. Finish. (London)*, Vol 51 (No. 1), Dec 1997-Jan 1998, p 10-11 [in English]. ISSN 0032-9762. PHOTOCOPY ORDER NUMBER: 199806-57-0914.

Microplasma Spraying and Surfacing

Set for Microplasma Spraying and Surfacing. The set is destined for metal and ceramics coatings applying by plasma method. It is characterized by small sizes and mobility. The use of the set allows spraying the coatings at a surface of any configuration and fusing the coatings of self-fluxing alloys using the same plasmotron that spraying produces. The set is recommended for applying the coatings to small-sized components. The pilot-plant examination of equipment is successful.

Yu.N. Pereverzev and Yu.S. Borisov. Cited: *Avtom. Svarka*, No. 10, Oct 1997, p 60-61 [in Russian]. ISSN 0005-111X. PHOTOCOPY ORDER NUMBER: 199805-55-1347.

Feedstock

Molybdenum-Base Alloys for HVOF Processing

Thermal Spraying of Mo_2NiB_2-Ni Cermet. A new significant thermal sprayed film was obtained by HVOF thermal spraying. The microstructure of this film was composed of dispersed ternary borides: $(Mo, W)_2NiB_2$ and matrices alloy: Ni-Mo. The spraying powder was prepared by milling of monoborides and metal powders, agglomerating, semisintering, and screen classification. The dense sprayed film with this powder had high hardness, especially at high temperature, and was not brittle relative to other ceramics and metal composite films. Heat treatments could raise the bonding strength of this sprayed layer to steel substratum, was higher than three times conventional thermal sprayed ceramics films. Abrasive volume of the specimen with this thermal spray was smaller than the Cr_3C_2-Ni/Cr thermal sprayed specimen in collision test by aluminum oxide particles at 700 °C.

K. Hamashima, Y. Shinozaki, and M. Sasaki. Cited: *Advances in Powder Metallurgy and Particulate Materials—1997*, Vol 1 (Proc. Conf.), Chicago, IL, 29 June-2 July 1997, Metal Powder Industries Federation, 1997, p 2.43-2.49 [in English]. PHOTOCOPY ORDER NUMBER: 199805-58-0531.

Nanophase Materials

Preparation of Nanophase Materials by Thermal Spray Processing of Liquid Precursors. Thermal spray processes were modified to spray liquid feedstocks. Nanophase Al_2O_3, Mn_2O_3, ZrO_2, and Y_2O_3-stabilized ZrO_2 powders and deposits were produced. Ceramic particles of 1 to 150 nm size were collected at a rate of ~20 mg/min, with ~20 to 35% collection efficiency. Organometallic precursors produced oxide deposits with a powdery morphology, while aqueous solutions yielded hydroxide deposits, requiring postspray heat treatments for producing oxide coatings. Spray feedstock and processing conditions affected the size, shape, and phase composition of the synthesized nanomaterials. Particles with wider distributions of larger size grains were produced from aqueous solutions, while a narrow distribution of fine-grained materials were produced when organometallic precursors were used.

J. Karthikeyan, C.C. Berndt, H. Herman, A.H. King, J. Tikkanen, and J.Y. Wang. Cited: Third International Conference on Nanostructured Materials (Proc. Conf.), Kona, HI, 8-12 July 1996, *Nanostructured Mater.*, Vol 9 (No. 1-8), 1997, p 137-140 [in English]. ISSN 0965-9773. PHOTOCOPY ORDER NUMBER: 199806-E4-C-0219.

Nickel Aluminide Properties

Processing, Microstructure, and Fracture Behavior of a Spray Atomized and Deposited Nickel Aluminide Intermetallic. In this study, nickel aluminide intermetallics (Ni_3Al) were synthesized using the spray atomization and deposition technique. Microstructure characterization studies were performed to provide an understanding of the intrinsic influence of spray processing parameters on the microstructure of the intermetallic. Numerical simulation was carried out to provide an understanding of the influence of deformation, heat transfer kinetics, and thermal history of the droplets on the thermal profile, distribution, and solidification. The microstructure of the intermetallic is discussed in the light of results obtained from experimental observations and numerical simulation. Ambient-temperature tensile tests reveal the intermetallics to have a high strength and acceptable ductility. The tensile fracture behavior of the polycrystalline intermetallic is presented and discussed in the light of processing and thermal conditions during spray deposition and intrinsic microstructural effects.

D. Lawrynowicz, T.S. Srivatsan, E.J. Lavernia, and X. Liang. Cited: *J. Mater. Sci.*, Vol 33 (No. 6), 15 March 1998, p 1661-1675 [in English]. ISSN 0022-2461. PHOTOCOPY ORDER NUMBER: 199806-54-0738.

WC-Co Materials

Parameter Study of HP/HVOF Deposited WC-Co Coatings. The deposition parameters of WC-17% Co coatings produced using the JP-5000 liquid-fuel HP/HVOF system (Eutectic TAFA) were investigated with the initial purpose of parameter improvement and optimization. The coating microstructures, porosities, phase compositions, and abrasion resistance were characterized. Preliminary work using the Taguchi statistical experimental design method aimed at optimizing the spray parameters in terms of the microstructure and phase composition was unsuccessful. The variations in the measured properties were too small to be correlated with the spray parameters. Subsequent experiments showed this was primarily due to the fact that the properties, particularly the abrasion resistance, of the WC-Co coatings were not primarily influenced by variations in the spray parameters, but were more dependent on the powder composition, particle size range, and manufacturing route. Hence, the application of Taguchi techniques would have been more effective over a much wider parameter space than was originally used. This result is valuable because it suggests that this process is robust and can be used for WC-Co coatings without large investments in spray parameter optimization and control once the coating and powder type have been fixed.

H.L. de Villiers Lovelock, J.M. Benson, P.W. Richter, and P.M. Young. Cited: *J. Therm. Spray Technol.*, Vol 7 (No. 1), March 1998, p 97-107 [in English]. ISSN 1059-9630. PHOTOCOPY ORDER NUMBER: 199806-57-0847.

Microstructure

Molybdenum and Cobalt Alloys

Phase Transformation Behaviors and High-Temperature Mechanical Properties of Plasma Sprayed Mo and Co Alloy Coating Layers. Phase transformation behaviors and high-temperature mechanical properties of Mo and Co alloy coating layers made by plasma spray coating method have been investigated by means of optical microscopy, x-ray diffraction, high-temperature microvickers hardness, and wear tests. The splat is relatively flat with the boundary in Mo coating layers, but wavy in Co alloy coating layers at high

temperature. Crystallization of Co alloy coating layers that were amorphous at room temperature started to occur at ~1073 K and consequently Co_7Mo_6 and Co_3Mo compounds were formed. Wear volume of Co alloy coating layers almost kept constant with increasing temperature <1073 K, and then started to increase at 1073 K. This was attributed to the crystallization that resulted in decrease in hardness. Wear resistance of Co alloy coating layers was superior to that of Mo coating layer over all test temperatures.

T.-H. Nam, G.-B. Cho, G.-H. Ha, B.-K. Kim, and S.W. Lee. Cited: *J. Korean Inst. Met. Mater.*, Vol 35 (No. 10), Oct 1997, p 1380-1385 [in Korean]. ISSN 0253-3847. PHOTOCOPY ORDER NUMBER: 199804-58-0425.

NiCr-Al Diffusion Couples

Application of Image Analysis in the Study of NiCr-Al Diffusion Couples Produced by Thermal Plasma Spraying. Metallography and image analysis were applied to study a plasma sprayed Ni20Cr coating on an Al substrate and the structure evolution by diffusion during the heat treatment of these couples. The results show that while the thickness of layers could be measured almost automatically, the particle characterization required some caution as manual editing and careful selection of the magnification.

J. Krejcová, J. Brezina, O. Ambroz, and J. Krejci. Cited: *Prakt. Metallogr.*, Vol 35 (No. 2), Feb 1998, p 71-79 [in English and German]. ISSN 0032-678X. PHOTOCOPY ORDER NUMBER: 199806-58-0672.

Processing of D-Gun Coatings

The Lamellar Structure of a Detonation Gun Sprayed Al_2O_3 Coating. The structural features of a detonation gun sprayed Al_2O_3 coating were examined using a copper electroplating technique. It is revealed that the detonation gun sprayed Al_2O_3 coating has a typical layer structure similar to that of coatings deposited using other thermal spraying processes. Despite having the highest particle velocity of the thermal spraying processes, lamellar bonding at the interfaces between flattened particles in detonation gun sprayed Al_2O_3 coatings is very poor. The mean bonding ratio of bonded interface area to apparent bonding interface for a typical detonation gun Al_2O_3 coating is about 10%, which is less than one-third the value for a typical plasma sprayed Al_2O_3 coating. However, the high particle velocity results in the formation of a rough surface on the spray splat, which may be effective in enhancing interlocking between flattened particles.

C.-J. Li and A. Ohmori. Cited: *Surf. Coat. Technol.*, Vol 82 (No. 3), 1 Aug 1996, p 254-258 [in English]. ISSN 0257-8972. PHOTOCOPY ORDER NUMBER: 199804-57-0455.

Thermal Barrier Coatings

Microstructural Changes and Phase Transformations in a Plasma Sprayed Zirconia-Yttria-Titania Thermal Barrier Coating. A thermal barrier coating comprising a zirconia-yttria-titania ceramic coat deposited by plasma spraying on an alloy steel substrate using an Ni-Cr-Al-Co-Y intermediate bond coat has been soaked at various temperatures in the range 700 to 1400 °C and cooled to room temperature in static air. Some thermal treatments were also carried out in an argon atmosphere. Scanning electron microscopy (SEM) studies show that a discontinuous thickness of the bond coat is the reason for the failure of the coating due to thermal treatment. The phase transformations and microstructural changes due to thermal treatment have been investigated using x-ray diffraction and SEM. Thermal treatment did not affect the monoclinic phase of the ZrO_2 content present in the ceramic coat. In the case of thermal treatment in air and argon (<800 °C) the cubic tetragonal phase transformation occurred. The appearance of the fracture surfaces of the ceramic coat suggests that interlamellar fracture in the as-sprayed condition changed to intralamellar fracture after thermal treatment <1200 °C. At higher temperatures, the fractures were intergranular in appearance. Reasons for these changes in the appearance of the fracture surfaces are suggested with reference to the microstructure. Microstructural investigations also show some changes in the area of porosity distribution of the ceramic coat. Thermal treatment heals some pores, but other voids appear (cracking of the coating).

P. Diaz, M.J. Edirisinghe, and B. Ralph. Cited: *Surf. Coat. Technol.*, Vol 82 (No. 3), 1 Aug 1996, p 284-290 [in English]. ISSN 0257-8972. PHOTOCOPY ORDER NUMBER: 199804-57-0457.

Modeling

Computational Fluid Dynamics of the High-Velocity Oxygen Fuel Process

Computational Analysis of a Three-Dimensional High-Velocity Oxygen Fuel (HVOF) Thermal Spray Torch. An analysis of a high-velocity oxygen fuel thermal spray torch is presented using computational fluid dynamics (CFD). Three-dimensional CFD results are presented for a curved aircap used for coating interior surfaces such as engine cylinder bores. The device analyzed is similar to the Metco diamond jet rotating wire torch, but wire feed is not simulated. The feed gases are injected through an axisymmetric nozzle into the curved aircap. Argon is injected through the center of the nozzle. Premixed propylene and oxygen are introduced from an annulus in the nozzle, while cooling air is injected between the nozzle and the interior wall of the aircap. The combustion process is modeled assuming instantaneous chemistry. A standard, two-equation, k-ε turbulene model is employed for the turbulent flow field. An implicit, iterative, finite volume numerical technique is used to solve the coupled conservation of mass, momentum, and energy equations for the gas in a sequential manner. Computed flow fields inside and outside the aircap are presented and discussed.

B. Hassan, A.R. Lopez, and W.L. Oberkampf. Cited: *J. Therm. Spray Technol.*, Vol 7 (No. 1), March 1998, p 71-77 [in English]. ISSN 1059-9630. PHOTOCOPY ORDER NUMBER: 199806-58-0637.

Finite Element Method for Residual Stresses

Effects of Thermal Gradient and Residual Stresses on Thermal Barrier Coating Fracture. Driving mechanisms that lead to internal crack growth and failure in the thermally sprayed coatings are identified using detailed finite element models. Coatings are assumed to contain embedded cracks, and they are thermally loaded according to a typical high-temperature environment. In order to determine the accurate stress state, the thermal gradient within the coating is calculated from the steady-state heat transfer analysis. Our models take into account various locations of cracks, temperature-dependent and temperature-independent plasticity, thermal conductivities of different layers and thermal insulation across crack surface. The results indicate that the energy release rate of large cracks can reach close to fracture toughness of ceramic coatings. We have also studied the effect of residual stresses on the fracture behavior. For a penny-shaped crack located parallel to the coating layers, a limited influence of residual stresses is observed. The effect is more pronounced when the crack orientation is perpendicular to the coating layers where it has shown a beneficial influence. In both cases, the effects of residual stresses are relevant to the cracks close to the ceramic-bond interface. In addition, we have modeled functionally graded material and investigated its mechanical influence on the embedded cracks. The implications of the present work to internal crack initiation and growth, which can lead to coating failure, are also addressed. (Example materials: yttria-stabilized zirconia coating on nickel CrAlY interphase on titanium alloy Ti64 substrate. Also considered: functionally gradient materials and an alumina-titania system.)

T. Nakamura, C.C. Berndt, and G. Qian. Cited: *Mech. Mater.*, Vol 27 (No. 2), Feb 1998, p 91-110 [in English]. ISSN 0167-6636. PHOTOCOPY ORDER NUMBER: 199806-57-0915.

Finite Element Method of TBCs

Characterization of ZrO_2-7 wt% Y_2O_3 Thermal Barrier Coatings with Different Porosities and FEM Analysis of Stress Redistribution During Thermal Cycling of TBCs. Superalloy samples (IN 738) were coated with thermal barrier coatings (TBC). This TBC system consisted of two layers. The first layer was a vacuum plasma sprayed, corrosion-resistant layer (MCrAlY) that also acted as a bond coat. The ceramic top layer was atmospheric plasma sprayed Y_2O_3 partially stabilized ZrO_2. In order to produce different microstructures, the plasma spraying parameters for the production of the ceramic coatings were varied. The different ceramic coatings were characterized in terms of porosity and mean elastic modulus. The porosity distribution was also investigated due to its influence on the measured elastic modulus. One series of TBC coated specimens was cyclically oxidized at a maximum temperature of 1100 °C. After 500 h of thermal cycling, creep within the MCrAlY bond coat led to a coating failure at both the internal beveled edge and free edge around the specimen. A finite element analysis study of the cyclic oxidation experiment was performed to gain insight into the stress redistributions within the bond coat as a function of time. During the initial temperature increase, critical tensile normal stresses developed within the zirconia coating at the free edge. However, these normal stresses became compressive for all following cooling cycles. On the other hand, large tensile normal stresses developed within the zirconia coating at the beveled edge during all the cooling cycles. Therefore, high normal stresses responsible for debonding were present within the zirconia coating during all cooling cycles, with the most critical stresses occurring at the free edge during the first cooling cycle and near the beveled edge for all the following cooling cycles.

C. Funke, B. Siebert, D. Stöver, R. Vassen, and J.C. Mailand. Cited: 24th International Conference on Metallurgical Coatings and Thin Films (Proc. Conf.), San Diego, CA, 21-25 April 1997, *Surf. Coat. Technol.*, Vol 94-95 (No. 1-3), Oct 1997, p 106-111 [in English]. ISSN 0257-8972. PHOTOCOPY ORDER NUMBER: 199805-57-0641.

Splat Formation of Tin, Copper, and Nickel Droplets

Splat Formation of Molten Tin, Copper, and Nickel Droplets. Plasma spraying and other deposition or coating techniques cause splat formation of the molten droplets. This paper presents free-falling and splat-formation experiments in which molten droplets of Sn, Cu, and Ni were impinged on the cooled 304 substrate and solidified after the flattening process. The flattening ratio, defined as the flattening disk diameter to the droplet diameter, was measured under different conditions. The obtained results were different

from the proposed theories, which neglect the solidifying effect. The flattening ratio experimentally obtained was proposed with respect to Re and We numbers, independently. The unevenness ratio was introduced and is defined by the contour length of the flattening disk to the circumferential length of an equivalent circle that has the same area as the flattening disk. This was measured with respect to Re and We numbers and represented an experimental formula of the unevenness ratio. It was concluded that the unevenness ratio was closely related to surface tension and impinging velocity.

S. Amada, M. Haruyama, and K. Tomoyasu. Cited: *Surf. Coat. Technol.*, Vol 96 (No. 2-3), 25 Nov 1997, p 176-183 [in English]. ISSN 0257-8972. PHOTOCOPY ORDER NUMBER: 199804-58-0444.

Postprocessing

Laser Remelting

X-ray Imaging of Laser Remelted Plasma Sprayed Zirconia Coating. The purpose of this letter is to describe observations obtained by x-ray imaging of the crack propagation, porosity, residual strain, and mass distribution of laser posttreated plasma sprayed zirconia coating. The test samples were prepared by plasma spraying ~0.4 mm thick commercially pure zirconia on a 3 mm thick Al6061 aluminum alloy sheet and then laser remelting the coating using an Nd-YAG laser. X-ray imaging is found to provide a nondestructive means to characterize surface coatings such as plasma sprayed coatings. It was found to be effective in acquiring simultaneously data on internal cracking, residual stress, porosity, and mass distribution in the coating.

X. Huting, A.W. Batchelor, M. Chandrasekaran, and F. Yongqing. Cited: *J. Mater. Sci. Lett.*, Vol 17 (No. 2), 15 Jan 1998, p 163-165 [in English]. ISSN 0261-8028. PHOTOCOPY ORDER NUMBER: 199805-57-0706.

Pulsed Laser Modification of Hydroxyapatite

Pulsed Laser Treatment of Plasma Sprayed Hydroxyapatite Coatings. Plasma sprayed hydroxyapatite (HA) coatings have complex microstructures. There are often variations in phase, structure, and chemical composition among the starting material and coating. Some of these changes may not be acceptable for biomedical applications. Attaining all the requirements for a functional coating in a single spraying process is not easily achieved. Additional posttreatment may be necessary. This study examines the use of a pulsed laser to enhance the coating characteristics of plasma sprayed HA coatings. Preliminary results show the laser-treated coatings having a modified microstructure with crack networks and pores in the size range 5 to 30 μm. The pores and cracks were quantified by an image analyzer. The crack network is less significant in coatings that are treated at lower energy intensity, and this could be interesting in that the laser can be used to alter the surface phase composition and the morphology. However, repetitive passes with the pulsed laser did not help to seal the cracks that formed.

K.A. Khor, P. Cheang, S.C. Tam, and L.L. Teoh. Cited: *Biomaterials*, Vol 17 (No. 19), Oct 1996, p 1901-1904 [in English]. ISSN 0142-9612. PHOTOCOPY ORDER NUMBER: 199804-57-0537.

Processes

Diamondlike Coatings

The Elaboration of Diamond Coatings on Plates of Cutting Tools. The exceptional mechanical properties of diamond-type coatings let us anticipate the wide range of possible applications, in particular in cutting tools for materials. Since 1990, intensive research has been developed in the coatings processes. One of the processes discussed, the flame method, was mentioned for the first time in 1988 by Hirose and Kondo in Japan and later (1994), taken up by the LPMM laboratory-ERMES team (URA CNRS 1215). This method allows diamond-type coating deposits on very localized sites such as on cutting tools with a high growth speed and an excellent quality. (Machining tests performed on AU4G aluminum, turning.)

D. Paulmier, J.F. Larose, T.L. Huu, T. Mathia, J. Rousseau, H. Zahouani, and H. Zaidi. Cited: Evolution of Cutting Materials (L'évolution des Matériaux pour Outils de Coupe) (Proc. Conf.), Saint-Étienne, France, 13-14 Nov 1996, *Bull. Cercle Étud. Métaux*, Vol 16 (No. 13), Nov 1996, p 20.1-20.14 [in English and French]. ISSN 0366-4104. PHOTOCOPY ORDER NUMBER: 199806-57-0852.

Flame Sprayed Chromium Coatings

High-Speed Flame Sprayed Chromium Coatings Wear and Corrosion Protection. Faced with the ever more restrictive environmental legislation, increased alternatives are being sought in surfacing technology for the galvanic manufacture of wear- and corrosion-protective coatings. For this, the thermal spraying of chromium coatings in thicknesses of ~100 μm should provide a possible alternative. High-speed flame spraying offers advantages over other processes for processing pure Cr, because it enables the formation of toxic Cr^{6+}-vapors to be prevented by adjustment of the flame temperature. Thin layers with properties comparable to those of electroplated coatings were produced. Substrate was St37-2 steel.

E. Lugscheider and H. Reymann. Cited: *Schweissen Schneiden*, Vol 50 (No. 2), Feb 1998, p E36-E39 [in English]. ISSN 0036-7184. PHOTOCOPY ORDER NUMBER: 199806-57-0842.

Reactive Spraying of 80/20 Ni/Cr Powders

Reactive Plasma Spraying of 80/20 Nickel-Chromium Powders. Results are reported from a study of the reactive plasma spraying of 80/20 Ni-Cr powders while injecting methane gas into the reactor of a modified APS system. Coatings exhibiting improved mechanical properties, e.g., higher hardness, have been deposited, and the change in properties has been correlated with processing conditions and microstructure. The conversion of a conventional d.c. plasma torch to undertake reactive plasma spraying has resulted in significant modifications to the microstructure and properties of 80/20 Ni-Cr deposits. A graphite reactor has been used that increases the residence time for chemical reactions to occur within the plasma. Furthermore, adjusting powder characteristics, for example reducing powder particle size to increase powder surface area, can produce conditions that result in enhanced reactivity and a greater degree of coating modification.

O. Al-Sabouni, J.R. Nicholls, and D.J. Stephenson. Cited: *J. Mater. Sci. Lett.*, Vol 17 (No. 5), 1 March 1998, p 377-379 [in English]. ISSN 0261-8028. PHOTOCOPY ORDER NUMBER: 199805-54-0580.

Processing

Diamondlike Coatings

Synthesis of Diamond by Thermal Plasma CVD on Blasted Mo Substrate. Diamond synthesis by thermal plasma CVD on blasted Mo substrate was conducted, and the effect of substrate roughening on diamond nucleation and growth behavior was fundamentally investigated. The results obtained are summarized as follows. By using the conventional plasma spraying torch, triangular or rectangular automorphic diamond could by synthesized under CH_4/H_2 ratio of 1% and torch-substrate distance of 80 mm. When diamond scratched substrates are used, the effect of diamond seeds on the promotion of diamond nucleation was recognized, while the micro defects did not always have a serious influence on that. When blasted substrates are used, the promotion effect of surface roughness on the diamond growth is noticeable at longer blasting time. This promotion seems to be attributed to the promotion of the carbide formation of the substrate material, and followed by the diamond formation.

M. Fukumoto, M. Ariga, and Y. Yokoyama. Cited: *Nippon Yosha Kyokai Shi (J. Jpn. Therm. Spraying Soc.)*, Vol 34 (No. 3), Sept 1997, p 127-134 [in Japanese]. ISSN 0916-6076. PHOTOCOPY ORDER NUMBER: 199804-57-0544.

LPPS of NiCrAlY Coatings

Formation of NiCrAlY/NiAl Multilayered Coating by Low-Pressure Plasma Spraying. NiCrAlY/NiAl multilayered coating was produced on SUS310S steel by means of mutual low-pressure plasma spraying of NiCrAlY and Al powders that was accompanied with self-propagating high-temperature synthesis (SHS) reaction of metal deposits. The NiAl layer contained Ni_3Al particles and Cr_2Al phase along the fine grain boundary. Also, Ni_3Al was detected in the NiCrAlY layer with a small amount of NiAl particles. As the result, high hardness was obtained in both the layers, i.e., 650 HV in NiAl layer and 450 HV in NiCrAlY one at 673 K. The structure of the multilayered coating hardly changed during annealing <973 K because enriched Cr at NiCrAlY/NiAl interface suppressed NiAl + $Ni_3AlNi_5Al_3$ peritectoid reaction. The SHS reaction time of an compressed Al droplet in diameter of 50 μm was calculated as 4.17 × 10^{-3} seconds.

H. Takizawa, M. Kobayashi, K.-I. Sugimoto, and K. Yonehama. Cited: *J. Soc. Mater. Sci., Jpn.*, Vol 46 (No. 12), Dec 1997, p 1436-1441 [in Japanese]. ISSN 0514-5163. PHOTOCOPY ORDER NUMBER: 199805-57-0693.

Residual Stresses

HVOF Processes

Residual Stresses in Structures Coated by a High-Velocity Oxy-fuel Technique. The high-velocity oxyfuel thermal spray coating technique is investigated with regard to the residual stresses that can develop in the coating and in the coated material. The hole-drilling strain-gage method is used to measure the stresses. Different preheating temperatures of the specimen surface and the influence of the coating thickness are explored. Substrate was 316L stainless steel; coating was Diamalloy 1003, a premium-grade austenitic stainless steel similar to 316.

M.S.J. Hashmi, C. Pappalettere, and F. Ventola. Cited: *J. Mater. Process. Technol.*, Vol 75 (No. 1-3), March 1998, p 81-86 [in English]. ISSN 0924-0136. PHOTOCOPY ORDER NUMBER: 199806-58-0676.

Thermal Barrier Coatings

A new electrocoating system for cast iron-installation and start up. In the early 1990s, Vermont Castings, Inc. became interested in improving its capacity utilization by finding more work for our foundry and enameling departments. An extensive review of the market for enameled gray cast iron showed one particular family of products where we might be able to provide a service to potential customers. These products were enameled cast iron burner grates for gas cooking ranges. The greatest advantage we felt we could provide was that we have our own captive foundry and enameling facilities. Examining the large variety of burner grates being produced by appliance manufacturers, it was obvious that design was limited only by an engineer's imagination. Several different enamel application techniques were investigated for production application of the enamel to these grates, including manual spraying, automatic spray application, electrostatic spraying and electrophoretic dip application (EPE). Manual spraying was quickly rejected due to the complexity of the parts and the problem of ensuring uniform thickness of application within tight tolerances. Automatic spraying was considered seriously, the issue here being material transfer efficiency. Electrostatic spraying was also seriously investigated. Both wet and powder application seemed to be possibilities. However, potential areas of high current density and Faraday cage effects caused concern regarding uniformity of application thickness on all surfaces of the castings.

L. O'Bryne (Vermont Castings). *Vitr. Enameller,* Summer 1997, Vol 48 (No. 2), p 40-42 [in English]. ISSN 0042-7519.

Review

Continual Development in the Thermal Spray Industry. The thermal spray industry has developed into a major consumer of metal powders since its development in the 1920s. The industry now consumes in excess of 400,000 kg/year of a variety of materials including tungsten and chrome carbides, and nickel- and iron-base powders. Article provides an overview of the industry and its latest developments.

T. Lester. Cited: *Weld. Join.*, March 1998, p S4-S6 [in English]. ISSN 0819-8277. PHOTOCOPY ORDER NUMBER: 199806-54-0741.

Plasma Arc Powder Surfacing—Comparison of Standard and High-Productivity Processes. In the last few years, there have been efforts to make use of the advantages of plasma arc powder surfacing with increased deposition rates. Installations for a high-productivity variation of plasma arc powder surfacing have been developed for this purpose. It has been proven that, with the aid of constant energies per unit length and by optimizing the welding parameters, it is possible to achieve comparable structural conditions not only with the standard process but also with the high-productivity process. The influence of the most important welding parameters on the coating results was investigated. Using a spectral pyrometer for high-speed processes, it was possible to compare the molten-pool temperatures of both process variations and to establish the suitability of the pyrometer as a sensitive measuring instrument for process regulation or control.

R. Lugscheider and G. Langer. Cited: *Schweissen Schneiden*, Vol 50 (No. 2), Feb 1998, p 96, 98-101 [in German and English], p E28-E31. ISSN 0036-7184. PHOTOCOPY ORDER NUMBER: 199806-58-0634.

Testing

Acoustic Emission for Cracking Studies

Observation on Cutting Phenomena of Sprayed Ceramics by Acoustic Emission Method. This paper describes the relationship between a cutting event and the generated acoustic emission (AE) information. The AE method enabled us to collect the time-dependent information on cracks and damage when a flame coating layer is cut. Four types of Al_2O_3-TiO_2 ceramics were used as substrates for plate by plasma spraying. The straight groove was made on the surface of the sprayed coating using a sintered diamond tool at a low cutting speed and low cutting depth. The AE information was collected with an AE sensor placed on the end face of the workpiece to process the number of AE events and the AE level which changed with cutting time. The ceramics coating was formed by piling up fine particles on the substrate. A crack that was formed during cutting extended along the particle boundary of the sprayed coating. Especially, the scale of crack was greatly affected by cutting depth. As the depth of cut increased, the scale of cracks enlarged and block-form chips were ejected. But when cutting was made with a shallower cutting depth than the thickness of the coating particles, fine powder-form chips were ejected. The AE information varied depending on the scale of cracks and damage. With increasing cutting depth, the number of AE events decreased and the noise increased. The AE method successfully detected the movements of cracks and damage generated by cutting in real time and presented information useful for qualitative evaluation of the cutting condition.

Y. Inui, T. Ikuta, S. Ito, and M. Yoshihara. Cited: *Zairyo Gijutsu (Mater. Technol.)*, Vol 15 (No. 7), Sept 1997, p 253-260 [in Japanese]. ISSN 0289-7709. PHOTOCOPY ORDER NUMBER: 199804-E3-C-0075.

Cohesion of Coatings

Cohesion in Plasma Sprayed Coatings—A Comparison between Evaluation Methods. The integrity, and especially, the cohesive strength of alumina plasma sprayed coatings prepared from a range of precurser powders of different size and crystallinity has been investigated by several different methods. Several chromia and alumina-titania coatings, and a sintered bulk alumina, have also been studied for comparison and reference purposes. Methods of characterization have included assessment of the coatings resistance to open tribosystem wear by dry particle erosion and abrasion on the one hand, and their resistance to mechanical failure during controlled scratch testing and tensile fracture in four-point bending on the other. Controlled scratching was carried out on both top and cross sections, with the cross-sectional scratching done inside a scanning electron microscopy (SEM). Bending was carried out, in ambient conditions, using test equipment small enough to be placed in the SEM, in order to observe the progressive cracking behavior and failure of the coatings. Some correspondence was found between most of the techniques/methods studied, but erosion and abrasion with large, hard particles and scratch testing on both top surfaces and cross sections provided the best correlation. It is concluded that these are the most promising methods found so far to rank the cohesion characteristics of plasma sprayed coatings.

L.C. Erickson, H.M. Hawthorne, N. Axén, S. Hogmark, R. Westergård, and U. Wiklund. Cited: *Wear*, Vol 214 (No. 1), Jan 1998, p 30-37 [in English]. ISSN 0043-1648. PHOTOCOPY ORDER NUMBER: 199805-31-2677.

Fatigue of High-Velocity Oxygen Fuel Coatings

Fatigue Cracks in HVOF Thermally Sprayed WC-Co Coatings. Initiation and early growth of fatigue cracks of a medium carbon steel with HVOF thermally sprayed WC-Co coatings prepared from two types of commercially available powders with similar total chemical composition were investigated under rotating bending conditions. The morphology of the fatigue crack is divided into two types, linear cracks and netlike cracks, depending on the types of powders and the thickness of the coatings. The fatigue cracks in thinner coatings were closer to each other than those for the thick coatings.

S. Watanabe, N. Sakoda, T. Tajiri, and J. Amano. Cited: *J. Therm. Spray Technol.*, Vol 7 (No. 1), March 1998, p 93-96 [in English]. ISSN 1059-9630. PHOTOCOPY ORDER NUMBER: 199806-57-0846.

Fatigue of Thermal Barrier Coatings

Investigation of Thermal Fatigue Behavior of Thermal Barrier Coating Systems. In the present study, the mechanisms of fatigue crack initiation and propagation and of coating failure under thermal loads that simulate those in diesel engines are investigated. Surface cracks initiate early and grow continuously under thermal low cycle fatigue (LCF) and high cycle fatigue (HCF) stresses. It is found that, in the absence of interfacial oxidation, the failure associated with LCF is closely related to coating sintering and creep at high temperatures. Significant LCF and HCF interactions have been observed in the thermal fatigue tests. The fatigue crack growth rate in the ceramic coating strongly depends on the characteristic HCF cycle number, N_{HCF}, which is defined as the number of HCF cycles per LCF cycle. The crack growth rate is increased from 0.36 μm/LCF cycle for a pure LCF test to 2.8 μm/LCF cycle for a combined LCF and HCF test at N_{HCF} about 20,000. A surface wedging model has been proposed to account for the HCF crack growth in the coating systems. This mechanism predicts that the HCF damage effect increases with heat flux and thus with increasing surface temperature swing, thermal expansion coefficient, and elastic modulus of the ceramic coating, as well as with the HCF interacting depth. Good correlation has been found between the analysis and experimental evidence. Substrates studied: 4140 and 1020 steels.

D. Zhu and R.A. Miller. Cited: 24th International Conference on Metallurgical Coatings and Thin Films (Proc. Conf.), San Diego, CA, 21-25 April 1997, *Surf. Coat. Technol.*, Vol 94-95 (No. 1-3), Oct 1997, p 94-101 [in English]. ISSN 0257-8972. PHOTOCOPY ORDER NUMBER: 199805-57-0640.

Fracture of Thermal Barrier Coating Oxides

Modes of Oxide Spallation from MCrAlY Overlay Coatings. Oxide scale cracking and spallation becomes a particular threat during temperature changes, due to thermal expansion mismatch strains between the scale and the underlying substrate. In most cases of cooling from the oxidation temperature, in-plane compressive stresses are developed in the scale. Various failure processes are possible depending on the scale thickness, substrate geometry, temperature transient and the mechanical properties of the materials and interfaces. The oxidation behavior of air plasma sprayed NiCrAlY and argon-shrouded plasma sprayed CoNiCrAlY coatings has been investigated in 1 atm air at 1100 °C. Scales and spallation zones were observed using scanning electron microscopy. Scale spallation invariably occurred in regions of local convex curvature of the irregular and tortuous as-sprayed coating surfaces. For the NiCrAlY coating, scale spallation caused the underlying coating to be exposed and the fracture face of the scale formed a large angle to the coating surface. A different scale morphology and scale composition for the CoNiCrAlY led to spalling by a combination of lateral shear cracking in the scale and failure

at the coating/scale interface. Mechanisms are proposed to explain the spallation configurations.

A. Strawbridge, H.E. Evans, and C.B. Ponton. Cited: *Microscopy of Oxidation* (Proc. Conf.), Cambridge, UK, 16-18 Sept 1996, Institute of Materials, 1997, p 320-329 [in English]. ISBN 1-86125-034-7. PHOTOCOPY ORDER NUMBER: 199805-58-0529.

Nondestructive Evaluation Methods for Coatings

Characterization of Plasma Sprayed Coatings Using NDE Techniques. A round-robin test was implemented where nine European research institutions and universities applied different thermal, ultrasonic, and magnetic methods for measuring the thickness of plasma sprayed coatings. The coatings, which had thicknesses ranging from 50 to 500 μm, were applied on substrates of AISI 316, a standard industrial structural material, and on Armco-iron in order to have a material of known thermal properties. Destructive testing was performed after the other methods had been applied, resulting in detailed information on the coating thickness, rugosity, and uniformity. The results obtained with the applied methods on the two unknown samples for each substrate type agreed within 20% with the destructive testing data.

L. Fabbri and M. Oksanen. Cited: *Insight*, Vol 39 (No. 12), Dec 1997, p 887-894 [in English]. ISSN 1354-2575. PHOTOCOPY ORDER NUMBER: 199804-57-0543.

Oxidation of HVOF Processed MCrAlY Alloys

The Oxidation Behavior of HVOF Thermal Sprayed MCrAlY Coatings. A new high-velocity oxygen fuel (HVOF) spraying process to produce MCrAlY coatings was developed and optimized. The HVOF sprayed MCrAlY coatings were isothermally oxidized at 950 and 1050 °C in air as well as in different oxidizing atmospheres (synthetic air, He-10% O_2 and He-10% synthetic air). The oxidation behavior of HVOF sprayed coatings is compared with that of VPS coatings. Under the chosen oxidation conditions, which assure a high oxygen partial pressure, the oxidation kinetics of the two coatings are very different, i.e., the oxidation rate of the HVOF sprayed coating is considerably lower than that of the VPS coating. In the present paper, this observation is explained by the presence of finely divided α-Al_2O_3 particles in the HVOF sprayed coating, which are formed during spraying. The Al_2O_3 probably hinders the grain boundary diffusion of the elements. As a consequence, the oxide scale growth is very low. This effect is more evident at high temperature. The as-sprayed coating as well as the oxidized coatings were examined by optical microscopy, x-ray diffraction, scanning electron microscopy, and transmission electron microscopy to study the appearance and the composition of the oxide scales and the phase transformations in the MCrAlY coating.

W. Brandl, J. Krüger, D. Toma, H.J. Grabke, and G. Matthäus. Cited: 24th International Conference on Metallurgical Coatings and Thin Films (Proc. Conf.), San Diego, CA, 21-25 April 1997, *Surf. Coat. Technol.*, Vol 94-95 (No. 1-3), Oct 1997, p 21-26 [in English]. ISSN 0257-8972. PHOTOCOPY ORDER NUMBER: 199805-35-0820.

Oxidation of Re-Containing MCrAlY Alloys

Long-Term Oxidation Tests on a Re-Containing MCrAlY Coating. The oxidation and interdiffusion properties of Re-containing NiCoCrAlY-coatings for application in gas turbines were studied in the temperature range from 950 to 1000 °C. For this purpose, cylindrical specimens of IN 738 were coated with a number of NiCoCrAlYs by vacuum plasma spraying and subsequently exposed in air under isothermal as well as thermocycling conditions. After exposure, the oxidation products, subsurface depletion layer as well as interdiffusion zone with the IN 738 substrate were analyzed by optical metallography and SEM/EDX. Very high amounts of Re led to extensive precipitation of Cr-rich phases, causing an embrittlement of the coating. Optimized coatings in respect to Re, Cr, and Al content appeared to possess excellent performance even up to exposure times of 20,000 h.

W.J. Quadakkers, W. Beele, N. Czech, and W. Stamm. Cited: 24th International Conference on Metallurgical Coatings and Thin Films (Proc. Conf.), San Diego, CA, 21-25 April 1997, *Surf. Coat. Technol.*, Vol 94-95 (No. 1-3), Oct 1997, p 41-45 [in English]. ISSN 0257-8972. PHOTOCOPY ORDER NUMBER: 199805-35-0823.

Reactivity of a Thermal Barrier Coating System

Wettability, Surface Tension, and Reactivity of the Molten Manganese/Zirconia-Yttria Ceramic System. A basic research study for improvement of plasma sprayed zirconia coatings has been conducted. The contact angle and surface tension of the molten manganese/zirconia-yttria ceramic system were measured at 1573 K by the sessile drop method, suggesting that molten Mn would spontaneously infiltrate open pores in zirconia coatings. Structure and elementary composition development of zirconia ceramics caused by reaction with Mn were examined by using scanning electron microscopy (SEM), an electron probe microanalyzer (EPMA), and an x-ray diffractometer (XRD). Manganese not only stabilized cubic zirconia, but also contributed to the growth and volume increase of zirconia particles. In this article, the mechanism of making zirconia coatings dense with Mn is discussed based on the results of experiments.

N. Shinozaki, K. Mukai, and M. Sonoda. Cited: *Metall. Mater. Trans. A*, Vol 29A (No. 3A), March 1998, p 1121-1125A [in English]. ISSN 1073-5623. PHOTOCOPY ORDER NUMBER: 199806-57-0893.

Rolling Contact Fatigue

Rolling Contact Fatigue Failure Mechanisms in Plasma and HVOF Sprayed WC-Co Coatings. The rolling contact figure (RCF) behavior of thermally sprayed WC-Co coatings with nominal compositions of WC-12%Co, WC-10%Co-4%Cr, and WC-17%Co was studied with a two-roll configuration roll-against-roll testing apparatus under 420 to 600 MPa Hertzian contact stresses in unlubricated pure rolling conditions. The coatings were prepared by atmospheric plasma spray (APS) and two high-velocity oxyfuel (HVOF) spray processes. In the APS sprayed WC-12%Co coating, the RCF damage was dominated by an increased surface roughness due to spallation of flakes and a formation of a network of cracks within the coating layer. HVOF sprayed WC-12%Co and WC-10%Co-4%Cr coatings were damaged either by the formation of vertical, linear cracks or pitting of the contact surface. The formation of pits in the HVOF sprayed coatings was significantly less than that found in the APS sprayed coating. The HVOF sprayed WC-17%Co coating showed the best RCF behavior among the studied coatings with unchanged surface roughness, no formation of cracks, and only a few pits found on the contact surface. The good resistance of this coating against formation of failure in the RCF testing is caused by its higher ductility and fracture toughness due to a higher metallic binder content in comparison with the other coatings. Other characteristics such as a low amount of brittle Co-W-C carbides and a dense microstructure are also believed to be beneficial for a RCF resistant coating.

R. Nieminen, G. Barbezat, T. Mäntylä, K. Niemi, and P. Vuoristo. Cited: *Wear*, Vol 212 (No. 1), 30 Nov 1997, p 66-77 [in English]. ISSN 0043-1648. PHOTOCOPY ORDER NUMBER: 199804-57-0580.

Scratch Test

A Novel Ball-on-Inclined Plane Scratch Test for the Evaluation of Ceramic Coatings. A ball-on-inclined plane scratch test method has been developed to determine the materials responses to stresses on thermally sprayed ceramic coatings. Material properties such as the critical damage load, damage patterns of the scratched surface, and subsurface crack patterns are evaluated. Results show that when the applied load is below the critical value, there is no subsurface damage, but plastic deformation occurs locally on the surface. Beyond the critical load, high-velocity oxygen flame (HVOF) sprayed Al_2O_3 coatings exhibit severe plastic deformation on the scratched surface and subsurface cracks propagating in the directions parallel to and at an angle to the sliding surface. In the case of a plasma sprayed ZrO_2 coating, beyond the critical load, cracks initiate at the surface and propagate into the subsurface at an angle about 30° to the sliding surface. (Article notes use of ceramic coatings on engine components, aircraft, as thermal barriers, and as wear-resistant coatings.)

Y. Wang and S.M. Hsu. Cited: *Advances in Coatings Technologies for Surface Engineering* (Proc. Conf.), Orlando, FL, 9-13 Feb 1997, Minerals, Metals and Materials Society/AIME, 1997, p 213-224 [in English]. ISBN 0-87339-371-6. PHOTOCOPY ORDER NUMBER: 199807-57-0917.

Shear Strength of Thermal Barrier Coatings

Shear Strength of a Thermal Barrier Coating Parallel to the Bond Coat. The static and low-cycle fatigue strength of an air plasma sprayed (APS) partially stabilized zirconia thermal barrier coating (TBC) is experimentally evaluated. The shear testing utilized the Iosipescu shear test arrangement. Testing was performed parallel to the TBC-substrate interface. The TBC testing required an innovative use of steel extensions with the TBC bonded between the steel extensions to form the standard Iosipescu specimen shape. The test method appears to have been successful. Fracture of the TBC was initiated in shear, although unconstrained specimen fractures propagated at the TBC-bond coat interface. The use of side grooves on the TBC was successful in keeping the failure in the gage section and did not appear to affect the shear strength values that were measured. Low-cycle fatigue failures were obtained at high stress levels approaching the ultimate strength of the TBC. The static and fatigue strengths do not appear to be markedly different from tensile properties for comparable TBC material. Substrate was AMS 4340 steel.

T.A. Cruse, P.C. Bastias, and R.C. Dommarco. Cited: *J. Eng. Mater. Technol. (Trans. ASME)*, Vol 120 (No. 1), Jan 1998, p 26-32 [in English]. ISSN 0094-4289. PHOTOCOPY ORDER NUMBER: 199806-57-0827.

Three-Body Abrasive Wear

Three-Body Abrasive Wear of Composite Coatings in Dry and Wet Environments. A comparison of three-body abrasive wear behavior of aluminum composite coatings in both wet and dry environments is presented. Composite coatings reinforced with discontinuous ceramic particles of either Al_2O_3, SiC, or TiC were studied. These metal-matrix composite (MMC) coatings were formed on AA5083 Al alloy using a plasma transferred arc (PTA)

surfacing technique. The aim of the present work was (1) to investigate the environmental influence on wear behavior, and (2) to study the effectiveness of each reinforcement phase toward coating wear resistance. Low-stress abrasive studies were conducted using a sand/rubber wheel abrasion tester. For similar wear conditions, the environment significantly influenced wear behavior. The wet environment promoted a higher wear rate compared to the dry conditions. The establishment of steady-state abrasive wear conditions was related to the formation of a tribolayer. This layer formed at the wearing surface (1 to 2 μm in thickness) and was composed of plastically deformed matrix material, silica fragments and in the case of MMC coatings, fractured particles of the reinforcement phase. The formation of a tribolayer has previously been identified under dry sliding wear conditions, but not in relation to abrasive wear. The wear performance of MMC coating was influenced by the type, size, and volume fraction (V_f) of the reinforcement phase and the wear environment.

R.L. Deuis, J.M. Yellup, and C. Subramanian. Cited: *Wear*, Vol 214 (No. 1), Jan 1998, p 112-130 [in English]. ISSN 0043-1648. PHOTOCOPY ORDER NUMBER: 199805-31-2685.

Wear Coatings

The Influence of Linear Velocity on the Wear Behavior of Thermal Sprayed Coatings under Dynamic Abrasion Test Conditions. Surface coatings applied by a high-velocity oxyfuel (HVOF) thermal spray process were subjected to a newly developed dynamic abrasion test. The test consists of combined impact and abrasion. Impact of samples with a round nose stylus was conducted at two specified linear velocities. The wear rates corresponding with the linear velocities were recorded and compared for a number of test cycles. Aluminum and mild steel substrate materials were used for the test, and a number of coating thicknesses were examined. Uncoated samples were subjected to identical tests. Unlike many wear test processes currently in use, the wear test developed and used here is severe and fast acting, making it suitable for thick coatings and situations involving combined wear. The results of the wear tests show the effects of the linear velocity prior to impact on the surfaces in term of material loss and crater depth caused by dynamic wear testing. The influence of rebound following impact, combined with the linear velocity of the reciprocating stylus, has a major effect on the wear rates of the samples tested.

D.M. Kennedy and M.S.J. Hashmi. Cited: *Surf. Coat. Technol.*, Vol 96 (No. 2-3), 25 Nov 1997, p 345-352 [in English]. ISSN 0257-8972. PHOTOCOPY ORDER NUMBER: 199804-58-0448.

Wear of Alumina

The Sliding Wear of Plasma Sprayed Alumina. The wear behavior of vacuum plasma sprayed (VPS) and air plasma sprayed (APS) alumina coatings was investigated against a number of sliding counterfaces and compared with that of bulk material. Both reciprocating wear tests using diamond cones and sapphire spheres and sphere-on-disk tests using sapphire and steel spheres against plasma sprayed flats were performed at a range of loads to investigate wear rates and determine the operating wear mechanisms and how these are changed as a function of variations in the deposition process. As expected, the VPS material shows much better wear performance compared with the APS coatings, but both are poor when compared with the bulk material. Examination of the wear scars shows that though the failure is predominantly brittle, with fracture both within the splats and at the intersplat boundaries, there is some evidence for plastic deformation in all the coatings investigated. With the steel counterface, considerable transfer of steel to the coating occurs during wear that has an effect both on the measured friction and on the operating wear mechanisms. These wear results are correlated with the microstructure and properties of the alumina prior to testing.

S.J. Bull, R. Kingswell, and K.T. Scott. Cited: *Surf. Coat. Technol.*, Vol 82 (No. 3), 1 Aug 1996, p 218-225 [in English]. ISSN 0257-8972. PHOTOCOPY ORDER NUMBER: 199804-57-0454.

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