Metal Alloy Coatings: Physical, Wear-Related, and Other Surface Characteristics

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ABSTRACT

The types, properties, and processes for metal alloy coatings are reviewed from the viewpoints of material properties, metallurgy, and tribology. Although other materials such as ceramics and polymers are used to coat materials to provide various useful properties, coatings consisting of metals and metal alloys offer excellent corrosion and wear resistances as well as useful physical, mechanical and high-temperature properties. Furthermore, metals and alloys provide a much wider range of properties than other coating materials. This, combined with numerous sophisticated coating processes recently developed, makes them the choice of coating in a large number of applications. This review has been written with an emphasis on coatings consisting of metal alloys as opposed to single metals. It is hoped that this review will serve as a useful source for literature survey as well as an introduction to the subject of surface modification with metals and metal alloys.

Keywords: coating, mechanical properties, alloys, corrosion, surface modification, tribology, surface layer, oxidation, wear, erosion, hardness, deposition, substrate, spray, laser cladding, sputtering, plating, implantation

Articles reviewed are grouped according to the major constituents of the coated layers and discussed in terms of the compositions of the coated layers, substrates, deposition methods, property testing methods, the properties of the coatings, and their interaction with the substrates. The emphasis is on coatings consisting of metal alloys as opposed to single metals. A summary of the salient literature articles with brief descriptions of these related aspects of the investigations is given in Table I.

1. Ni-Cr COATINGS

It is well known that Ni-based alloy coatings show good high temperature corrosion resistance. Cr_3C_2-NiCr cermet materials in particular have traditionally been used for high temperature wear and erosion protection, including exhaust flaps on turbine engines, knife edge seals, and pump seal and liners. In the temperature range (530~820°C) of typical applications, the chromium from the chromium carbide and the nickel-chromium alloy oxidizes to form a protective and adherent surface layer of chromium oxide /1,2/. As a thick wear-resistance coating, Cr_3C_2-25% NiCr coating is prepared by plasma spray and detonation spray method and used to resist various types of wear /3/.

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Table I

Summary of salient references on metal and metal alloy coatings.

Reference		Coating			Experiments	Results and Comments
No.	Year	Film	Deposition Method	Substrate/ Counter-part		
4	1995	Cr_3C_2-25% NiCr	APS-Ar/H_2 APS-Ar/He CDS	Al_2O_3 SiO_2	Pin-on-disk	Increased fracture toughness and wear resistance
6	1996	75/25 Cr_3C_2/NiCr	HVOF		Pin-on-disk	Sliding wear test
7	1997	Cr_3C_2-25% NiCr	APS-Ar/H_2 APS-Ar/He HVOF	Steel	Self-made test rig	Impact wear test
8	1994	Cr_3C_2-NiCr Cermet	HVOF	1018 Steel		Erosion-oxidation behavior
9	1997	Cr_3C_2-NiCr	Plasma Spray	TiO_2	Block-on-ring	Wear -mechanism
10	1998	Cr_3C_2-NiCr	Plasma Spray	TiO_2	Block-on-ring (water and ethanol lubrication)	Friction and wear behavior
11	2000	Ni-Cr-W-Mo-B	HVOF	Mild steel		Effect of heat treatment
12	1999	Ni-W-Cr-B-Si	HVOF	1020 steel		Microstructure and properties
13	1997	Ni-WC Self-fluxing alloy	Thermal spray	Metals		Erosion resistance
14	1994	Incoloy 800H (20Cr, 32Ni) Ni-Cr-Al	Laser cladding	Metals		60Ni, 19Cr, 11Al, 6.4Fe composition best corrosion resistance
15	2000	NiCrBSi, NiCrBSi+WC	Plasma spray and laser	Al-Si alloy	Pin-on-disk	Ni-Cr-B-Si laser melted highest wear resistance
16	2000	NiCrBSi	Laser clad	Ti alloy (Ti6Al4V)	Pin-on-disk	Wear rate an order of magnitude less
17	1998	TiC-NiCrBSi	Plasma spray (APS, VPS)	AISI 4140 Steel	Pin-on-disk	Average coefficient of friction to decrease with sliding speed. VPS higher wear resistant than APS
18	1989	Ni-Cu	Electro-co-deposition	AISI 52100 Steel	Crossed-cylinder Wear tester. Paraffin oil lubricants	Lubricated wear behavior. Ni-Cu layer less wear. Friction coefficient lowest

Table I (continued)
Summary of salient references on metal and metal alloy coatings.

Reference		Coating			Experiments	Results and Comments
No.	Year	Film	Deposition Method	Substrate/ Counter-part		
24	1989	Ni-Cu	Electro-co-deposition	AISI 52100 Steel	Crossed-cylinder Wear tester. Unlubricated	Sliding wear behavior. Smallest layer (10nm) showed highest wear resistant.
25	1997	Ni-Cu	Electrodeposition	Beryllium bronze (Be 2.0, Ni 0.5%)	Ball-block	2:1 layer thickness of Cu and Ni gave the highest wear resistance.
26	1996	Cu-Ni/Cu, Ni-Cu-Ni/Cu	electrodeposition	Pure copper	Single pendulum	Multilayer alloys better than single layer. Abrasive wear behavior
33	1996	Ni-P	Autocatalytic chemical (source $NiCl_2$)	AISI 1020 Steel	Pin-on-disk	400°C heat treatment yields more effective wear resistance. Electroless Ni-P coating studied.
34	2000	Ni-P-W	Pulse plating	Mild steel	Pin-on-disk, Lubricated (anti-wear oil)	Friction coefficient 0.035~0.1. wear volume and wear mechanism. Lubricated sliding wear behavior
38	1998	CoNiCrAlY	HVOF, APS, ASPS	Nickel-base alloy	Fretting tester	APS and HVOF CoNiCrAlY induced detachment of entire splats and more severe wear. Tribological behavior.
44	1991	Stellite alloy 6 (60Co, 28Cr, 4W, 3Fe%) Stellite-SiC	Laser cladding	Mild steel	Two disk type	Stellite + 10% SiC → twofold increase in hardness and wear resistance.
45	1996	Stellite alloy 6 (60Co, 27Cr, 5W, 2.5Fe)	Laser clad	AISI 4140, 4340	Pin-on-disk	Spalling of oxide. Fatigue mechanism that controls the wear rate of specimen. wear behavior.
50	1990	Al-Zn-Sn	Ion plating	Mild steel	Pin-on-disk	Al-1.5wt% Zn-5wt% Sn alloy coatings → considerable improvement in the frictional behavior.
52	1996	Al-Mo	Sputtering	Mild steel	Pin-on-disk	Friction coefficients
54	1993	Al-Al	IVD			Aerospace applications
55	1995	Al-Steel, Al-Al, Al-Mg	IBAD	Carbon steel		Corrosion protection

Table I (continued)
Summary of salient references on metal and metal alloy coatings.

Reference		Coating			Experiments	Results and Comments
No.	Year	Film	Deposition Method	Substrate/ Counter-part		
56	1993	Al/Al-Mg, Al/AlN$_x$, Al/Al-Mg/CrN$_x$	IBAD	Carbon steel	Cylinder-on-disk	Wear and corrosion protection improved by use of bifunctional multilayer.
57	1997	Al-Mg	Magnetron sputtering	Silicon <100> wafers		Stoichiometry
58	1997	Al-Cu-Fe	Magnetron sputtering		Scratch tester	Friction coefficient low (0.09~0.11). Wear resistance increases with increasing annealing temperature.
66	1996	Ti-Al-B-N	P.V.D	High speed steel	Pin-on-disk	TiAlB(N) is a suitable coating to transform brass.
67	1996	(W, Ti)-C-Ni WC-Co	Detonation-gun spray	1044 steel, Ti6Al4V	Block-on-ring	Wear resistance
68	1999	TiAlAgCr	Magnetron sputtering	Stainless steel		Addition of Ag or Cr does not lead to a significant improvement in mechanical properties.
69	2000	Ti-47Al-2Nb-2Cr	N_2 ion beam implantation	WC	Pin-on-disk	N ion implantation yields the best modification of tribology.
70	1999	TiAlBN	Electron-beam evaporation	Stainless steel		Ti/B = 1.73~2.31 → twofold increase in wet cutting performance compared to TiN, TiAlN.
72	2000	$MoSi_2$-Ti	Magnetron sputtering			$MoSi_2$ coating affected by energetic particles.
73	2000	Ni-Cr-Al-Ti	Magnetron sputtering			Good oxidation resistance despite the formation of TiO_2.
74	2000	Nickel aluminide	Electrolytic process	TiAl alloy		Oxidation resistance, ductile structure, good adhesive properties
75	1997	Ti-6Al-4V	Ion implantation	UHMWPE, PMMA polymers	Pin-on-disk	Appropriate parameters lead to a reduction of wear.
78	1995	Ti-6Al-4V	MEVVA Ion implantation	Ti-6Al-4V	Pin-on-disk	Wear rate improvement by a factor of 2.

Barbezat *et al.* /4/ stated that the wear resistance of a Cr_3C_2-25% NiCr coating increases in the following order of preparation method: atmospheric plasma spray (APS)-Ar/H_2 deposition, APS-Ar/He deposition, and continuous detonation spray (CDS).

The recently developed hypersonic velocity oxygen fuel (HVOF) thermal spray process produces coatings with excellent qualities in terms of porosity, hardness, bond strength, density, and roughness /5/. Mohanty *et al.* /6/ tested an HVOF sprayed Cr_3C_2-25% NiCr wear resistance coating with a pin-on-disk tribometer. They determined that the break-in sliding coefficient is more significantly affected by load than any other test parameters. The results also indicated that friction decreased with increasing velocity but wear decreased first and then increased with increasing velocity. In another investigation, Li *et al.* /7/ studied Cr_3C_2-25% NiCr coatings prepared by APS-Ar/H_2, APS-Ar/He, and HVOF spraying. The HVOF sprayed Cr_3C_2-25% NiCr coatings showed the best impact wear resistance due to dense structure and few defects. The wear mechanism of Cr_3C_2-25% NiCr coatings under impact condition was determined to be impact fatigue, which consists of two wear processes of plastic smearing and breaking-off. The erosion and oxidation behavior of HVOF Cr_3C_2-NiCr coating on 1018 steel and other thermal sprayed coatings, including FeCrSiB (Armacor M), Cr_2O_3-6SiO_2-4Al_2O_3 (Rokide C), Cr_2O_3-12SiO_2-2Al_2O_3-4MgO (Rokide MBC) and WC-NiCrCo (SMI 712), was studied. It was determined that the HVOF Cr_3C_2-NiCr coating had the highest resistance, and that the erosion and oxidation behavior was closely related to the coating morphology /8/.

The wear mechanism of a plasma-sprayed Cr_3C_2-NiCr coating against a TiO_2 coating was explained in terms of fatigue-induced detachment of the TiO_2 layer at a low load and plastic deformation, shear fracture and melting wear at a high load /9/. The same group also studied the behavior under the conditions of water and ethanol lubricated sliding /10/. Ethanol reduced the friction and wear coefficients of Cr_3C_2-NiCr coating, which was attributed to the formation of a smooth surface film mainly consisting of Cr_2O_3. Ethanol also increased the wear coefficient of TiO_2 coatings by absorption-induced cracking as a result of low fracture toughness of the coating.

Lee and Min /11/ investigated wear resistance of Ni-based alloy coatings with W and Mo additions. The HVOF sprayed Ni-Cr-W-Mo-B alloy coatings had good corrosion resistance, especially those that were composed of a Ni matrix and Cr, W and Mo-rich phases segregated in the grain boundary. Gil and Staia /12/ examined the microstructure and properties of Ni hard-surfacing alloy (Colmonoy 88, NiWCrBSi) prepared by HVOF and reported on the porosity, microhardness and corrosion resistance in 5% NaCl solution as related to the spraying parameters.

Ni-based self-fluxing thermally sprayed coatings such as NiCrBSi do not readily provide erosion protection at high temperatures. Dispersed hard WC particles (>2100 Hv) in Ni solid-solution matrix can enhance the coating hardness and improve the erosion resistance at elevated temperatures. Tu *et al.* /13/ showed that a Ni-WC coating with a composition of 65% Ni-base alloy and 35% WC had the highest microhardness and improved erosion resistance compared with coatings of other compositions.

The high-temperature oxidation behavior of a laser-clad Incoloy 800H containing Ni 32, Cr 20 and Mn, C, Si, Ti, and Al was tested by de Damborenea *et al.* /14/. The excellent oxidation resistance was due to the formation of ceramic and metallic oxides on the surface of the specimen, which prevented the spread of alloy elements towards the exterior and the entry of oxygen into the material.

Liang *et al.* /15/ prepared Ni-Cr-B-Si and Ni-Cr-B-Si + WC coatings on Al alloys by plasma spraying and laser remelting. The laser-remelted Ni-Cr-B-Si sample exhibited the highest wear resistance. The plasma-sprayed Ni-Cr-B-Si + WC sample had better wear resistance compared with the laser-treated Ni-Cr-B-Si sample. Analysis of the worn surface showed that the alloyed layer of the laser-treated sample was very compact, and the worn surface was smooth and granular peeling was hardly observed. The worn surface of the plasma-sprayed sample was rather loose and there was granular peeling on the worn surface. A laser clad NiCrBSi coating on a titanium alloy substrate (Ti-6Al-

4V) was also determined to substantially improve the wear resistance /16/. The wear mechanism was found to be a mixed type between reduced peeling-off and abrasion. On the other hand, Betancourt-Dougherty and Smith /17/ tested TiC-NiCrBSi coatings prepared by air or vacuum plasma spraying (APS or VPS) by the use of a pin-on-disk tribometer. The VPS processing resulted in coatings with higher wear resistance than the APS method.

2. Ni-Cu COATINGS

Another group of Ni-containing coatings that have been tested are multilayer alloy coatings or mainly electro-deposited composition-modulated coatings of Ni-Cu, Cu-Ni/Cu, Ni-Cu-Ni/Cu, Fe-Cu, Au-Cu, or Cu-Pd /18~21/. The improvements in wear resistance by these coatings are attributed to the formation of barriers to dislocation slide through the interface between adjacent layers and the increase in flow stress due to the small dimensions of the individual layers. Substantially increased tensile strengths and yield strengths, by factors of 2.3~4.2, have been reported /20,22,23/. Ruff and Myshkin /18/ coated a 52100 bearing steel with 10 and 100 nm layers of Ni-Cu by electro-codeposition, and tested for wear and friction coefficient using a crossed-cylinder wear tester. Ni-Cu layered coatings generally showed less wear than pure metal coatings, and the coating with the smaller layer spacing (10 nm) showed the least wear, particularly at low loads. Friction coefficients were also generally lower for the Ni-Cu coatings. Ruff and Wang /24/ made measurements for sliding wear for similar coatings as above, examined the worn specimens, and collected wear debris. They concluded that the layer microstructure in these composition-modulated coatings provide internal barriers to wear damage, thus leading to the increase in wear resistance. Zhang and Xue /25/ studied the tribological properties of 8~300 nm Ni-Cu layers electrodeposited onto a beryllium bronze substrate. The most wear-resistant coating was the Cu/Ni multilayer that had the smallest Ni-layer thickness (8 nm) with a 16 nm Cu layer. The increase in wear resistance was attributed to the layer microstructure and grain-size strengthening. On the other hand, Liang *et al.* /26/ investigated the abrasive wear behavior of Cu-Ni/Cu and Ni-Cu-Ni/Cu multilayer alloys. Triple-layer specimens had better wear resistance than the conventional monolayer specimens. In multilayer alloys, even the softer layers can be strengthened against three-dimentional compression stresses, when sandwiched between harder layers.

3. Ni-P COATINGS

Chemically placed Ni-P deposits are rather widely used in industry because of their high wear and corrosion resistances. While most Ni coatings are produced from solutions based on $NiSO_4$ as the cation source /27,28/, most multilayer Ni-P coatings are prepared by vacuum deposition because high-quality metallic multilayers can be made less expensively by this technique /29~32/. Staia *et al.* /33/ tested the wear performance of an electroless Ni-P coating obtained from a $NiCl_2$ solution. Panagopoulos *et al.* /34/ studied the lubricated sliding wear behavior of a Ni-P-W multilayer alloy coating deposited on mild steel by pulse plating. The result showed a friction coefficient in the range of 0.035~0.1. The thickness of each layer of the multilayered coatings had no effect on the wear volume and wear mechanism.

4. MCrAlY COATINGS

MCrAlY coatings, where M is Fe, Ni, Co, Co + Ni, etc., prepared by thermal spraying methods are used to prevent high-temperature oxidation and corrosion, as in the case of gas-turbine blade. In such applications, adhesion and plastic deformation are important /35/. Additionally, solid particle erosion (SPE) is a serious problem for the electric power industry. To reduce this problem, HVOF coatings of FeCrAlY-Cr_3C_2 as well as other cermets like WC-Co and NiC_2-Cr_3C_2 are used /36, 37/. Li *et al.* /38/ studied the tribological behavior of CoNiCrAlY coatings prepared by HVOF, argon-surrounded plasma spray (ASPS), and APS methods and NiCoCrAlYTa coatings made by low-pressure plasma spraying (LPPS). The substrate was a nickel-based superalloy (Hastelloy X). The results showed that the main wear mechanism was the oxides and porosity present in these samples inducing detachment of splats. Stein *et al.* /39/ evaluated the erosion resistance of FeCrAlY-Cr_3C_2 and NiCr-Cr_3C_2 cermet coatings. The erosion rate for 90-degree impact decreased with decreasing contents of carbide and overall hard phase (oxides and carbides), but the erosion rate for 30-degree impact remained essentially constant with the hard-phase content.

Surface cladding using high-power lasers has often been used since the 1970's owing to such advantages as low degrees of thermal damage to the substrate and little distortion compared with conventional hard-facing methods /40,41/. A number of investigators /42, 43/ have studied the wear performance of such laser-clad alloys. For example, Molian and Hualun /43/ evaluated the performance of a laser-clad layer of NiCrCoAlY-added hexagonal BN powder deposited on the Ti-6Al-4V alloy. Wear resistance of such a clad layer showed a remarkable improvement (10~200 times) over age-hardened and surface-melted layers. The improved wear performance was attributed to the high hardness and low friction properties of the clad layers.

5. Co-Cr COATINGS

Abbas and West /44/ deposited Stellite Alloy 6 (60 wt% Co, 28 wt% Cr, 4 wt% W, 3 wt% Fe, 1.1 wt% C) and SiC composites on mild steel by laser surface cladding to enhance hardness and wear resistance. A cladding with a mixture of Stellite + 10% SiC achieved an approximately two-fold increase in hardness and wear resistance as compared with just Stellite cladding. This is attributed mainly to the enrichment of Stellite in carbon by the dissolution of SiC, rather than to the presence of undissolved SiC particles. So *et al.* /45/ studied the wear behavior of the same Stellite Alloy 6 coated on steel by laser cladding. The spalling of oxides was found to control the wear rate of the specimens. It was shown that the oxides formed on Stellite Alloy 6 were tougher than those formed on AISI 4140 or 4340 steel.

6. Al-BASED COATINGS

Aluminum and aluminum alloy coatings have been used to reduce corrosion of aircraft steel parts. The ion-vapor-deposition method has been widely used for these coatings, but recently the Closed-Field-Unbalanced-Magnetron-Sputtering (CFUBMS) method has been developed /46~48/. These coatings, however, have inferior tribological and corrosion protection properties with respect to the steel substrate. These properties are improved by adding Zn, Sn, Mo, or Mg to the coating material /49, 50/. Abu-Zeid /50/ determined by a study of tribological and corrosion behaviors of Al-1.5% Zn-5% Sn ion platings that the zinc and tin additions substantially improved the friction properties. The improvement was explained by the formation of a continuous matrix of Sn-rich phase surrounding the Al-rich phase. Hot-dip galvanized zinc and Al-Zn alloy coatings are widely used for corrosion protection of commercial sheet-steel products /51/.

Abu-Zeid and Bates /52/ investigated the friction and corrosion resistance of Al-Mo alloy coatings prepared by sputtering, based on the consideration that molybdenum was known to have good lubricating and corrosion resistance properties. According to their results, Al-Mo coatings had low wear rates at various Mo contents, and friction coefficients as low as 0.18 against steel were obtained with relatively high Mo contents (>80%). Other coating methods include the popular PVD technique as well as ion plating, magnetron sputtering, and ion-beam-assisted deposition /53~55/.

Monaghan *et al.* /54/ investigated a series of corrosion-resistant Al-alloy films to determine the corrosion and tribological properties with respect to aerospace applications. Enders *et al.* /55/ studied the corrosion properties of Al and Al-Mg alloy coatings prepared by ion-beam-assisted deposition (IBAD). The alloys had less noble equilibrium potentials and increased passive regions than pure aluminum. It was observed from glancing-angle X-ray diffraction measurements that the structural changes affected by the ion beam paralleled the changes in the localized corrosion behavior. They had earlier studied the behaviors of Al, Al/(Al, Mg), Al/AlN_x, and Al/(Al, Mg)/CrN_x coatings /56/. Shedden *et al.* /57/ indicated that the control of stoichiometry was quite difficult when Al-Mg alloys were deposited by IBAD using an unbalanced magnetron sputtering technique. In their investigation of magnetron-sputtered Al-Cu-Fe quasi-crystalline films for tribological applications, Ding *et al.* /58/ determined that as-sputtered (amorphous) and annealed (amorphous + quasi-crystalline) Al-Cu-Fe films had low coefficients of friction (0.09-0.11) that were of the same order as for TiN films produced by reactive ion plating (RIP).

7. Ti-BASED COATINGS

Titanium and Titanium alloys have far higher corrosion resistance and hardness than stainless steels. For example, the Ti-6Al-4V alloy has a hardness of about 36 HRc. It has, however, poor resistance to sliding wear and particular weakness to sliding contact such as galling and seizure, thus requiring surface modification to improve these weaknesses. The methods used for this purpose include nitriding, cyaniding, oxidation, flame spraying, chromium plating, electroless nickel plating, and chemical conversion coating /59~62/.

Another method is laser cladding. Ayers /63/ coated the Ti-6Al-4V alloy by TiC and WC by a laser melt and particle injection process, and showed that the coefficient of friction was only about half that of the uncoated alloy. Recently, Palmers and Van Stappen /64/ succeeded in coating (TiAl)N by electrobeam ion plating, and showed those coatings deposited without supplied bias voltage to have the best adhesion properties.

Gissler and Van Stappen /65/ studied the structure and properties of Ti-B-Al coatings. In spite of their ultrahigh hardness and good adhesion to metallic substrates, most tribological tests revealed that these coatings did not perform as well as TiN and (TiAl)N coatings. Heck *et al.* /66/ compared the tribological behavior of Ti-Al-B-N based coatings such as TiB_2, TiAlB(N), TiAl(N) and TiB_2/TiAl(N) coatings with those of steel (100Cr6), aluminum, brass and bronze. The combinations of TiAlB(N) and TiB_2 had a lower wear volume and adhesive tendency than aluminum. Brass led to abrasive wear on all coatings whereas bronze showed a strong adhesive tendency on all tested coatings. The dominant wear mechanism was tribochemical oxidation.

Bahadur and Yang /67/ investigated the friction and wear behavior of tungsten and titanium carbide coatings. The SEM and EDX analysis of the wear surfaces revealed material removal by mechanisms such as micropolishing, adhesion, delamination, and cracking, and provided evidence of material transfer from the ring to the block but none in the opposite direction.

The effects of the addition of silver and chromium to TiAl coatings were studied /68/. Contrary to the as-deposited state, the silver or chromium addition did not lead to significant improvements in the mechanical properties, hardness and ductility of the heat-treated films (γ-TiAl structure). Yu *et al.* /69/ tested tribological modification and high-temperature behavior of Ti-47Al intermetallic alloy nitrided by N-ion implantation. N-ion implantation, particularly with a high beam current and high ion dose without post-annealing, resulted in the best modification of tribology.

Rebholz *et al.* /70/ evaluated the effect of the Ti/B ratio of TiAlBN coatings deposited by direct electron-beam evaporation and determined that coatings with Ti/B = 1.73~2.31 showed a twofold increase in wet cutting performance compared to commercially available TiN and TiAlN coatings. In studying Ti and Mo coatings /71/, coatings of up to 0.02 inch were obtained by flame (or plasma) spraying with excellent adhesion. These high-titanium self-lubricating coatings are utilized today in large-scale production. More recently, ion beam treated $MoSi_2$-Ti composite has also been studied /72/.

On the other hand, Chen and Lou /73/ tested monocrystalline coatings of Ni-Cr-Al-Ti by sputtering. Good oxidation resistance was shown by such coatings despite the formation of TiO_2. Katsman *et al.* /74/ deposited a nickel-aluminide coating onto TiAl by a two-stage process and found that the coating provided good adhesion of Ni to the TiAl alloy surface.

The following several articles summarize research results on the performance of several coatings on the Ti-

6Al-4V alloy substrate to improve its sliding wear characteristics by seizure, galling, and scuffing. Schmidt *et al.* /75/ carried out ion implantation of various elements (C, N, O, Y, Hf, Pt, Au) with different energy levels and determined the sliding properties against ultrahigh molecular weight polyethylene (UHMWPE) and polymethylmethacrylate (PMMA). The results showed that ion implantation of selected elements with appropriate parameters led to a reduction of wear during the sliding movement of the alloy. Grögler *et al.* /76/ coated the Ti-6Al-4V alloy with diamond by CVD for erosion resistance in aerospace applications. Coatings prepared under relatively high methane concentrations (4~10%) in the process gas atmosphere exhibited superior performances. Plasma sprayed (PS 212) and metal-bonded (PM 212) composite coatings were shown to result in low friction and wear of the Ti-6Al-4V alloy in space power stirling engines /77/. Cornelius *et al.* /78/ investigated the wear characteristics of the Ti-6Al-4V surfaces after ion implantation of Al by the metal vapor vacuum arc (MEVVA) ion source. Aluminum implantation improved the wear rate by a factor of two.

8. CONCLUDING REMARKS

Although other materials such as ceramics and polymers are used to coat materials to provide various useful properties, coatings consisting of metals and metal alloys offer excellent corrosion and wear resistances as well as useful mechanical and high-temperature properties. Furthermore, they provide a much wider range of properties than other coating materials. This, combined with numerous sophisticated coating processes recently developed, makes them the choice of coating in a large number of applications. This review has emphasized coatings consisting of metal alloys as opposed to single metals.

It is hoped that this review will serve as a useful source for literature survey as well as an introduction to the subject of surface modification with metals and metal alloys for materials scientists, metallurgists, and tribologists.

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