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Influence of Substrate Material on Plain Fatigue and Fretting Fatigue Behavior of Detonation Gun Sprayed Cu-Ni-In Coating

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Cu-Ni-In coating was formulated on two substrate materials—Ti-alloy (Ti-6Al-4V) and Al-alloy (AA 6063) fatigue test specimens using detonation gun (D-gun) spray process. Coating on both substrates was dense with low porosity, high hardness, and high surface roughness. Relatively higher surface compressive residual stress was present at the coating on Ti-alloy specimens. In case of the coating on Al-alloy samples, tensile residual stress was also present in some places. Uniaxial plain fatigue and fretting fatigue experiments were conducted on uncoated and coated specimens. The detrimental effect of life reduction due to fretting was relatively larger in the Al-alloy compared to the Ti-alloy. While Cu-Ni-In coating was found to be beneficial on the Ti-alloy, it was deleterious on the Al-alloy substrate under both plain fatigue and fretting fatigue loading. The results were explained in terms of differences in the values of surface hardness, surface roughness, surface residual stress, and friction stress.

Keywords Al-Mg-Si alloy, Cu-Ni-In, detonation spray coating, fretting fatigue, Ti-6Al-4V

1. Introduction

Lightweight engineering components, made up of aluminum and titanium alloys, widely used in aeronautical, automotive, and other applications, often encounter fretting damages whenever two contact surfaces undergo relative tangential motion of small amplitude due to vibration or cyclic loading. Aluminum alloys undergo fretting fatigue damage in contact conditions such as bolted, press fitted, riveted joints, coupling, clutches, etc. Typical examples of fretting fatigue damage sites in case of titanium alloy components are gas turbine rotor blade roots and dovetail joints in turbine blade assembly, orthopedic implants, etc. (Ref 1, 2). Fretting damage sites are potential places to initiate fatigue cracks earlier leading to reduction in the life of the components. Especially aluminum and titanium alloys are easily susceptible to fretting damages due to greater tendency toward material transfer (Ref 3). This poor tribological performance of light alloys resulted in the development of new surface modification techniques in order to increase the life of engineering components.

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Thermal spray coatings such as plasma spraying, high velocity oxy-fuel (HVOF), and detonation gun (D-gun) spraying are commonly used in the field of surface engineering to protect engineering components against surface deterioration resulting from surface/environment interactions, such as wear, fretting, oxidation, corrosion, and erosion. There have been attempts to study the influence of spray coatings on fatigue behavior of different materials—for example, see Refs 4 and 5. It has been reported that bending fatigue lives of plasma sprayed alumina coated low carbon steel samples were about two times longer than those of uncoated specimens (Ref 4). This was attributed to compressive residual stresses in the substrate originating during the spray process. Price et al. have reported a 15% reduction in bending fatigue limit of Ti-6Al-4V alloy coated with pure titanium by cold gas dynamic spraying (Ref 5). However, when the substrate was grit blasted before coating, no significant reduction was observed. The reduction in fatigue limit was related to the substrate-coating interface properties, the elastic modulus and the residual stress state.

D-gun is one of the well-established thermal spray techniques to spray a dense coating of different materials—metals, alloys, oxides, ceramics, and materials in different combinations (Ref 6). D-gun sprayed coatings have been widely used for protection against wear rather than fatigue and fretting fatigue. There are very few reports on the fatigue behavior of D-gun sprayed coatings. Ahmed and Hadfield studied the performance of D-gun sprayed WC-Co and Al_2O_3 coatings under rolling contact fatigue loading (Refs 7, 8). They discussed elaborately the mechanisms of contact fatigue failure in thermal spray coating in terms of substrate and coating material properties, viz., elastic modulus and hardness. The stress distribution or the stress field in the thermal spray coating will be affected by the mismatch of elastic properties of coating and substrate materials especially when the coating thickness is greater than the depth of maximum shear stress. Further, they commented on the influence of bulk deformation on a hard coating when coated on a soft substrate. It is possible that the given contact stress can be in the elastic range of the coating material while it can be in the plastic range to that of substrate. This may lead to bending and cracking of coating material in the initial stages itself (Ref 8).

Shima et al. (Ref 9) studied the influence of substrate material and hardness on fretting wear behavior of TiN coating on three ferrous alloys, Ti-6Al-4V and aluminum alloy ASCM 20 (Composition in mass%—18-22Si, 2.5-4.0Cu, 5.0-6.5Fe, 0.8-1.5Mg, rest Al). They reported that the number of cycles for coating breakdown decreased with decrease in substrate hardness. They reported that the beneficial effect of TiN coating on fretting wear resistance was most pronounced for Ti-6Al-4V substrate. In general, the substrate material may affect the fretting behavior of coatings in a number of ways (Ref 9). The hardness of the substrate will influence the normal force at which plastic deformation of the substrate commences and, in consequence, the normal force at which micro cracking of the coating commences. The elastic modulus of the substrate will affect the stress distribution in the coating, if the coating thickness is small compared to the width of the fretting contact. The surface properties of the substrate will affect the adhesion of the coating. In the present study, the influence of substrate material on the performance of D-gun sprayed Cu-Ni-In coating was studied under plain fatigue and fretting fatigue loading. Two different light alloy substrates, aluminum alloy AA 6063 and titanium alloy Ti-6Al-4V were considered.

2. Experimental Details

The chemical compositions and room temperature mechanical properties of the test materials Ti-6Al-4V and AA 6063 are given in Tables 1-3. Hereafter, Ti-6Al-4V will be referred to as Ti-alloy and AA 6063 as Al-alloy in this paper. Fatigue samples with a gauge length of 65 mm and a gauge width of 10 mm were fabricated. The thickness of Ti-alloy samples was 5 mm and that of Al-alloy specimens was 8 mm. Fretting pads with a pad span of 30 mm were used in uncoated conditions. Ti-alloy pads were used for Ti-alloy specimens and Al-alloy pads were employed for Al-alloy samples. Cu-36Ni-5In (in wt%) powder having spherical particles was used as a coating material. Prior to coating process, the test specimens were cleaned, degreased and shot blasted using alumina grit (60-mesh size) and then ultrasonically cleaned. The specimens were fixed in the specimen holder of a horizontal type detonation spray coating system (AWAAZ, ARCI, Hyderabad, India) and then sprayed with Cu-Ni-In powder. Multipass coating of Cu-Ni-In was formulated on all four sides of the gauge portions of the fatigue test samples.

Table 1 Chemical composition of Ti-6Al-4V

Elements	Al	V	Fe	N	C	H	O	Ti
(Wt%)	6.0	3.9	0.17	0.01	0.03	0.01	0.15	Balance

Table 2 Chemical composition of AA 6063

Elements	Mg	Si	Fe	Cu	Mn	Zn	Ti	Cr	Al
(Wt%)	0.44	0.41	0.35	0.1	0.1	0.1	0.1	0.1	Balance

Table 3 Mechanical properties of two different substrate materials

Material	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Hardness ($HV_{0.2}$)
Ti-6Al-4V	960	1010	16	330
AA 6063	208	247	21	80

While the coating thickness was about 140-150 μm in Ti-alloy specimens, it was about 100 μm in Al-alloy samples. Fridrici et al. have studied fretting wear behavior of plasma sprayed Cu-Ni-In coated Ti-6Al-4V with the coating thickness of about 150 μm (Ref 10). Keeping this as a reference, it has been planned by the present authors to take up a study on fretting wear and fretting fatigue behavior of D-gun sprayed Cu-Ni-In coated Ti-6Al-4V. So in the present study the coating thickness of 140-150 μm was selected for Ti-alloy. To study the effect of substrate material, the results pertaining to another investigation dealing with the effect of coating thickness on Al-alloy have been used (Ref 11). In that study two values of coating thickness were considered—40 and 100 μm. Though ideally the coating thickness should be the same for both substrate materials, due to the reasons mentioned above, the coating thickness was slightly different—140-150 μm for Ti-alloy and 100 μm for Al-alloy samples.

Porosity of the coating was measured on sectioned and polished surface in 20 different regions using an optical microscope (Leitz-Metallovert, Germany) interfaced with an image analyzer (Quantimet 520, Germany) and average value was taken (see Table 3). The hardness values of coating and substrate materials were measured using a microhardness tester (Leitz-112473, Austria) on sectioned and polished surfaces. The hardness of coating was also determined using a nanoindentation tester (Nanoindenter XP, MTS Corporation, USA) on sectioned and polished surface. The elastic modulus of the coating was determined using the nanoindentation tester on sectioned and polished surface. The indentation was made only on the coating. The elastic modulus values of the substrate materials were determined from the slope of the linear portion of stress-strain data of tensile tests conducted on substrate specimens. Surface roughness of coating was measured using a roughness tester (TR 200, Time Group Inc., China). $\text{Sin}^2\,\Psi$ diffraction method was employed to measure residual stresses on the coating surface using an x-ray diffractometer (Rigaku, Tokyo, Japan).

Uniaxial plain fatigue and fretting fatigue tests were conducted on uncoated and coated specimens at room temperature with a stress ratio of 0.1 at different maximum cyclic stresses using a servohydraulic testing machine (MTS 810, MTS Corporation, USA). For plain fatigue tests the cycle frequency was 20 Hz and for fretting fatigue tests it was 10 Hz. The fretting fatigue tests were carried out at a constant average contact pressure of 100 MPa. The average contact pressure was calculated by dividing the contact (normal) load by the apparent contact area (=pad foot size X specimen thickness; in case of Ti-alloy it was $2\times5=10$ mm^2 and in case of Al-alloy it was $2\times8=16$ mm^2). An experimental facility with a ring type load cell and bridge type fretting pads, which can simulate flat-on-flat contact fretting fatigue conditions was used in fretting fatigue tests. Full details of the test setup are given elsewhere (Ref 12).

The contact surfaces of the uncoated pads were polished with four grades (1/0, 2/0, 3/0, and 4/0) of silicon carbide paper and cleaned with acetone prior to each test. Friction force between the fretting pads and the specimen was measured by bonding strain gauges to the underside of the fretting pads, with the strain gauge grid centered between the pad feet. During fretting fatigue testing the values of contact load and friction force between the specimen and fretting pads were recorded with the help of a data acquisition system (HBM-spider8-600 Hz and catman Express 4.0 software, Darmstadt, Germany). The contact load was continuously monitored and in case of any change in the contact load it was adjusted to the originally set value. A maximum change of 2% was noticed in the contact load. Non-contact inductive displacement sensors (Micro-Epsilon, Ortenburg, Germany) were used to measure the displacement of pad and the specimen during tests. The difference between the two displacement ranges was calculated to obtain the relative slip values. The relative slip values reported in the present study are macroscopic or global relative slip values. Observations on fracture surfaces and fretted area were made using a scanning electron microscope (SEM) (Hitachi 4300 SE/N, Japan). A digital camera was used to take photographs of fretted regions.

3. Results and Discussion

3.1 Surface Characteristics

Figure 1 shows cross section views of D-gun sprayed Cu-Ni-In coatings on Ti- and Al-alloy substrate trial pieces. (Small trial pieces were initially used to check the quality of coatings. So the coating thickness in Fig. 1 will not be equal to 150 μm for Ti-alloy and 100 μm for Al-alloy specimens. But in actual test specimens the coating parameters were adjusted to obtain the required thickness values.) Coating exhibited low porosity and good adhesion strength with clean crack-free interface. Substrate material did not influence the hardness of D-gun sprayed Cu-Ni-In coating (see Table 4). Coating exhibited higher hardness on both substrates, which could be attributed to extensive strain hardening experienced by the coating, the inherent characteristic of D-gun spray process. In case of Ti-alloy, there was not a significant

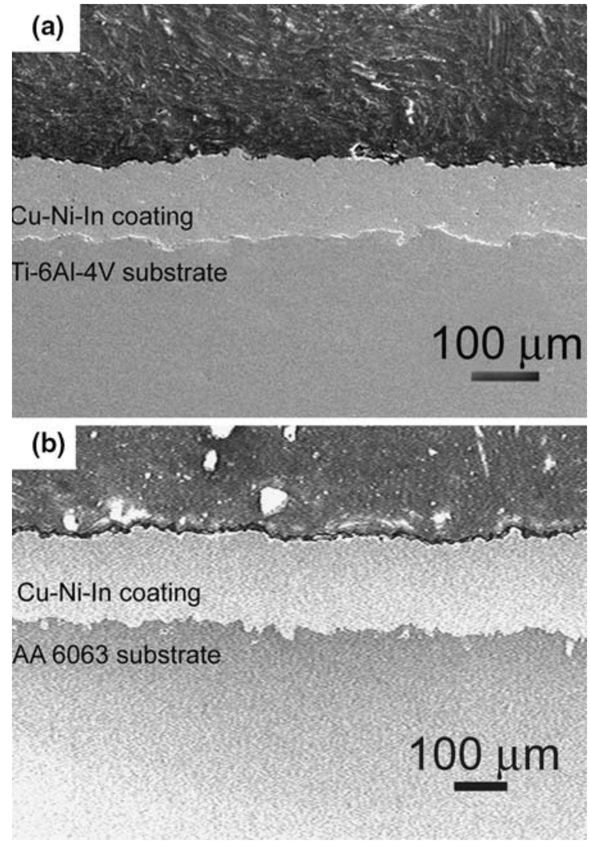

Fig. 1 SEM micrographs showing the cross section of Cu-Ni-In coating on two different substrates: (a) Ti-6Al-4V; (b) AA 6063

difference between the coating and substrate hardness values (360 against 330 $HV_{0.2}$). However, in case of Al-alloy, the coating hardness was much higher than that of the substrate (350 against 80 $HV_{0.2}$). A similar trend was noticed with reference to elastic modulus too. The mismatch between the properties of coating and substrate materials was significant in case of Al-alloy samples. The morphology of coating on both the substrates was similar (see Fig. 2). The coating surface was very rough compared to the substrate due to the presence of unmelted powder particles and their irregular distribution resulting from spray kinetics (Ref 6).

Residual stresses are crucial and inevitable in D-gun spraying due to rapid solidification and high velocity projection that induce extensive plastic deformation. The values of residual stresses measured at the surface level are given in Table 4. But a thorough analysis of residual stresses beneath the surface of coating and more importantly at the interface is needed to have a clear understanding. The coating on Ti-alloy exhibited compressive residual stress at the surface. In case of coating on Al-alloy tensile residual stress was also noticed at the surface in some places in addition to compressive residual stress. In a thermal spray process, residual stresses arise from two sources—(i) cooling of spray particles from their solidification temperature to substrate temperature and (ii) differences between the thermal expansion coefficient values

Table 4 Surface characteristics of substrate materials and coatings

Material	Porosity (%)	Hardness: Micro indentation ($HV_{0.2}$)	Hardness: Nano indentation (GPa)	Elastic modulus (GPa)	Surface residual stress (MPa)	Surface roughness (µm): R_a	Surface roughness (µm): R_{max}
Uncoated Ti-6Al-4V	···	330	···	117	−3 to −10	0.80	3.78
Cu-Ni-In on Ti-6Al-4V	0.40	360	4.2	139	−94 to −107	6.60	49.94
Uncoated AA 6063	···	80	···	69	−57 to −66	0.60	3.83
Cu-Ni-In on AA 6063	0.30	350	4.2	139	+16 to −85	6.33	34.15

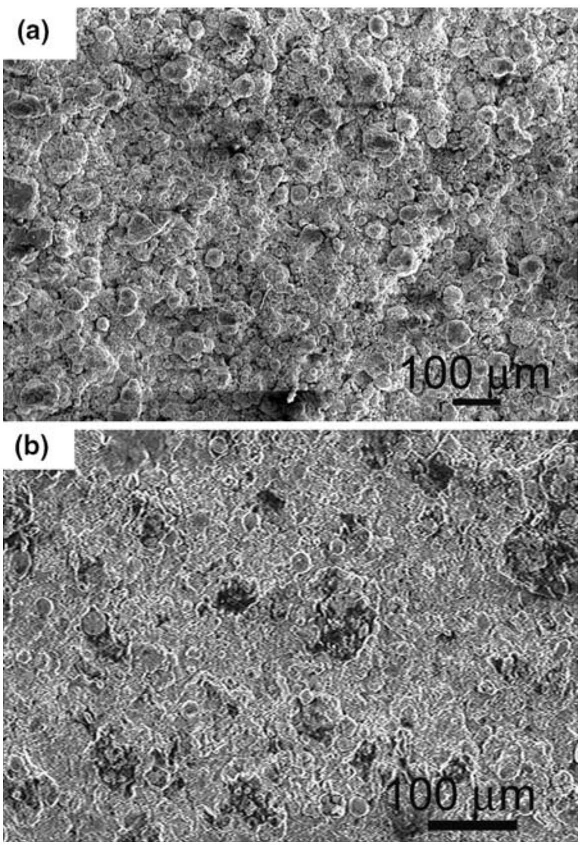

Fig. 2 SEM micrographs showing the morphology of coating on two different substrates: (a) Ti-6Al-4V; (b) AA 6063

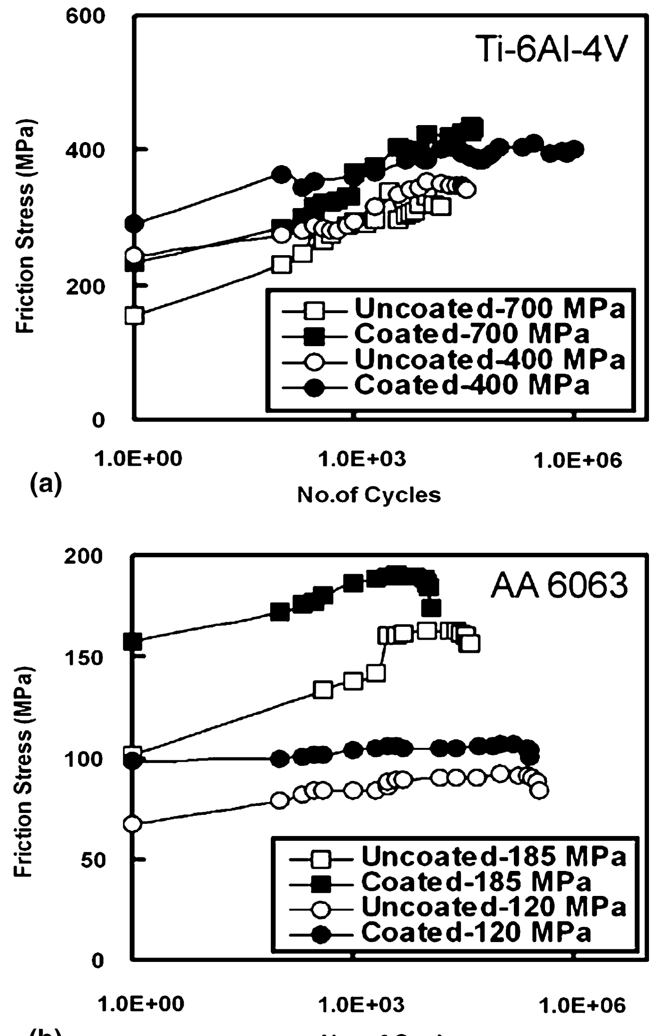

Fig. 3 Variation of friction stress with number of fretting cycles at different maximum stress levels corresponding to uncoated and coated specimens of two different substrates: (a) Ti-6Al-4V; (b) AA 6063

of coating and substrate materials. The differences in the residual stresses and the wide range of values may be attributed to difference in the heat dissipation, cooling rates, quenching stresses, relative movement between the work piece and gun and the coefficient of thermal expansion of the substrate materials and the physiothermal properties of coating material (Ref 6).

3.2 Friction Stress

Figure 3 shows the variation of friction stress with number of fretting cycles at two different stress levels. Friction stress increased with increasing cyclic stress level. Coated samples exhibited higher friction stress compared with the uncoated specimens. Coating is usually selected to reduce friction. In the present study coated specimens exhibited higher friction stress compared with the uncoated samples in both Ti- and Al-alloy substrates. Figure 4 shows fretting hysteresis loops. The half-life values of friction stress and the relative slip were considered for the plots. From the shape of the fretting loops, it

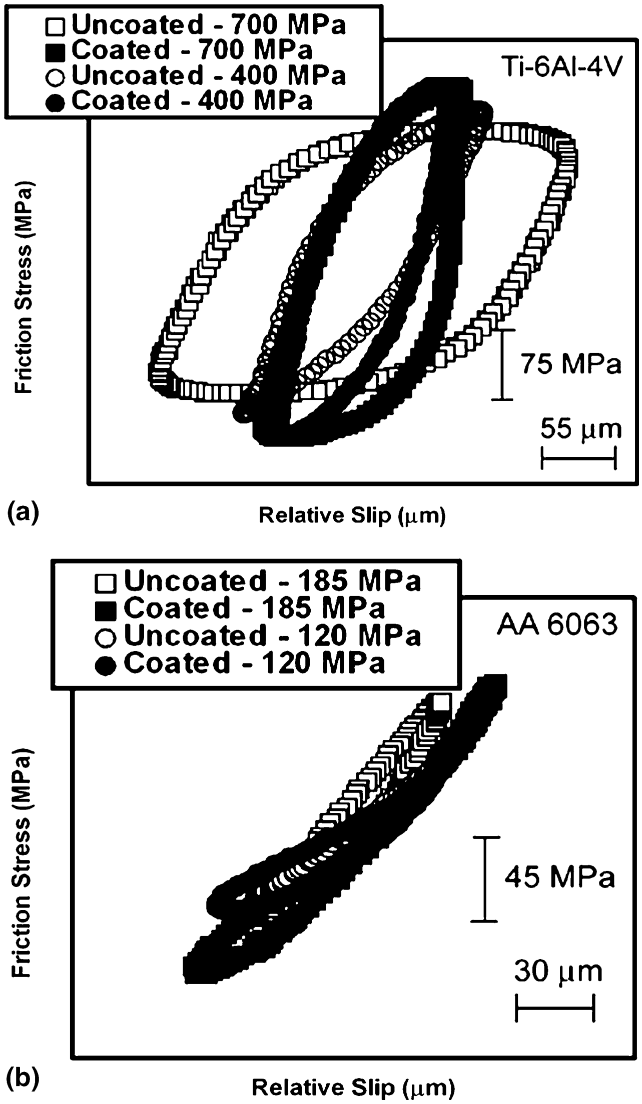

Fig. 4 Fretting hysteresis loops at different maximum stress levels corresponding to uncoated and coated specimens of two different substrates: (a) Ti-6Al-4V; (b) AA 6063

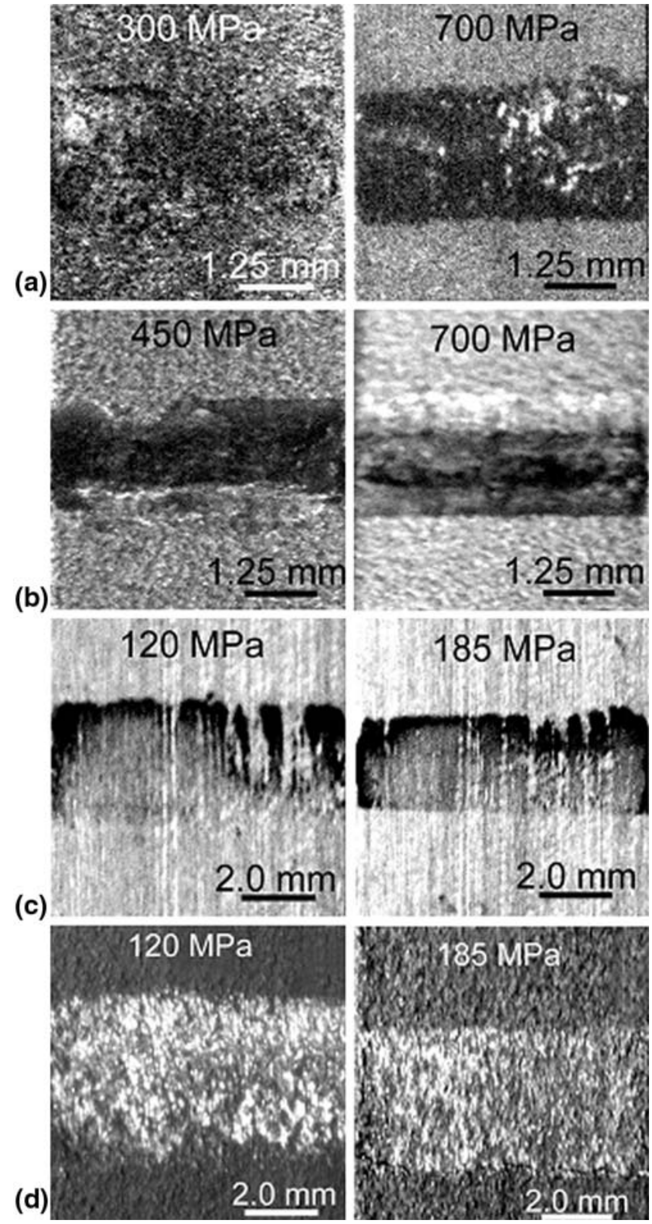

Fig. 5 Appearances of fretting scar in different specimens tested at different maximum cyclic stress levels: (a) Uncoated Ti-alloy; (b) Coated Ti-alloy; (c) Uncoated Al-alloy; (d) Coated Al-alloy

may be stated that uncoated Ti-alloy samples encountered partial slip at low stress levels and gross slip at high stress levels. On the other hand, coated Ti-alloy samples experienced partial slip at all stress levels. In case of Al-alloy, both coated and uncoated specimens experienced partial slip. As different sets of stress levels were used for Ti- and Al-alloys, comparison could not be made between the two alloys in terms of friction stress and relative slip.

3.3 Fretting Scar

Figure 5 shows the appearance of fretting scar in fretting fatigue tested samples. The width of fretting scar was larger in specimens tested at higher cyclic stress levels than that in samples tested at lower stress levels. The fretting scar was wider in uncoated Ti-alloy samples than that in coated specimens indicating relatively larger relative slip in uncoated samples (see also Fig. 4(a)). Converse was true in case of Al-alloy specimens. The fretting scar width was larger in coated Al-alloy samples than that in uncoated samples. Also, material transfer from the relatively softer uncoated Al-alloy pads (80 $HV_{0.2}$) to the harder coated specimen surface (350 $HV_{0.2}$) was more. In case of Ti-alloy, as the uncoated pads and coated specimen exhibited almost the same hardness (330 and 360 $HV_{0.2}$), the material transfer from the pad to the specimen was relatively lower. Surface roughness parameters (R_a and R_{max}) measured across the fretting scar region of the specimens tested at different stress levels are shown in Fig. 6. As different sets of cyclic stress levels were used for Ti- and Al-alloy samples, the cyclic stress levels were normalized with yield strength of the respective materials. The values of surface roughness parameters increased with increase in applied cyclic stress level for uncoated Ti- and Al-alloy specimens. As coated specimens had very rough surface with larger undulations, due to fretting fatigue deformation the undulations were reduced. This effect of reduction in R_{max} values increased with applied cyclic stress in all coated samples. However, the effect was more in Ti-alloy samples. This could be attributed to the relatively higher hardness of uncoated Ti-alloy pads, compared with the uncoated Al-alloy pads.

3.4 Fatigue Lives

Figure 7 shows the results of plain fatigue and fretting fatigue tests conducted on uncoated and coated specimens. The detrimental effect of fretting in reducing fatigue life was relatively more in Al-alloy than that in Ti-alloy. This may be attributed to the differences in the crystal structure. While Al-alloy has face centered cubic structure, Ti-alloy has hexagonal close-packed α phase and body centered cubic β phase. Five slip systems are required so that when two rough surfaces deform, there is a perfect conformance between them at each junction. Hexagonal metals, which have limited number of slip systems, when pressed against each other, deform by slippage leaving many air gaps at each junction (Ref 13). In contrast, face centered cubic metals, which have 12 slip

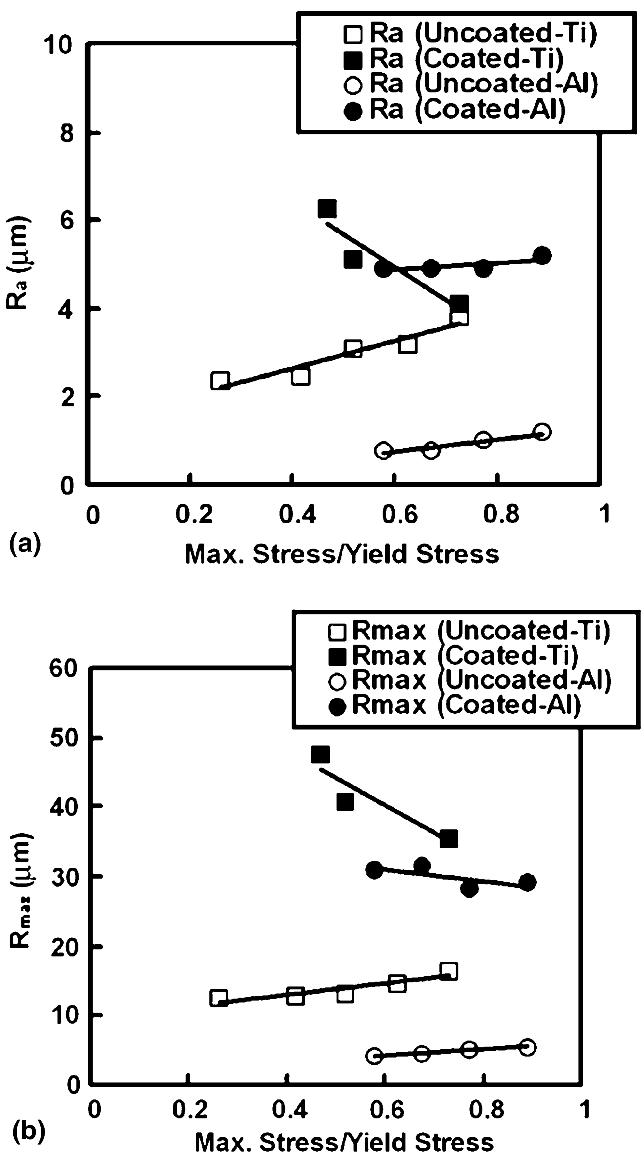

Fig. 6 Variation of surface roughness parameters across the fretting scar with the ratio between maximum cyclic stress and yield strength of the corresponding substrate: (a) R_a; (b) R_{max}

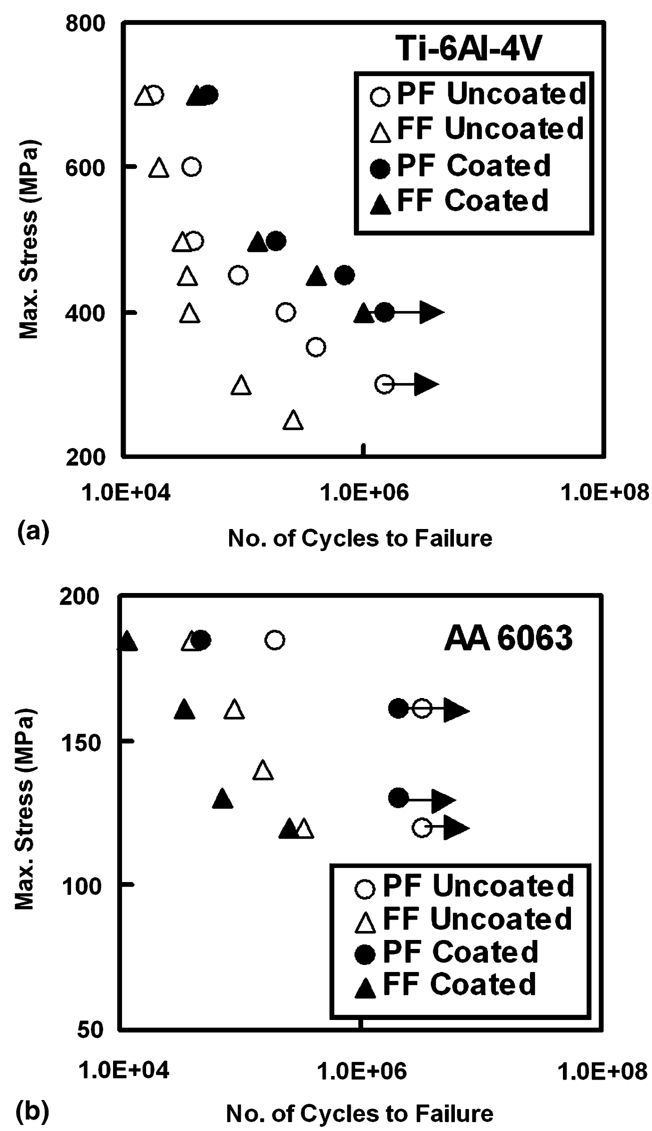

Fig. 7 Plain fatigue (PF) and fretting fatigue (FF) life data corresponding to uncoated and coated specimens of two different substrates: (a) Ti-6Al-4V; (b) AA 6063. Arrows indicate non-failure

systems have no such air gaps and for this reason the contact is stronger and friction and wear are correspondingly higher. This may be the reason for the relatively larger extent of reduction in fatigue life due to fretting in Al-alloy specimens.

While Cu-Ni-In coating enhanced plain fatigue and fretting fatigue lives of the Ti-alloy, it reduced the lives of the Al-alloy. Generally the fatigue lives of thermal sprayed materials are controlled by many factors such as porosity, adhesion, residual stress, hardness, and roughness. Porosity is usually considered to adversely affect fatigue life. Residual stress at interface plays an important role in affecting the adhesion of coating with the substrate. If the adhesion of the coating with the substrate is poor, then under loading interfacial cracking and delamination of the coating will take place resulting in inferior fatigue life. In case of Al-alloy samples, the mismatch between the properties of coating and substrate was larger and so severe interfacial cracking and delamination induced fracture was observed (see later). Though coated Al-alloy samples exhibited higher surface hardness, their surfaces were very rough and even tensile surface residual stresses

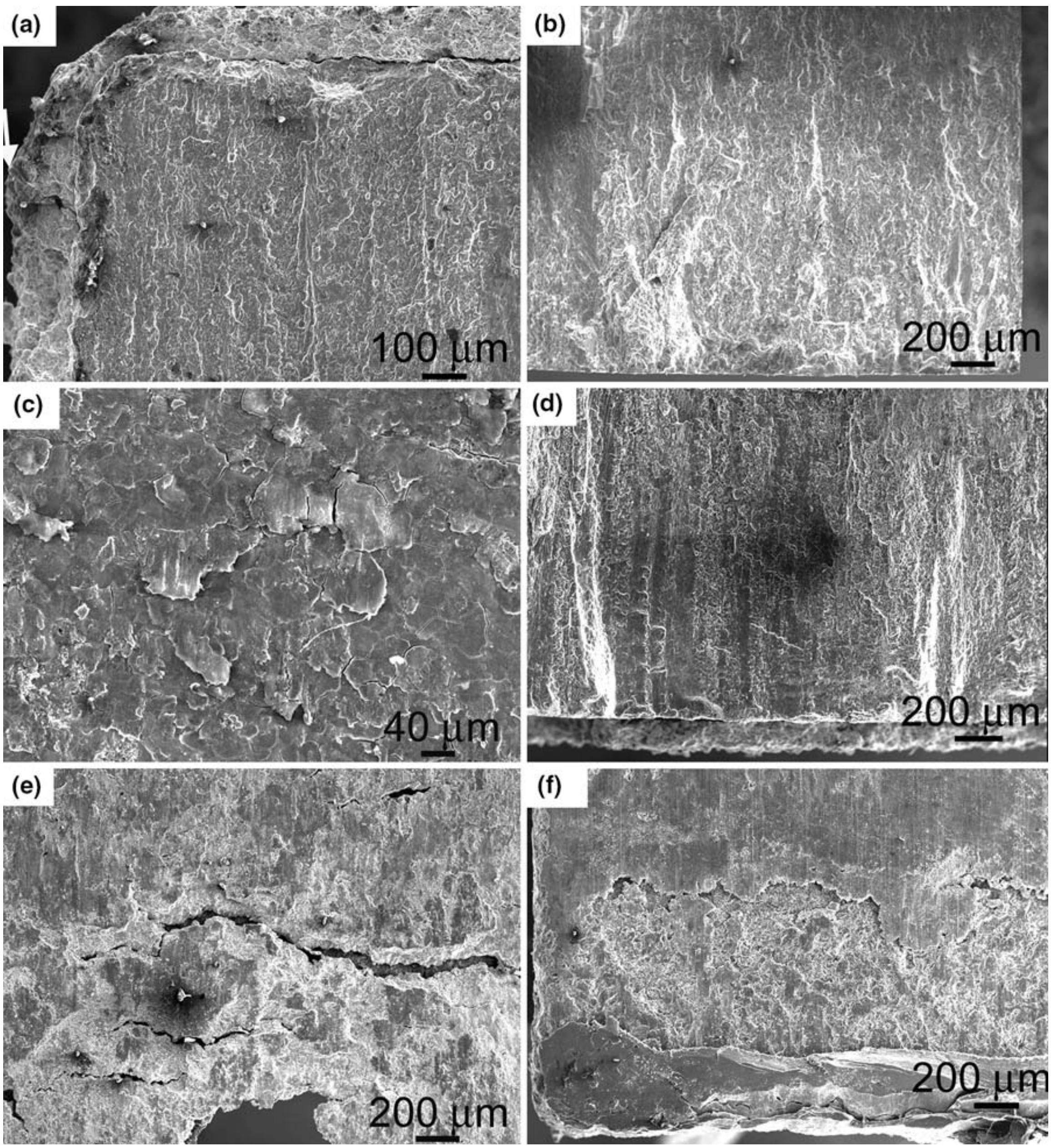

Fig. 8 Appearances of fracture surfaces (a, b, d) and side surfaces (c, e, f) of uncoated and coated Ti-alloy specimens tested at different stress levels under plain fatigue (PF) and fretting fatigue (FF) loading: (a) Coated-PF-450 MPa; (b) & (c) Uncoated-FF-250 MPa; (d) & (e) Coated-FF-450 MPa; (f) Coated-FF-700 MPa. Arrow indicates crack initiation point

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were present. This might also be the reason for their inferior plain fatigue lives compared with the uncoated specimens. Higher surface hardness, higher surface compressive residual stress, higher surface roughness, and lower friction stress are considered to enhance fretting fatigue lives (Ref 14). A hard coating will improve fretting fatigue resistance provided it has good adhesion or bond strength with the substrate. Though higher surface hardness and higher surface roughness of coated Al-alloy samples might have played a positive role of enhancing their fretting fatigue lives, this might have been overtaken by the ill effect of higher friction stress and the presence of tensile surface residual stress. Also, there was delamination of the coating. So this resulted in inferior fretting fatigue lives of coated Al-alloy samples compared with the uncoated specimens. In case of Ti-alloy, there was not such significant difference between the surface hardness and elastic modulus values of the coated and uncoated specimens. Though the surfaces of coated specimens were very rough and had pores, significantly high surface compressive residual stresses present in the coated specimens enhanced their plain fatigue lives. Under fretting fatigue loading, in addition to the beneficial role played by the higher compressive residual stresses, the higher surface roughness of coated Ti-alloy samples also contributed to the enhancement of their fretting fatigue lives.

3.5 SEM Observations

Figures 8 and 9 show the appearances of fracture surfaces and side surfaces of tested specimens. Under plain fatigue loading cracks initiated at the coating surface and propagated through the interface into the substrate. Cracking at the interfaces was also noticed. Under fretting fatigue loading, cracks initiated from contact region of the specimens due to stress concentration effect introduced by fretting. Many microcracks were observed on the fretted regions of uncoated Ti-alloy specimens tested under fretting fatigue loading (see Fig. 8c). It has been reported that fretting deformation of a two phase $\alpha+\beta$ structure of Ti-alloys results in the formation of a thin layer consisting of solely the α phase and cracks originate in this transformed layer (Ref 15). At fretting contacts local temperature will be high due to frictional heating. As Ti-6Al-4V has poor thermal conductivity, heat cannot be dissipated readily from the asperity contacts and this leads to build up of local temperature. The solubility of oxygen in titanium is significantly higher at high temperatures than that at room temperature. The oxygen in the surface stabilizes α-phase on cooling and so a higher volume fraction of α-phase is present. As the α-phase is brittle, it may be assumed that cracks are associated with surface transformed regions (Ref 15). At the end of tests coating peeled off from the substrate (see Fig. 8f).

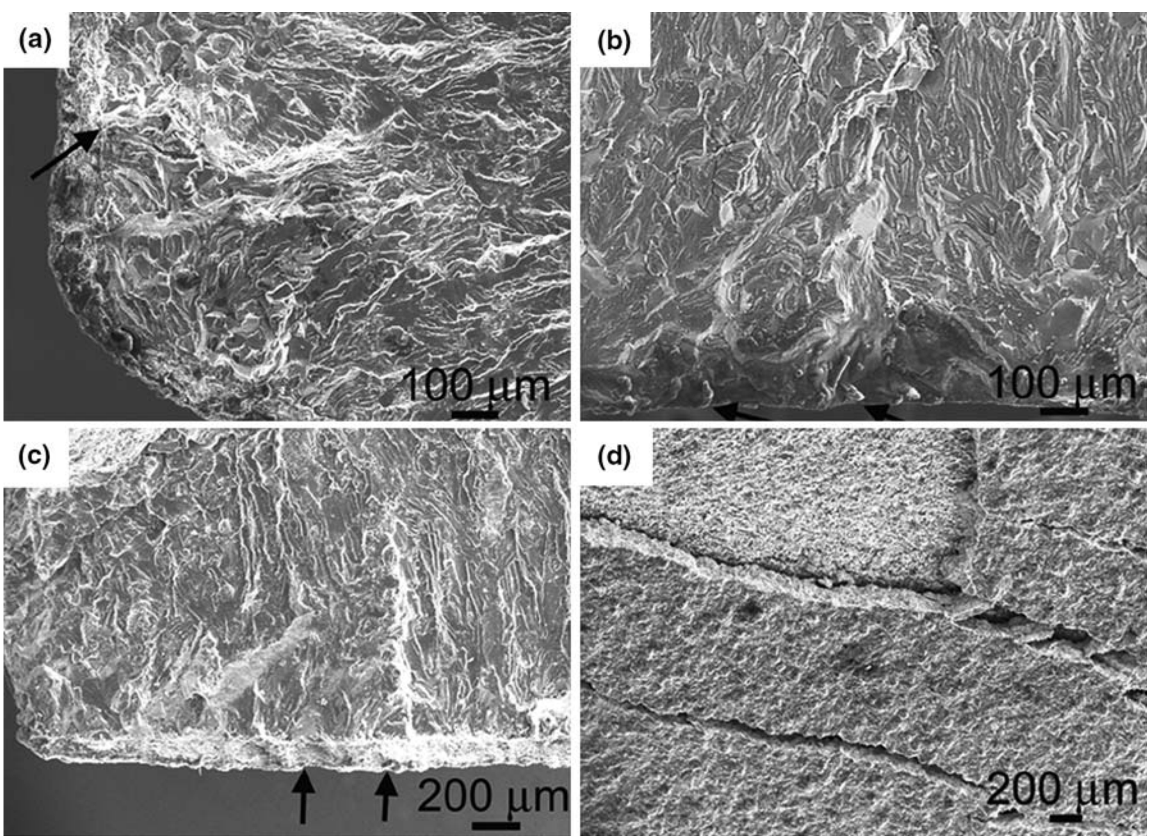

Fig. 9 Appearances of fracture surfaces (a-c) and side surface (d) of uncoated and coated Al-alloy specimens tested at 185 MPa under plain fatigue (PF) and fretting fatigue (FF) loading: (a) Coated-PF; (b) Uncoated-FF; (c) & (d) Coated-FF. Arrows indicate crack initiation points

In case of coated Al-alloy specimens, cracking was noticed at the interface. Delamination-induced fracture was observed. Interface cracked and the crack propagated through the substrate leading to a reduction in plain fatigue life compared with the uncoated samples. Under fretting fatigue loading multiple crack initiation was noticed in the contact region. Severe delamination was also observed on the surfaces (Fig. 9(d)). This has been discussed elsewhere (Ref 11).

4. Conclusions

The following conclusions were drawn based on the results obtained in the present study on the effect of substrate materials (Ti-6Al-4V and AA 6063) on plain fatigue and fretting fatigue behavior of D-gun sprayed Cu-Ni-In coating. The mismatch in the properties of coating and substrate was less in case of Cu-Ni-In coating on Ti-6Al-4V alloy than the Cu-Ni-In coating on AA 6063. The detrimental effect of life reduction due to fretting was relatively larger in the Al-alloy compared with that in the Ti-alloy. While Cu-Ni-In coating was found to be beneficial on the Ti-alloy, it was deleterious on the Al-alloy substrate under both plain fatigue and fretting fatigue loading. The results were explained in terms of differences in the values of surface hardness, surface roughness, surface residual stress, and friction stress.

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References

1. *Fatigue, Fretting Fatigue*, Vol. 19, ASM Hand book, Ohio, USA, 1996, p 321-336
2. R.B. Waterhouse, Occurrence of Fretting in Practice and its Simulation in the Laboratory, *Materials Evaluation under Fretting Conditions*, ASTM, Philadelphia, USA, 1992, p 3-16
3. D.W. Hoeppner, A.M.H. Taylor, and V. Chandrasekaran, Fretting Fatigue Behavior of Titanium Alloy, *Fretting Fatigue: Advances in Basic Understanding and Applications*, Y. Mutoh, S.E. Kinyon, and D. W. Hoeppner, Eds., ASTM STP 1425, ASTM, West Conshohocken, PA, USA, 2003, p 291-306
4. O. Kovarik, J. Siegl, J. Nohava, and P. Chraska, Young's Modulus and Fatigue Behavior of Plasma-Sprayed Alumina Coatings, *J. Thermal Spray Technol.*, 2005, **14**(2), p 231-238
5. T.S. Price, P.H. Shipway, and D.G. McCartney, Effect of Cold Spray Deposition of a Titanium Coating on Fatigue Behavior of a Titanium Alloy, *J. Thermal Spray Technol.*, 2006, **15**(4), p 507-512
6. Y.A. Kharlamov, Detonation Spraying of Protective Coatings, *Mater. Sci. Eng.*, 1987, **93**, p 1-37
7. R. Ahmed and M. Hadfield, Rolling Contact Fatigue Performance of Detonation Gun Coated Elements, *Tribology Int.*, 1997, **30**(2), p 128-135
8. R. Ahmed and M. Hadfield, Mechanisms of Fatigue Failure in Thermal Spray Coatings, *J. Thermal Spray Technol.*, 2002, **11**(3), p 333-349
9. M. Shima, J. Okado, J.R. McColl, R.B. Waterhouse, T. Hasegawa, and M. Kasaya, The Influence of Substrate Material and Hardness on the Fretting Behaviour of TiN, *Wear*, 1999, **225-229**(1), p 38-45
10. V. Fridrici, S. Fouvry, and Ph. Kapsa, Fretting Wear Behavior of a Cu-Ni-In Plasma Coating, *Surf. Coat. Technol.*, 2003, **163-164**, p 429-434
11. B. Rajasekaran, S. Ganesh Sundara Raman, S.V. Joshi, and G. Sundararajan, Effect of Detonation Gun Sprayed Cu-Ni-In Coating on Plain Fatigue and Fretting Fatigue Behaviour of Al-Mg-Si Alloy, *Surf. Coat. Technol.*, 2006, **201**(3-4), p 1548-1558
12. N.K. Ramakrishna Naidu and S. Ganesh Sundara Raman, Effect of Shot Blasting on Plain Fatigue and Fretting Fatigue Behaviour of Al-Mg-Si Alloy AA6061, *Int. J. Fatigue*, 2005, **27**(3), p 323-331
13. E. Rabinowicz, *Friction and Wear of Materials*, 2nd ed., John Wiley & Sons Inc., New York, 1995, p 40
14. Y. Fu, J. Wei, and A.W. Batchelor, Some Considerations on the Mitigation of Fretting Damage by the Application of Surface-Modification Technologies, *J. Mater. Proc. Technol.*, 2000, **99**, p 231-245
15. R.A. Antoniou and T.C. Radtke, Mechanisms of Fretting-Fatigue in Titanium Alloys, *Mater. Sci. Eng. A*, 1997, **237**(2), p 229-240