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Effect of substrate bias voltage on fretting fatigue behaviour of ceramic film deposited on Ti-6Al-4V alloy

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Abstract: A fracture behavior of PVD coated ceramic film deposited on Ti-6Al-4V specimens was evaluated for a fretting fatigue geometry in which specimens were contacted on both sides with pads of the similar material. Behavior against the ceramic film coated specimens was characterized through the determination of fretting fatigue strength up to 10^7 cycles. Fretting damage of specimen surface was characterized by SEM and surface profilometer. Ceramic film coating has a great effect to improve the fretting fatigue strength. From the experimental results of S-N tests it is clear that until about 10^6 cycles ceramic coating is effective to improve the fretting fatigue strength. But over 10^6 cycles the strength is lower than that of uncoated specimens. The enhanced fretting fatigue resistance can be attributed to the improved hardness of ceramic film due to change of bias voltage during the film deposition. It has also been concluded that there is smaller influence of bias voltage on fatigue strength below and about 10^6 cycles; whereas, over 10^6 cycles, fatigue strength is clearly changed by bias voltage as well as the contact pressure.

Keywords: Ceramic Film, Ti-6Al-4V Alloy, Contact Pad, Surface Treatment, Fretting Fatigue, Bias Voltage

1. Introduction

Alloys of Titanium offer several attractive material properties, including low density, high strength, high corrosion resistance, and low elastic modulus. Ti-6Al-4V is the most widely used titanium alloy, because it combines the attractive titanium properties with inherent workability allowing it to be produced in all types of mill-products [1]. However, the titanium alloy has poor wear and seizure resistance, fretting fatigue is easily caused.

Fretting fatigue often results in damage that may lead to premature component failure. The problem has been observed in many places, from the multi-strand steel cables used for ship rigging to the rotating components of aircraft engines. Because the problem is so widespread, it has been the focus of numerous investigations conducted worldwide on a variety of test geometries and material systems [2-7].

Physical vapor deposition (PVD) and nitriding are well-known surface treatment methods to improve the surface properties of titanium alloy. In particular, PVD method is very effective to high wear resistance, low coefficient of friction and seizure resistance; therefore, the coatings are widely used for tools etc. Ceramic film (CrN) is one of the film materials that can bring about a dramatic improvement in tribological properties such as wear and corrosion resistance [8-10]. Researches regarding this film mainly emphasized its promising anti-oxidative and corrosion resistance, and indicated that this ceramic film was superior to TiN [11]. Several studies have demonstrated the potentiality of coatings to minimize fretting fatigue damage in the substrate and the improvement of its fretting fatigue life [12-13]. The fretting fatigue resistance of titanium alloys would be improved by applying special coating.

This work presents the results obtained from the deposition of CrN film on Ti-6Al-4V substrates by arc ion plating (AIP) method at two different bias voltages and the influence that the application of bias voltage on the substrate has on the fretting fatigue resistance.

2. Experimental Procedure

2.1. Materials and Specimen

Ti-6Al-4V alloy was used as a substrate material which was heat treated at 740 ºC and furnace cooled. The chemical composition of the material is 0.01 % C, 4.20 % V, 6.07 % Al, 0.16 % O, 0.01 % N, 0.16 % F, 0.001 % H and balance Ti. The material was machined into the shape as illustrated in Fig. 1 and both the specimens and pads were polished using a series of standard metallurgical polishing steps. Then, annealing for stress relief was carried out at 650ºC in vacuum for 1 hour. The 0.2 proof stresses, tensile strength and the elongation was 915 MPa, 1065 MPa and 17% respectively.

2.2. Film Deposition

CrN film was deposited by AIP (AIP-201, Kobe Steel Co.) method. After ultrasonically cleaning in acetone, the substrates were placed in a vacuum chamber and evacuated to 9.98×10^{-3} Pa. The target material was commercially pure Cr disc (purity 99.9%). After initially preheated, ion bombardment process was carried out for surface cleaning in nitrogen atmosphere at gas flow rate of 53 sccm employing a voltage bias of 700 V and an arc current of 60 A for 1 min and then, the deposition process was started. Bias voltage was applied to the substrate, which draws the ions to the substrate surface. The film properties can be controlled by the bias voltage during the deposition. In this study, two different bias voltages; V_B =-20V and -300V were adopted. Deposition time was controlled to give a 2 µm thick film. The deposition conditions are shown in table 1.

2.3. Hardness Test

A micro-Vickers hardness test machine (MVK-E3) was used to measure the surface micro-hardness of the specimens applying 25gf load on the annealed uncoated specimen. In order to exclude the influence of the substrate material, a 20 µm thick film was applied onto the substrate and 100gf load was applied.

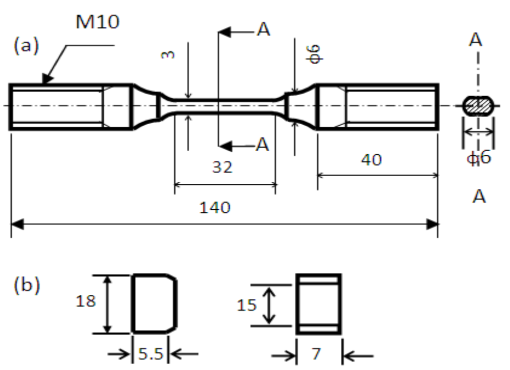

Figure 1. *(a) Ti-6Al-4V Specimen and (b) Ti-6Al-4V pad dimensions are in mm.*

Table 1. *CrN coating condition*

Bias voltage	-20V, 300V
Arc current	50A
Pressure	5.33Pa
Heater temperature	573K
Film thickness	2.0µm

2.4. Fretting Fatigue Test

The uni-axial tension-tension fretting fatigue test was carried out using a dynamic servo fatigue test machine (EFH-100) under load controlled condition at a frequency of 10 Hz and stress ratio of R =0.05. The static clamping load was imposed via instrumented bolts through proving ring, whose internal strain gages allow quantification of the average clamping load. The clamping load was two types; 1500N and 4500N.

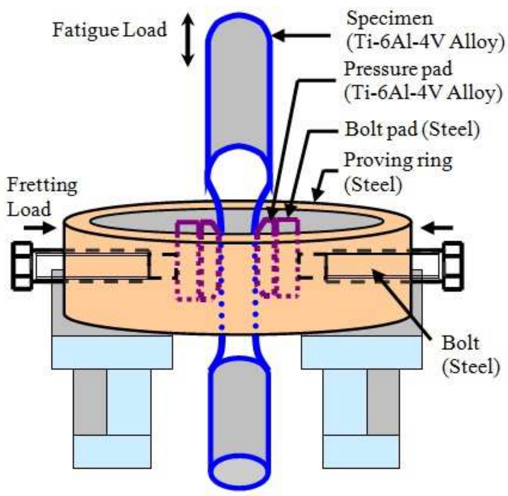

Figure 2. *Fretting fatigue test mechanism*

The specimens were axially loaded by a completely reversed cyclic stress in the range of 150MPa to 500MPa. Fracture surfaces of some selected coated specimens were observed by SEM (S-2400) in order to determine the crack initiation sites, the occurrence of delamination of the coating during cyclic loading and the role of the coating during the propagation of the cracks.

3. Experimental Results and Discussion

3.1. Film Properties

Micro Vickers hardness values at the surface were obtained for the substrates and films. The 30 points average hardness of the specimens is shown in Table 2. The average surface hardness of the uncoated specimen was 328 HV. It was found that the hardness of CrN films was strongly dependant on the bias voltage during the deposition and was higher for high bias voltage specimens than that of low bias voltage specimens.

Surface roughness was also measured with a surface profilometer. The average surface roughness (R_a) of the substrate was 0.231µm. The roughness of the coatings were 0.318 µm for V_B = -20V and 0.373 µm for V_B = -300V, respectively. The increase of surface roughness by coating was mainly caused by droplets on the film due to the scattering of melted target (Cr) during the deposition [14-15] shown as bright particles in Fig. 3.

Table 2. *Vickers hardness of specimen's surfaces*

Sample	Range	Average Hardness
Uncoated	290-352	328
V_B = -20V	1125-1520	1344
V_B = -300V	1998-2828	2408

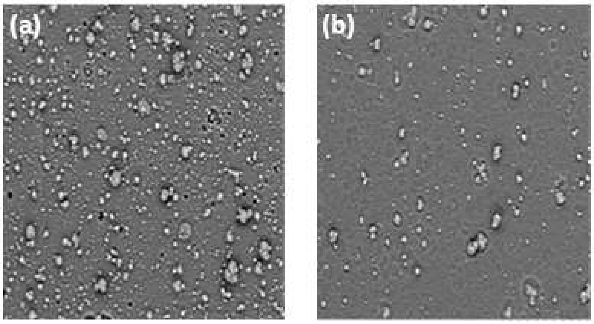

Figure 3. *Droplets grown on film during deposition. (a) V_B = - 300V (b) V_B = -20V*

3.2. Fretting Fatigue Test

Fretting fatigue tests under sinusoidal loading were carried out up to 10^7 cycles applying clamping force. Fig. 4 shows the results of fretting fatigue tests for uncoated and CrN coated specimens at clamping load *P* = 1500 and 4500N. The fatigue strength at 10^7 cycles for V_B = -20V was similar or slightly lower than uncoated specimen and increase in lower life region, especially for low clamping stress. For V_B = -300V specimens, although the CrN film was effective in lower life region for both clamping loads as well as low bias voltage specimens, the fatigue strength at 10^7 cycles clearly decreased compared with uncoated and low bias voltage specimens. The experimental results from the S-N tests indicate that the CrN coating is effective to improve the fretting fatigue strength below and about 10^6 cycles but over 10^6 cycles, the strength becomes similar level or lower than that of uncoated specimens. Higher surface hardness, higher surface compressive residual stress, higher surface roughness and lower friction stresses are considered to enhance fretting fatigue lives [16]. Though higher surface hardness and higher surface roughness of CrN coated Ti-6Al-4V alloy specimens might have played a positive role of enhancing their fretting fatigue lives, this might have been overtaken by the ill effect of higher frictional stresses especially for long life period for both contact loads. This might be the reason for inferior fretting fatigue property of the coated specimens compared with the uncoated specimens. At low stress amplitude, below 250 MPa for both low and high clamping loads; small slip was occurred and the film did not show large damage such as wear and delamination as shown in Fig. 5. It suggests that the contact state might be only "stick" condition. The debris particles as well as damage of coated specimens (Fig. 5(b) and (c)) were more than that of uncoated specimen (Fig. 5(a)). But the damage was remarkable for V_B = -300V specimen than V_B= -20V specimen especially for low clamping load. The decrease of fretting fatigue strength after 10^6 cycles might also be caused by this wear damage. The film surface (Fig. 5(d)) of the specimen failed just before 10^7 cycles shows that the damage was more severe than Fig. 5 (b).

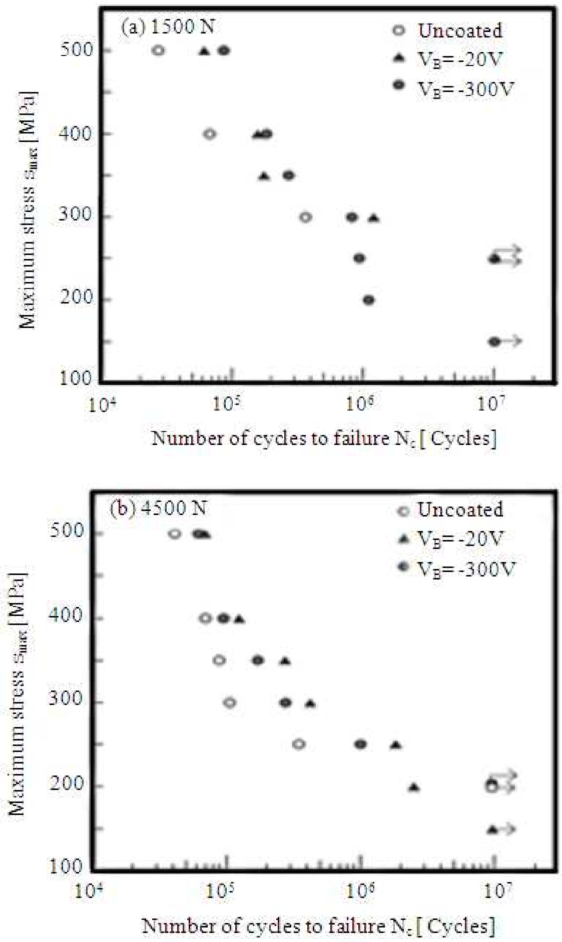

Figure 4. *Effect of bias voltage on fretting fatigue behavior under different clamping loads. Arrows indicate non-failure.*

It is difficult to estimate the life as well as crack initiation of any specimen due to complex interaction of contacts and micro-structural homogeneity or uniformity, which may vary for different specimens under test contact state might be only "stick" condition. The debris particles as well as damage of coated specimens (Fig. 5(b) and (c)) were more than that of uncoated specimen (Fig. 5(a)). But the damage was remarkable for V_B = -300V specimen than V_B= -20V specimen especially for low clamping load. The decrease of fretting fatigue strength after 10^6 cycles might also be caused by this wear damage. The film surface (Fig. 5(d)) of the specimen failed just before 10^7 cycles shows that the damage was more severe than Fig. 5 (b). It is difficult to estimate the life as well as crack initiation of any specimen due to complex interaction of contacts and micro-structural homogeneity or uniformity, which may vary for different specimens under test.

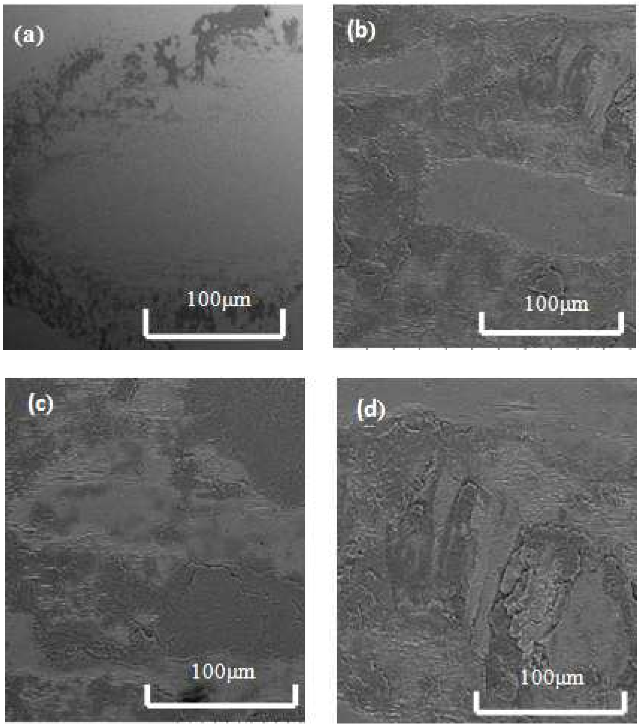

Figure 5. *Appearances of fretted surfaces of non-failure (a, b, c) and failure (d) specimens at low contact pressure: (a) Uncoated specimen,* $s_{max} = 250$ *MPa, (b)* $V_B = -300V$, $s_{max} = 150$ *MPa, (c)* $V_B = -20V$, $s_{max} = 250$ *MPa., (d)* $V_B = -300V$, $s_{max} = 200$ *MPa,* $N_f = 1.11\times10^6$ *cycles.*

4. Conclusions

The results obtained in this work, under the stated experimental condition, clearly showed that fretting fatigue strength is strongly affected by the applying bias voltage during the deposition. At high stress amplitude region the damage severity was very high due to metallurgical compatibility of the contact pairs. Results show that until about 10^6 cycles; there is small influence of bias voltage on fatigue strength whereas, over 10^6 cycles, fatigue strength is clearly changed by bias voltage for both contact loads. This will be caused by the difference of brittleness due to the difference of film hardness. At high stress amplitude the effect was low. In conclusion, the difference of the fatigue strength is caused by the difference of the crack initiation stress which is related to the film hardness.

References

[1] Mamdouh M. Salama, J. of Offshore Mechanics and Arctic Engineering. Vol. 123/141,(2001).

[2] U. Bryggman and S. Soderberg, Wear, vol.125 (1988), pp. 39–52.

[3] L.J. Fellows, D. Nowell and D.A. Hills, Wear, vol.205 (1996), pp. 120–129.

[4] S. Fouvry, P. Kapsa and L. Vincent, Wear, vol. 200 (1996), pp. 186–205.

[5] O. Vingsbo and J. Schon , Wear, vol.162-164 (1993), pp. 347–356.

[6] Z.R. Zhou and L. Vincent, Wear vol. 181-183 (1995), pp. 551–556.

[7] S. Adibnazari and D.W. Hoeppner , In: R.B. Waterhouse and T.C. Lindley, Editors, Fretting fatigue ESIS 18, Mechanical Engineering Publications, London (1994), pp. 125–133.

[8] B. Navinsek, P. Panjan, Surf. Coat. Technol., Vol. 74 - 75 (1995), pp. 919.

[9] J. Stockemer, R. Winand, P. Vanden Brande, Surf. Coat. Technol.,Vol. 115 (1999), pp. 230.

[10] M. Fenker, M. Balzer, H.A. Jehn, H. Kappl, J.-J. Lee, K.-H. Lee, H.-S. Park, Surf. Coat. Technol., vol.150 (2002), pp. 101.

[11] T. Kacsich, K.-P. Lieb., Thin Solid Films, 245(1994), pp. 4-6.

[12] K. Shiozawa, S. Ohshima, J. of the Mat. Sci. Japan,39 (442), (1990), pp. 927.

[13] K. Shiozawa, S. Ohshima, K.Handa, JSME International Journal, Series A 35(3),(1992), pp.347.

[14] M. Kumagai, K. Yukimura, E. Kuze, T. Maruyama, M. Kohata, K. Numata, H. Saito, and X. Ma., Surf. Coat. Tech., 169 –170(2003), pp. 401–404.

[15] Harris S.G., Doyle E.D., Wong Y.C., Munroe P.R., Cairney J.M., and Long J.M., Surf. Coat. Tech., 183(2004), pp. 283–294.

[16] Y. Fu, J. Wei, and A.W. Batchelor, J. Mater. Proc. Technol., 99 (2000), pp. 231-245.