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Enhancement of Fatigue Behavior of PVD Coated Ceramic Thin Film Deposited on Titanium Alloy

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Abstract

Hard thin ceramic film deposited by PVD technique is well-known to improve the wear resistance. The effect of intrinsic properties of ceramic coatings on fatigue behavior was studied in this paper. PVD technique incorporating ceramic coating (CrN) was applied to the titanium alloy (Ti-6Al-4V) and its effects on the fatigue life and fatigue strength were studied to explore the fatigue behavior of Ti-6Al-4V specimens. A CrN film deposited by arc ion plating (AIP) improved the mechanical properties; specially hardness, and fatigue life of Ti-6Al-4V specimens. Ti-6Al-4V alloy was used as a substrate material. Tension-tension fatigue test and tensile test were carried out to investigate the fatigue properties. The fatigue life of CrN-coated Ti-6Al-4V specimens was improved significantly compared to those of un-coated specimens. Scanning electron microscopic (SEM) investigations were used to correlate fatigue induced surface damage. The initiation of fatigue cracks is likely to be retarded by the presence of hard and strong layers on the substrate surface. It has been determined that the fatigue fracture of the substrate-coating composite is dominated by the fracture of the CrN film since fatigue cracks have been observed to form first at the surface of the film and subsequently to propagate towards the substrate, It has also been concluded that the increase in fatigue properties of the coated substrate is observed in most of the maximum alternating stress range explored in this work.

Keywords: PVD, Ceramic thin film, Titanium alloys, Surface treatments, Fatigue.

1. Introduction

Thin film hard coatings are widely used as wear-resistant coatings and thermal corrosion barriers. Such films are usually deposited onto steel to be used in high-speed tool steel, such as punching dies and cutting tools, to extend the useful life of these parts. CrN is an important material useful for its corrosion resistance, oxidation protection properties and its good wear resistance [1]. Much research is being conducted to study growth and properties of CrN film deposited by CVD and PVD methods [2-5] .Titanium alloys 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 [7]. However, the titanium alloy has poor wear and seizure resistance.

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 world wide on a variety of test geometries and material systems [8-13].

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. Chromium-nitride (CrN) film is one of the film materials that can bring about a dramatic improvement in tribological properties such as wear and corrosion resistance [14-16]. Researches regarding this film mainly emphasized its promising anti-oxidative and corrosion resistance, and indicated that this ceramic film was superior to TiN [17]. Several studies have demonstrated the potentiality of coatings to minimize fretting fatigue damage in the substrate and improve its fretting fatigue life [18-19]. 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 740ºC 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 hr. The 0.2 proof stresses, tensile strength and the elongation was 905 MPa, 1040 MPa and 18% respectively.

2.2 Deposition

CrN film was deposited by AIP (AIP-201, Kobe Steel Co., Japan) 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. Deposition time was controlled to give a 2 μm thick film. The deposition conditions are shown in table 1.

2.3 Film Properties Test

A micro-Vickers hardness test machine (MVK-E3, Akashi Factory Corporation, Japan) 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.

Surface roughness was measured by surface profilometer for the specimens and fig. 4.13 shows the measurement principles. Surface roughness was measured with the electro-mechanical diamond stylus tip tracing the surface. High precision vertical movement, rotation, and control can fit horizontally, one feeding speed (3 levels), distance (50μm ~ 30mm) can also be set arbitrarily.

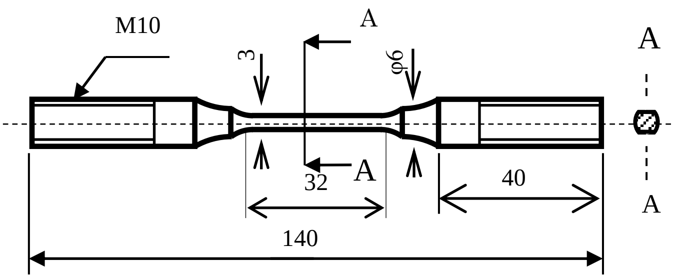

Fig.1. Ti-6Al-4V Specimen

Table-1: CrN coating conditions

Parameters	Value
Bias voltage	700V
Arc current	60A
Pressure	5.33 Pa
Heater temperature	573 K
Film thickness	2.0μm

2.4 Fatigue Test

The uni-axial tension-tension fatigue test was carried out using a dynamic servo fatigue test machine (EFH-100, Saginomiya,) of 10 ton capacity. Axial stresses were applied in the range of 450 to 800 MPa with a frequency of 10 Hz. The fatigue tests were run in a load controlled and tension-tension mode of stress ratio R =0.05. The maximum of fatigue testing cycles was 10^7 cycles. The specimens were axially loaded by a completely reversed cyclic stress of sinusoidal form. After fatigue testing the fracture surfaces of some selected coated and uncoated specimens were observed by SEM(S-2400, Hitachi). The SEM observation was mainly focused on the determination of the fatigue 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. 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 320

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 by a surface profilometer for the specimens. 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 surface roughness was increased by 0.087-0.142μm due to deposition. At a bias voltage of 0 V, a large amount of crystal growth and titanium particles called droplets which sputtered from the titanium target (Cr) and are observed on the surface of CrN film. This increase of surface roughness by coating was mainly caused by droplets during the coating process [20-21]. However, the CrN film surface, which is shown as the dark color in Figure 2, was very smooth for each film thickness. Applying bias voltage, the arc ion is accelerated by the external electric field. The collision between the incident ions and the growing film occurs, which results in the removal of loosely bonded macroparticles. At higher bias voltage, the accelerated particles have higher momentum and more macroparticles are removed, which agrees with the observation in another article [22].

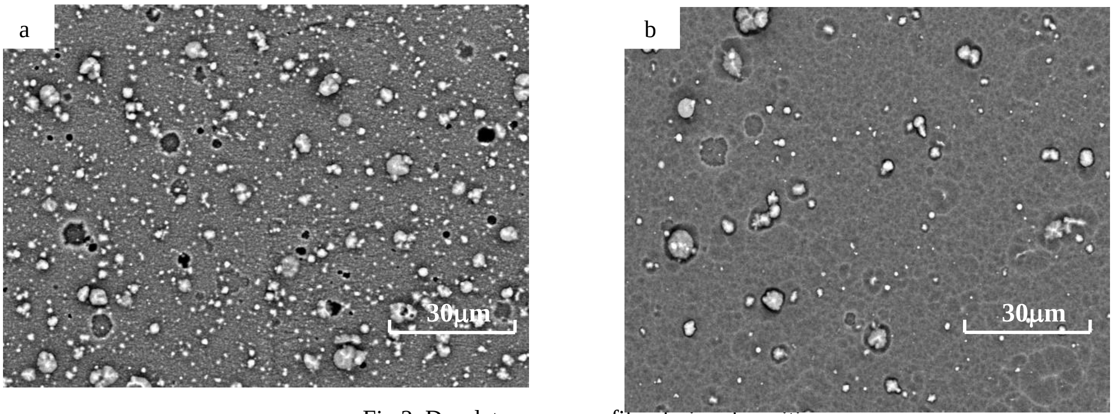

Fig.2. Droplets grown on film during deposition
(a) V_B = - 20V (b) V_B = -300V

3.2 Fatigue Test

Fatigue tests under sinusoidal loading were carried out up to 10^7 cycles applying clamping force. Figure 3 shows the results of fatigue tests for uncoated and CrN coated specimens. The fatigue strength at 10^7 cycles was changed by the deposition of CrN film. The fatigue strength for V_B = -20 V was similar to uncoated specimen and slightly increase in low cycles region. However, fatigue strength for V_B = -300 V clearly decreased compared with uncoated and low bias voltage specimens. The difference of the fatigue strength of these coatings was approximately 200 MPa.

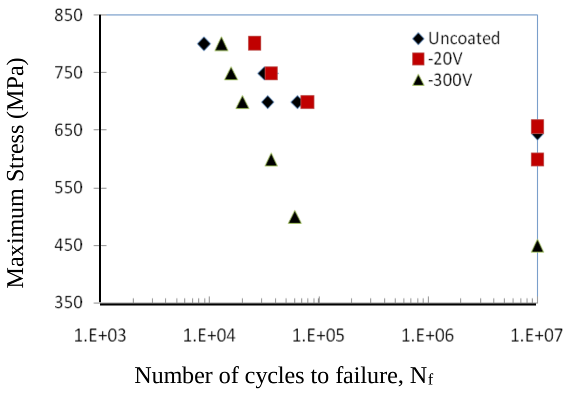

Fig.3. S-N curves of uncoated and coated specimens.

Table-2 Vickers hardness of sample surfaces

		Vickers Hardness
Uncoated sample		320 HV
CrN coated sample	V_B = -20V	1320 HV
	V_B = -300V	2380 HV

The experimental results from the S-N tests indicate that the CrN coating is effective to improve the 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. It is difficult to estimate the life of any specimen due to complex interaction of contacts. The tendency for crack initiation also depends upon the surface micro-structural homogeneity or uniformity, which may vary for different specimens under test.

3.3 Fracture Surface Characterization

Figure 4 shows the typical micrographs of fracture surfaces of uncoated and coated specimens around the crack initiation site for uncoated, coated at bias voltage -20V and -300V. The CrN film showed good adhesion and there was no delamination of the film along the interface and only small delamination was observed at the part of final fracture mode where no large plastic deformation was observed Fig 4 (b) and (c). In the case of high bias voltage, the more brittle film is cracked due to the impossibility to sustain the imposed strain before the plastic deformation of the substrates; therefore, the cracking strength of the film might be dominant factor of the high bias voltage specimens. The difference in the tensile residual stress might cause the difference in the crack initiation behavior of the coatings. The fracture surface of the high bias voltage films was more brittle than that of V_B= -20V.The film deformation might be caused by local plastic deformation of the substrate during the cyclic loading.

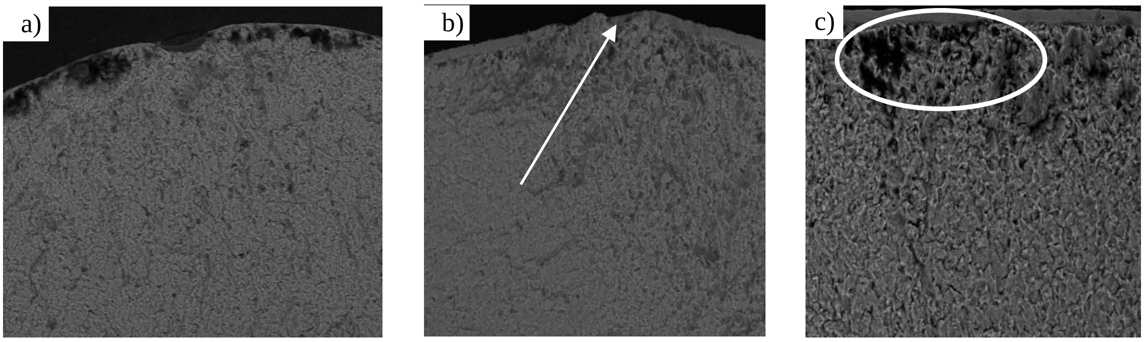

Fig.4. SEM observation of fracture surfaces around the crack initiation site at σ_{max} = 750MPa:
(a) Uncoated sample, N_f = 3.2x10^4 cycles, (b) CrN coated by V_B = -20V, N_f = 7.45x10^4 cycles,
(c) CrN coated by V_B = -300V, N_f =1.95x10^4 cycles.

In this case, tensile residual stress generates near the substrate surface resulting from the strain balance between the film and substrate surface. It has been reported that the tensile residual stress generates in the substrate for tool steel substrate with CrN film and the maximum is about +400MPa at 30-60 μm depth from interface [23]. The tensile residual stress in the subsurface might causes the local plastic deformation at the crack initiation site below the proof stress of the substrate and the deformation might cause the generation of the film crack. However, it has been reported that the compressive residual stress in the CrN film deposited by low bias voltage is lower than that by high bias voltage films [24]. It means that the higher tensile residual stress generates near the substrate surface for high bias voltage sample.

4. Conclusions

The results obtained in this work, under the stated experimental condition, clearly showed that 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. 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.

6. References

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