S2–16

Hard Coating Effects on Fatigue Crack Initiation Mechanism of Ti Alloys

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Summary

Titanium has high strength/weight ratio, stiffness and corrosion properties, but the property of poor wear resistance. Surface coating is one of the most popular surface treatments strategies for improving the wear resistance of Ti alloys. However, the effect of coatings on the initiation and propagation of the fatigue crack of Ti–based alloys has not been investigated intensively yet, which makes the associated mechanism still unclear. In the present work, two types of brittle coatings (CrAlN and TiN) were deposited on the surface of TC4 titanium alloy by Physical vapor deposition (PVD). The tension–tension fatigue tests and the observations of fatigue crack morphologies were performed to study the coating effects on the initiation and propagation fatigue crack of Ti–6Al–4V (TC4) alloy. It was found that brittle coatings significantly decrease the fatigue properties of TC4, which the fatigue limit is reduced from 510–530MPa for TC4 to 315–330MPa for the CrAlN coated samples. The experimental results reveal that, the existence of brittle coatings impede the deformation of the TC4 samples at the beginning stage of fatigue tests, while promote the deformation in the coming middle stage of the fatigue process. The fatigue crack was found to be initiated from the brittle coatings and propagated to the interface between coating and substrate, inducing a micro crack at the surface of the substrate. Then the micro crack propagates into the bulk material and forms the distinct propagation path in the fracture surface. Besides, the formation of non–propagation fatigue cracks was also observed. The corresponding models were proposed respectively to explain the coating effects on the initiation and propagation of the fatigue crack, and influence of coating thickness were also studied. This study should be of significance for the film improvement and provides a theoretical basis for improving fatigue properties of coating materials.

Keywords: Surface coatings; Fatigue crack initiation; Ti alloys.

1. Introduction

Titanium alloys have been finding tremendous applications due to their high strength/weight ratio, stiffness and corrosion resistance (Baptista, Barboza et al. 2009), but the poor wear resistance restricts the applications. Surface treatment is considered to be a convenient and effective additional surface strengthening technique for titanium alloys. Traditional methods, such as shot peening, nitriding and surface induction, improve alloy fatigue life by forming a strengthened surface layer with improved microstructure, mechanical properties and residual stress from the surface to the interior of treated components (Zhang and Lindemann 2005, Roland, Retraint et al. 2006, Yang, Tao et al. 2013). Also, thin hard coatings of different oxides, nitrides and carbides on the surface of parts and components are widely used to improve tribological performance without compromising corrosion resistance (Puchi–Cabrera, Matínez et al. 2004).

The effects of coatings on fatigue properties have attracted a lot of researchers' attention. The change of fatigue life was considered to be dependent on the residual stress and the hardness of the film and the substrate near the film ((Hotta, Itou et al. 1995), and also adhesion between the film and the substrate (Ferreira, Costa et al. 1997). Saini illustrated that the WC/C coating led to 7% gain in endurance limit without considerably affecting the hardness and tensile strength, which was attributed to the presence of large residual compressive stress in the coated specimens (Saini and Gupta 2010). On the other hand, researchers have studied the effects of thin film metallic glasses with titanium adhesion layer on fatigue properties of TC4 (Lee, Chu et al. 2014). Compared with the TiN coating, the positive effects of the two kinds of coatings on fatigue properties were attributed to strong adhesion with the substrate and retarded defects in the surface. Literature reports (Chu, Greene et al. 2012) also indicated that ceramic hard coatings, such as TiN with higher hardness, often could not offer better protection to the substrate due to its brittle nature. The study on the influence of brittle films on the fatigue properties and fatigue crack initiation mechanism of ductile substrates is helpful to evaluate the fatigue life of coating materials and understand the initiation mechanism. It is of great significance for the film improvement and provides a theoretical basis for improving fatigue properties of coating materials.

2. Materials preparation and experimental procedure

The test material in this research is Ti–6Al–4V (TC4), with the following chemical composition in wt. %: 6.2 Al, 4.1 V, 0.04 Fe, 0.015 C, 0.018 N, 0.13 O, 0.001 H and Ti balance. The microstructure is lamellar consisting of $\alpha+\beta$ phases and the grain size is about 200 μm. The yield and tensile strength of TC4 is 860 MPa and 967 MPa, respectively. Two kinds of coatings were studied, including TiN and CrAlN.All coatings were deposited in industrial setting and all deposition processes were finished in the factory. The thickness of CrAlN coatings is 4.5μm and 9μm (marked as CrAlN and CrAlN×2), and 10 μm for TiN. The coatings surface hardness and elastic modulus were obtained by nanoindentation tests (Nano Indenter XP, unloading method, the maximum displacement into surface was controlled to be about 1/10 of the film thickness) and the results are shown in Fig. 1.

Tension–tension fatigue tests were conducted using the electrodynamic test system (Acumen, MTS) in high cycle fatigue region at a relatively low frequency of 60 Hz, in order to observe the crack initiation and propagation behavior, and the stress ratio was R=0.1. Fatigue tests were divided into two groups. (i) The tests stopped automatically when the specimen fracture happened, the S–N data were record and the fracture surface was observed to study the difference of the crack initiation source of the coated and uncoated samples to discuss the coating effect on fatigue life and fatigue crack initiation mechanism. (ii) Optical microscopy was used to observe fatigue crack growth during fatigue tests, and the tests were stopped immediately when the cracks propagated to about 500 μm length, in order to observe the cross section of crack tips to study the influence of coatings on crack propagation path and substrate plastic deformation around crack tips.

3. Results

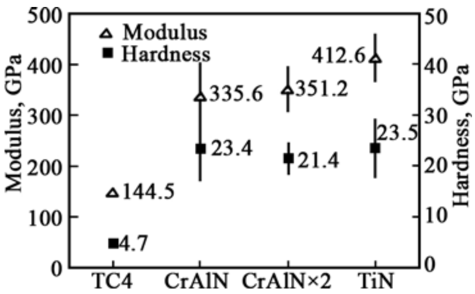

Figure 1. Elastic modulus and hardness of materials.

The specimen's maximum displacement during tension–tension fatigue test was recorded automatically by the control system. Field emission scanning electron microscope (FESEM, Zeiss Auriga) was used to examine fatigue fracture surfaces and the micro–cracks around the crack tip in the cross section perpendicular to the loading direction.

Fatigue test results in terms of the S–N data are plotted in Fig. 2. The fatigue limit of TC4 was between 510 and 530MPa, and the coatings decreased the TC4 fatigue properties significantly, as the fatigue limit of the CrAlN coated samples was between 315 and 330MPa. The Nf (number of cycles to failure) of the TiN and CrAlN×2 coatings were nearly the same at 560MPa, and Nf (TiN) < Nf (CrAlN×2) at 350MPa, both lower than N_f (CrAlN) at tested stress levels. TiN coated samples failed at 300MPa, while the CrAlN coated samples failure did not happened.

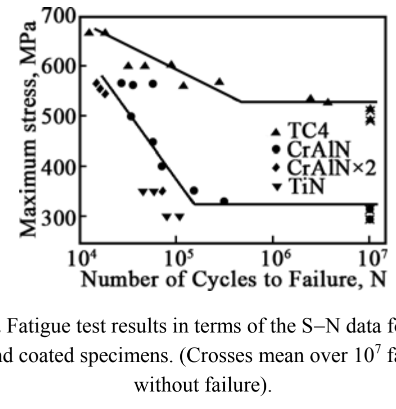

Figure 2. Fatigue test results in terms of the S–N data for the TC4 substrate and coated specimens. (Crosses mean over 10^7 fatigue cycles without failure).

The crack tip cross–section morphology of the CrAlN coated sample is shown in Fig. 3, the tested conditions were σ_{max}=500MPa, R=0.1, f=40Hz, and the fatigue test was stopped manually when the crack propagated to about 500μm length and crack tip cross section sampling location is showed in Fig. 3(c). As shown in Fig. 3(a), the propagation process of fatigue cracks can be divided into several stages. The fatigue cracks propagated along the maximum shear stress direction first, and in this stage most of the cracks became non–propagating fatigue cracks, so only one could go into the next stage and became the main fatigue crack, which led to the final failure. Then the main fatigue crack propagated perpendicular to the loading direction, and created fatigue bands on the fracture surface. Finally the shear lip formed until instant fracture of the samples happened. Fig. 3(b) shows typical non–propagating fatigue cracks observed near the main crack. The mechanism of whether a micro–crack continues propagating or becomes a non–propagating fatigue crack is not clear yet, and will be discussed later.

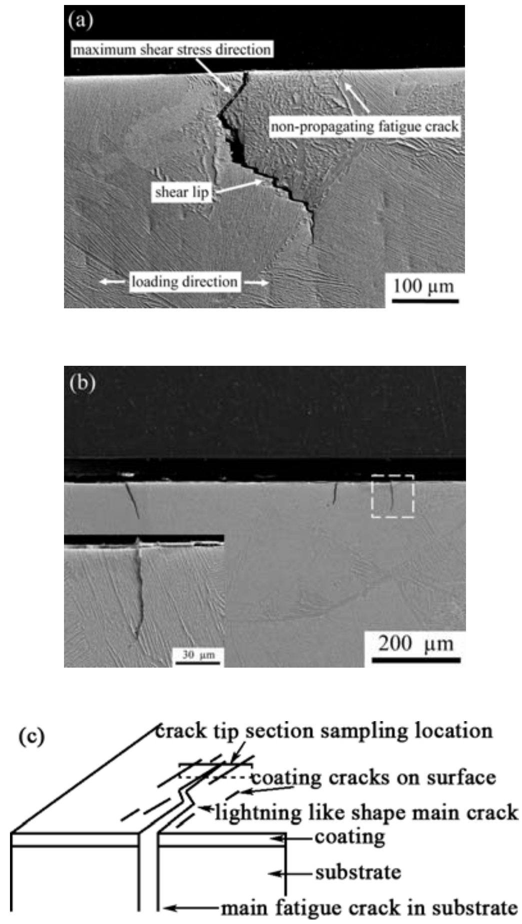

Figure 3. SEM of (a) cross section morphology crack tip and (b) non–propagating cracks in CrAlN coated sample surface, tested under 500 MPa and stopped manually when the cracks propagated to about 500 μm; (c) sketch map of crack tip section sampling location.

It should be noted that the crack initiation source on the fracture surface of coated samples differs a lot from uncoated TC4 (Fig. 4). There was no fatigue crack initiation area on the fracture surface of the substrate, but obvious crack propagation path from the film–substrate–interface into the substrate. And for the coated specimen, there were more than one fatigue crack initiation area on the fracture surface, as showed and magnified in Fig. 4(b), (c) and (d). The crack propagation path from interface into bulk material indicates the crack initiated in coating, different from TC4 (Fig. 4(a)) which initiated at the subsurface of the specimen. These results proved that the fatigue crack initiation mechanism is absolutely different from that of TC4.

As reported in the literature (Chai 2006, Heinz and Eifler 2016), titanium alloy is a typical material that shows subsurface non−defect fatigue crack origins, and the reason is considered to be microstructure inhomogeneity (Heinz, Balle et al. 2013). Material damage due to cyclic plastic deformation can occur in the soft phase (α−phase) during cyclic loading when the applied cyclic stress is higher than the yield point of the soft phase, so micro−cracks formation occurs in the grains of the primary α−phase and coalesce into crack clusters during further cycling, and clusters of micro−cracks are considered the origin of the rough facet area (Hong, Lei et al. 2014, Heinz and Eifler 2016), as showed in Fig. 4(a).

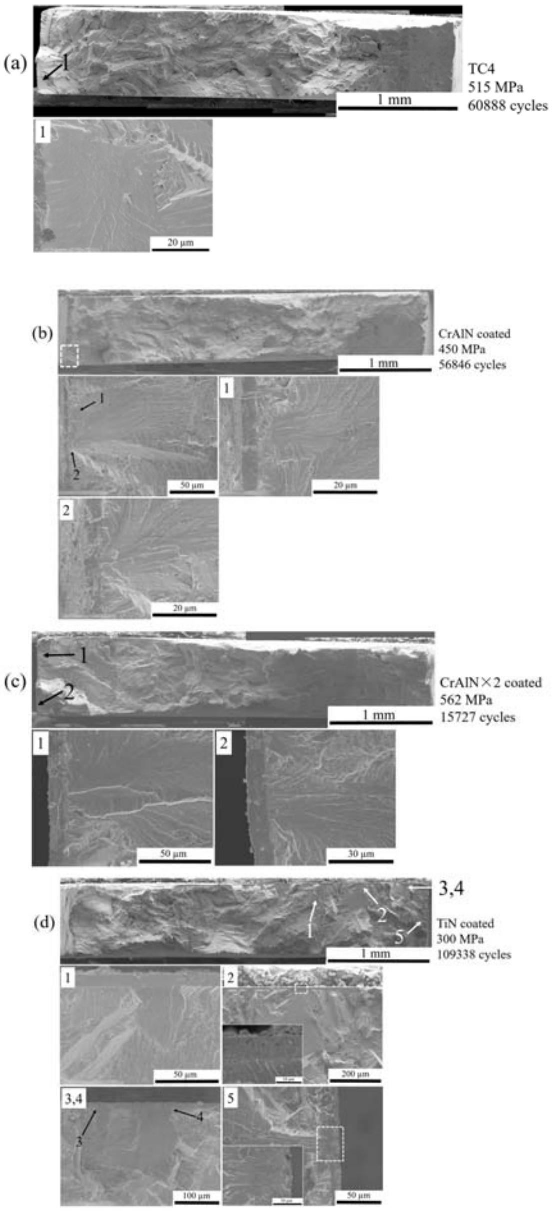

Figure 4. Detailed morphology of fatigue crack initiation region in: (a) TC4, (b) CrAlN, (c) CrAlN×2 and (d) TiN coated samples.

According to our research, the fast−running film crack could cause cracking of a ductile substrate, and the analytical calculation based on energy conservation shows that the depth of the crack penetrating into the substrate is a function of the crack velocity when it leaves the film and the number of dislocations emitted from the crack tip. From this point of view, when the fatigue crack extend from coating to substrate, the crack velocity will remain the same, and since E of brittle film is larger, D value of the material is larger than crack extend simply in substrate material.

Thus, although under low stress condition the crack velocity when the crack extend into substrate is relatively low, but the plastic zone, D, is larger than fatigue crack propagates in ductile substrate, so the brittle coating cracking under low tension stress fatigue condition can also cause substrate damage and induce ductile substrate cracking, and finally influence the fatigue life of the material.

4. Conclusion

The fatigue crack initiation mechanism and propagation behavior of coated TC4 alloys were given detailed investigation in this paper. Two kinds of CrAlN coatings were prepared, with the thickness of 4.5μm and 9μm, respectively, and the thickness of TiN was 10 μm. Tension−tension fatigue tests were performed on the TC4 alloy and coated samples with the stress ratio of 0.1.

The coating gives a rise to a significant decrease in fatigue behavior. The fatigue limit of TC4 was between 510and 530MPa, and that of the samples with 4.5 μm thick CrAlN coating was between 315 and 330MPa. The coatings prevented the deformation of TC4 samples at the beginning of fatigue process, and had a positive effect on sample deformation after the coating cracking occurs.

Normally, the fatigue cracks initiate mechanism is totally different for the coated and uncoated materials. The fatigue crack initiation process for coated TC4 is substituted by the micro cracks on the substrate surface induced by coating cracking, and there is obvious crack propagation path from the film−substrate−interface into the substrate on the fracture surface.

Acknowledgement

This work was supported by the Beijing Nova Program (Z171100001117075), the National Natural Science Foundation of China (51771025) and the Fundamental Research Funds for the Central Universities (FRF−TP−17−002C1).

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