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Effect of contact pressure on fretting fatigue behavior of Ti-1023

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ABSTRACT

With a new test facility, we have investigated fretting fatigue properties of Ti-1023 titanium alloy at different contact pressure. Both fatigue fracture and fretting scar were analyzed by scanning electron microscopy (SEM). Moreover, the depth of crack initiation area in fatigue fracture has been analyzed quantitatively, to investigate the relationship between the depth of crack initiation area and the fretting fatigue strength. The changing trends of the depth of crack initiation area and fretting fatigue strength with the increase of contact pressure show obvious opposite correlations. The depth of crack initiation area increases rapidly with the increase of contact pressure at low contact pressure (smaller than 10 MPa), and the fretting fatigue strength drops rapidly. At the contact pressure of 10–45 MPa, both the depth of crack initiation area and the fretting fatigue strength do not vary significantly. Contact pressure influences fatigue strength through influencing the initiation of fatigue crack. The main damage patterns are fatigue flake and plow.

1. Introduction

Ti-1023 titanium alloy is widely used in aircraft structural components due to its high specific strength, good fracture toughness, excellent stress corrosion resistance, and enhanced processing characteristics [1,2]. The process known as fretting fatigue occurs at the contact surfaces of two components that have an oscillatory motion of small amplitude, and the relative movement is the consequence of cyclic loading of one of the components. Compared with other alloy kinds, titanium alloys are more susceptible to fretting fatigue, which is a serious failure problem in critical structural components. The reason might be the damage of the protective surface oxide, the deformation or temperature-induced phase transformation and the great tendency for material transfer when rubbing with other materials [3,4]. In most practical applications, titanium alloy components need to be mechanically connected with other components. The connection interface is often under some fretting loading, which easily results in fretting fatigue damage [4]. However, there are few reports on fretting fatigue of Ti-1023 titanium alloy.

Many factors might influence fretting fatigue of titanium alloy: contact pressure, surface condition, slip amplitude, microstructure, etc. Much research has been conducted for understanding influences of various parameters on fretting fatigue strength [5–25]. The main parameters include fretting amplitude, contact pressure, and coefficient of friction [26]. Among the three factors, fretting amplitude is affected by coefficient of friction and contact pressure, and the coefficient of friction has a great connection with inherent properties of materials. So, the largest variable is contact pressure. The effect of contact pressure has been studied by many researchers using various materials and a variety of conclusions have been obtained.

Carbon steel was experimentally investigated by Endo and Goto [27]. 4130 Steel was experimentally investigated by Gaul and Duquette [28]. Ti6Al4V alloy was experimentally investigated by Mall and coworkers [29,30]. These analyses show that fretting fatigue life or strength decreases with increase in contact Hertzian peak pressure. However, among these results data points are too few to reflect the complete picture of contact pressure effect. The investigation of high strength steel by Lee et al. [31] and the investigation of 7075-T6 aluminum alloy by Adibnazari and Hoeppner [32] prove the existence of a normal pressure threshold, increasing the pressure above which does not affect the life, in fretting fatigue when the contact pressure is large enough. Fernando et al. [33] reported the variation of fretting fatigue life with contact stress for BS L65 4% Cu–Al alloy. At low contact pressure, fretting fatigue life decreases with increase in contact pressure whereas at high contact pressure fretting fatigue life increases with increase in contact pressure. Furthermore, the fretting fatigue life of Al–Mg–Si alloy 6061 exhibits a minimum and a maximum with increase in contact pressure. With increase in contact pressure, fretting fatigue life decreases, shows a minimum at 100 MPa contact pressure and

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then increases, reaches a maximum at an intermediate contact pressure of 150 MPa and thereafter decreases [34].

A variety of testing devices have been developed to study different hardware configurations and service components [34–36]. However, little or no standardization has been made to allow comparison of test results between various existing test systems. Therefore, fretting fatigue testing results might be different (even opposite) to each other. For example, Naidu and Raman [34] reported for one kind of aluminum alloy (AA6061) that the fretting fatigue life exhibited a variable behavior with increase in the contact pressure. With a different kind of testing device, Benhamena et al. [36] reported for another aluminum alloy (5086H24), which is similar to AA6061 in composition and properties, that the fretting fatigue life increased with the increase of contact force. Among different kinds of testing devices, the ring-type is widely used for its simple structure, easy operation, low cost and good generalization. However, there are still some problems which need to be paid enough attention to, such as low accuracy, poor stability and the effect of its self-weight. To this end, a loading device was designed in this study, which solved the problem that part of load was unapplied due to vibration. It also eliminated the impact of the self-weight of the device. Thus, the device has substantially increased the accuracy and reliability for the fretting fatigue test, and has enabled testing condition closer to actual working condition [37].

Suh and coworkers [38,39] advanced the delamination theory which was based on the behavior of dislocations at the surface, subsurface crack and void formation, and subsequent joining of cracks by shear deformation of the surface in the 1970s. It indicates that, under fretting condition, plastic deformation and damage are accumulated below the contact surfaces and then caused strain hardening. Thin flake-shaped debris particles were then generated by a process of subsurface delamination occurring via cracks which originated from hard particles within the deformed zones (but not at the contact surface) and propagated parallel to the surface. Furthermore, some cracks may propagate perpendicularly to the surface and become the fatigue crack. The delamination theory provided the theoretical foundation for fatigue crack nucleation. According to literature, a large fraction of the life, approximately 80–90% of total life, is generally spent in crack nucleation and only a very small fraction of the life is spent in crack propagation to a critical size under high cycle fatigue [40,41]. Thus, we will pay much attention to the fatigue crack initiation area.

Table 1
Composition of Ti-1023 titanium alloy.

Element	V	Fe	Al	O	N	C	H	Ti
wt%	9–11	1.6–2.2	2.6–3.4	<0.13	<0.05	<0.05	<0.010	Balance

Table 2
Tensile properties of Ti-1023 titanium alloy at room temperature.

Property	Tensile strength σ_b/MPa	Yield strength $\sigma_{p_{0.2}}$/MPa	Elongation δ_5/%	Reduction of area ψ/%
Value	1123	1059	15.3	64.4

Contact pressure and stress evolve during fretting tests in general, and this will obviously affect the evolution of fatigue damage leading to nucleation. In the work of Ding et al. [42], for example, the evolution of contact scars for titanium alloy (Ti6Al4V) is presented for gross slip, partial slip and mixed slip regimes. They have made successful prediction of fatigue crack nucleation in fretting, due to fretting-induced wear.

With a new test facility, we have investigated fretting fatigue properties of Ti-1023 titanium alloy at different contact pressure. Both fatigue fracture and fretting scar were analyzed by scanning electron microscopy (SEM). Moreover, the depth of crack origin zone in fatigue fracture has been analyzed quantitatively, to investigate the relationship between this depth and fretting fatigue strength and to identify the mechanism of the contact pressure effect. The emphasis of the paper is on the fatigue crack initiation area and fracture surface analysis.

2. Materials and experiments

Ti-1023 titanium alloy specimens machined from hot rolled bar were used in fretting fatigue and plain fatigue tests. The heat treatment was 755 °C for 2 h, water cooling, and then 530 °C for 8 h, air cooling. The composition of Ti-1023 titanium alloy is shown in Table 1, and the tensile properties at room temperature are shown in Table 2. Commercial 30CrMnSiA high strength structural steel was used as fretting pad material, which was heated to 880 °C, oil cooled, and then tempered at 540 °C for 1 h, water cooled. The composition of 30CrMnSiA high strength structural steel is shown in Table 3. One aim of the research is to simulate the practical case of helicopter hub sleeves, where the materials involved are the combination of steel and the titanium alloy. The choice of the steel was made to match this real application case. The geometry of the fretting fatigue specimen and the fretting pad with bridge-type were shown in a previous publication [37]. The gage parts of the fretting fatigue specimen and the fretting pad required $R_a \leq 0.8$ μm surface conditions, and both of them were degreased with acetone.

The fretting fatigue tests were performed using PLG-100 computerized high-frequency push–pull fatigue testing machine. They were carried out according to HB 5287-1996 standard, using a sinusoidal wave at frequency of 74–80 Hz, stress ratio of 0.1, in atmospheric condition and room temperature with fretting pad pressed onto specimen to simulate fretting condition. The fretting fatigue strength was defined as the maximum cyclic stress ($\sigma_{\max}$), throughout this paper. Five levels of contact pressure, namely 3 MPa, 5 MPa, 10 MPa, 20 MPa, and 45 MPa, were considered. The contact pressure was in plane–plane contact state, and applied using the loading device specifically designed by the authors. The fretting fatigue testing system is shown in Fig. 1. The high strength spring was used to load, which solved the problem that part of load was unapplied due to vibration in the case of screw loading. Digital force measurement device was used to monitor contact pressure, which assured the accuracy. The proving ring on the fatigue testing machine with supporting arm eliminated the influence of its self-weight, and made the laboratory condition closer to actual working condition. The observation of fracture surface of fretting fatigue and the fretting area was carried out using a JSM-5800 scanning electron microscope (SEM).

Table 3
Composition of 30CrMnSiA high strength structural steel.

Element	C	Si	Mn	P	S	Cr	Fe
wt%	0.28–0.34	0.90–1.20	0.80–1.10	≤ 0.025	≤ 0.025	0.80–1.10	Balance