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An investigation on fretting fatigue mechanism under complex cyclic loading conditions

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ABSTRACT

In this paper, a methodology was proposed and an experimental configuration was designed to investigate the fretting fatigue mechanism under complex cyclic loading condition. This condition is common and highly influences the fretting fatigue behavior. However, it is barely studied at present. A series of fretting fatigue tests shown that cyclic normal load will enlarge the slip region of contact interfaces, making the crack nucleation location moves toward the middle range of contact region. It is demonstrated that complex cyclic loads have a positive effect of fretting damage, making the fatigue life shorter than those in constant normal loading conditions.

1. Introduction

Fastened joint or interference fit usually suffers cyclic loading and mechanical vibrations, which cause small relative sliding (usually less than 100 μm) between contact interfaces. Such phenomenon is known as ‘fretting’. It produces wear, surface damage, stick, micro-plasticity, etc., making the fatigue cracks nucleate more easily and the service life of the mechanical structures much shorter than those under normal plain fatigue conditions. The fretting fatigue problem is so wildly on fastened joints and interference fit that many researchers focus their attention on this problem. Table 1 shows some typical fretting fatigue failure cases in industry [1–11].

Fretting fatigue is a very complicated physical-chemistry process. Dobriomirski [12] investigated the effective parameters of fretting fatigue and pointed out that up to 50 variables played a role in fretting. Although there is not a satisfactory theory to explain the mechanism of fretting fatigue, most researchers have a consensus that fretting fatigue is a mechanical damage dominated process. Slip amplitude, tangential force, contact pressure etc. are considered to be the primary set which can directly affect the fretting process. Many studies have shown that the slip amplitude was one of the most important factors of fretting fatigue [13,14]. It is shown that the fatigue life decreases with the increasing of the slip amplitude up to a certain threshold value, then increases again. Tangential force also plays a major role in fretting behavior. It originates from friction between contacting bodies and primarily results from the mechanical interlock of surface asperities and adhesive bonding. Many studies [15,16] shown that there was a certain relationship between slip amplitude and the tangential force, the fatigue life will decrease as the increasing of the tangential force. The contact pressure directly influences the fatigue life and contact behavior of the component. Adibnazari and Hoeppner [17] pointed out that fretting fatigue life decreased with the increasing of the contact pressure. Nakazawa et al. [18] also proposed the same conclusion. Their researches shown that the fretting fatigue life was almost unchanged at low contact pressure. However, it decreased drastically at contact pressure beyond a certain value. While, other studies shown that the fatigue life decreased with the increasing of the contact pressure up to a certain threshold value, then increased again [19,20].

Most reported studies on fretting fatigue are based on similar test apparatus which are modified from standard plane fatigue test fixture. The typical fretting fatigue testing equipments are illustrated in Fig. 1. The main difference of these equipments is the shape of the pad. The bridge-type pad fretting fatigue test structure (Fig. 1a) is the earliest used apparatus in fretting fatigue studies.

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Nomenclature

a	half width of the contact zone
E_1, E_2	Young's modulus of the two contact parts respectively
E^*	the equivalent Young's modulus of the two contact parts
v_1, v_2	Poisson's ratio of the two contact parts respectively
R_1, R_2	the radius of the two contact parts respectively
R^*	the equivalent radius of the two contact parts
μ	coefficient of friction
σ_B	bulk load
σ_T	tangent stress (normal stress along the length direction of the specimen)
τ	shear stress on the contact interfaces
N_f	number of cycles to failure
P	normal load
P_a	normal load amplitude
P_m	mean normal load
p_0	maximum contact pressure
Q	tangential force
k, b	the coefficients of the load distribution function P_L
M	the torque added on the specimen
l	the half width of the specimen
w	the half width of the bridge of the pad
θ	orientation of the crack with the contact interface

Table 1
Fretting fatigue failure cases in industry.

Harming object	The failure parts
Turbine engine	Dovetail joint on aero-engine Flange joint on helicopter turbine engine
Mechanical joints	Bolted joints and rivet joints Spline joints Interference fits
Electrical cable and rope	Power transmission lines The cable car rope Submarine cable
Biologic implants	Bolted joints of the bone and the support plate Pelvic bone replacement parts
Power generation unit	Dovetail joint on power generation unit Fretting wear on nuclear power generation unit

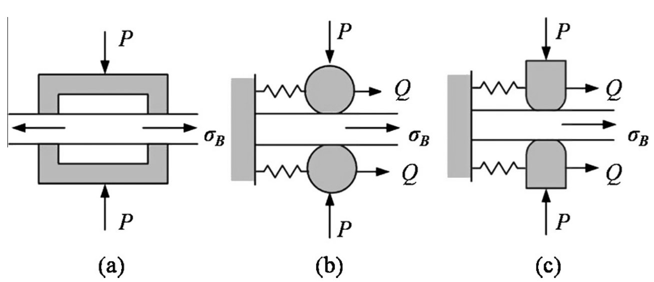

Fig. 1. Illustration of the fretting fatigue testing equipments: (a) bridge-type pad arrangement, (b) spherical type arrangement and (c) cylinder type arrangement.

The contact type of this structure is face-to-face contact or so celled complete contact. The chief virtue is that a normal fatigue specimen can be used. The bridge is simply clamped to the sides of the specimen by a proving ring or similar arrangement. However, the contact conditions at the pad feet are difficult to describe, particularly if there is bending in the bridge itself. So, this type of equipment is replaced by spherical type (Fig. 1b) and cylinder type (Fig. 1c) structures. The contact stress distribution of these arrangements can be described by Hertz contact mechanics. Meanwhile, the important parameters of fretting fatigue (normal load P, tangential force Q and bulk load σ_B) can be readily measured and controlled. This type of equipment is first proposed by Nishioka and Hirakawa [21]. Then, Bramhall [22], Szolwinski and Farris [23] also developed their fretting fatigue testing systems using the similar apparatus.

Although the cylinder (or spherical) type arrangements are wildly used on fretting fatigue studies, it cannot fully reflect the fretting fatigue conditions of the actual engineering problems. As shown in Fig. 2a, the normal load in the present fretting fatigue tests are set to be constant, while for most actual engineering problems, both the normal load and the tangential load are cyclic loads (e.g. Fig. 2b and c). How the complex cyclic load, especially the cyclic normal load, influences the fretting fatigue mechanism is barely investigated. The aim of this paper is to investigate the influence of the complex cyclic load on fretting fatigue behavior, which is important for investigating actual engineering fretting fatigue problems. For this purpose, a methodology was developed to investigate fretting fatigue behavior under complex cyclic loading conditions. Accordingly, an experimental system was designed to simulate the complex cyclic loading conditions. The study about the fretting fatigue mechanism under complex cyclic loading conditions has a significant meaning for a better understanding of fretting fatigue mechanism.

2. Experiment setup

2.1. Design of the biaxial loading fretting fatigue testing system

Fig. 2a illustrates a typical fixture used for investigation of fretting fatigue. After establishing contact between the pad and the specimen, a tangential force can be induced on the pads by the application of an axial bulk load to the specimen fixed at one end. The spring attached to the pad resists motion of the pad along with the specimen, resulting in a tangential load that varies in phase with the bulk axial loading. In this study, a fretting fatigue testing system was designed based on this type of fixture.

As mentioned in the instruction section, the aim of this study is to investigate the influence of complex loading (cyclic normal load and cyclic tangential load) to fretting fatigue, so a biaxial loading system is needed. An electro-hydraulic servo tension–torsion fatigue test system was modified to simulate the complex cyclic loading. As shown in Fig. 3, besides the bulk load σ_B, the specimen also suffers a torque. The torque acts on the contact region between the pads and specimen, making the distribution of the normal load changed. Thus, the cyclic normal load can be generated using this method. Another difference between this fixture and the present fixture is that the cylinder surface of the pad is cut to form a 'bridge' shape (as shown in Fig. 6).

To achieve the function of this testing system, one side of the plate specimen is fixed on the upper hydraulic wedge grip, which is connected with the force and torque sensors. The other end of the specimen is fixed on the platform II which is captured by a tension and torsion actuator. Two cylinder pads are placed on platform I which is connected with platform II by two flexible plates. This platform/flexible plate structure forms the fretting chassis. For the stiffness of the platforms are much larger than the flexible plates, the stiffness of the whole fretting chassis approximately