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径向与复合微动的运行和损伤机理研究

全国百篇优秀博士学位论文

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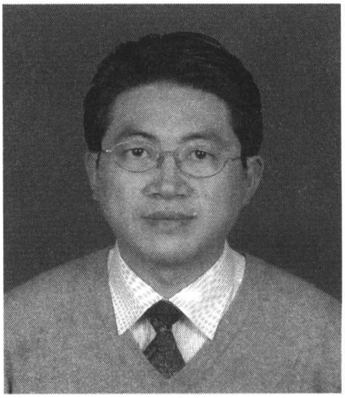

摘 要

【关键词】 微动损伤 径向微动 切向微动 复合微动

切向微动、径向微动、滚动微动和扭动微动是四种基本的微动运行模式，但至今绝大多数的研究都集中在切向微动，关于两种基本微动模式复合的研究还未见报道。开展径向和复合微动模式的研究，在铁路、汽车、航空、航天、核反应堆、电信、电力系统、人体植入器械等许多领域都具有广阔的工程应用前景，不仅具有探索未知科学的意义，而且对抗工业微动损伤具有重要的指导意义。本论文完成的主要工作和取得的主要结论如下：

（一）研制了新型径向微动试验装置，真实模拟了径向微动，为径向微动的研究奠定了实验基础。

本研究通过对高精度切向微动试验台夹具系统和控制程序的改造，成功研制了新型径向微动试验装置。该装置可以分别在控制载荷和控制位移两种模式下进行试验，可以通过改变加载速率或频率来控制接触副间的相对运动速度，因此能模拟真实的径向微动。该试验结果有很好的可比性和重现性。

（二）系统研究了径向微动的运行和损伤机理。

在球/平面接触和不同载荷水平下，研究了 Fe-C 合金（工业纯铁、45# 钢、GCr15 钢）、2091 铝锂合金、TiN 涂层、MoS_2 涂层和 TiN＋MoS_2 复合涂层等材料的径向微动动力学行为；分析了随循环周次的变化，两接触表面间法向载荷与位移的变化规律。结果显示径向微动的载荷-位移曲线（F-D 曲线）具有两种基本类型，即张开型和闭合型。引入耗散能（E_d）、平均变形刚度（R）和张开位移（δ）等 3 个参数可以描述径向微动条

件下的 $F\text{-}D$ 曲线。$F\text{-}D$ 曲线和径向位移，强烈地受载荷水平和材料性质的影响，径向位移随循环周次的增加而逐渐减低，并趋向于一极限值。不同材料具有不同的变形刚度、耗散能和张开位移值，并随循环周次的增加而变化。

考察了加载速度和表面粗糙度对径向微动运行行为的影响，结果显示加载速度明显影响径向微动的变形过程，加载速度降低，径向位移增加，同时 $F\text{-}D$ 曲线的耗散能、变形刚度和张开位移均增大。增大试样表面粗糙度，则径向位移、变形刚度和张开位移明显增加，但耗散能变化不明显。

在弹性力学分析的基础上，结合表面轮廓仪、光学显微镜、扫描电子显微镜(SEM)和电子能谱(EDX)等的微观分析，可以推断：

① 对于相同材料组成的接触副，因为变形处于弹性协调状态，故不可能在振动载荷下发生接触界面间的微滑。

② 对于不同材料组成的接触副，微滑产生于随法向载荷变化的最大和最小接触半径之间。换言之，径向微动损伤发生于不同材料组成的接触副之间。

径向微动损伤研究表明，损伤主要发生在第二相和材料缺陷存在的区域。虽然不同材料的损伤程度不同，但损伤机制主要表现为表面的接触疲劳，即颗粒的剥层。

3 种涂层的径向微动运行和损伤研究表明：硬质高弹性模量的 TiN 涂层，明显提高了基体材料的变形刚度，降低了耗散能，同时也缩短了张开型 $F\text{-}D$ 曲线的持续时间；而低摩擦系数的 MoS_2 软涂层，则获得了相反的结果。TiN 涂层明显提高了基体材料的承载能力，扩大了其应用范围；MoS_2 涂层和 TiN＋MoS_2 复合涂层具有较好的抗径向微动损伤能力；固体润滑涂层增加了径向微动界面的微滑，并可吸收更多的系统能量，有利于系统的减振。TiN＋MoS_2 复合涂层还表现出两种单一涂层复合的特征。

硬质涂层的接触疲劳损伤主要取决于试验参数和涂层特性，因此径向微动试验有望成为一种新型评价硬质涂层接触疲劳寿命的方法。

（三）首次成功地实现了切向与径向两种基本微动模式的复合。

在径向微动的基础上，通过一个巧妙而简洁的设计，即倾斜平面试样，首次成功地实现了切向与径向微动模式的复合。复合微动的 $F\text{-}D$ 曲线强烈地反映出径向和切向微动模式的特征。复合微动的研究对减缓工程实际中复杂形式的微动损伤具有重要意义。

（四）系统研究了复合微动的运行和损伤机理。

在两种倾斜角度下（45°和 60°），对 45# 钢、GCr15 钢、2091 铝锂合金和 MoS_2 涂层等材料进行了复合微动的试验。结果显示，复合微动的载荷-位移曲线具有 3 种基本形式（准梯形型、椭圆形型和直线型）；*F-D* 曲线随循环周次的演变，强烈地依赖于载荷水平、倾斜角度和材料性质。根据 3 种 *F-D* 曲线，可将复合微动过程划分为 3 个阶段，这 3 个阶段的运行和损伤特征为：

① 阶段Ⅰ（准梯形型 *F-D* 曲线）：引入 F_1、F_s 和 δ_c 等参数可以描述准梯形型 *F-D* 曲线。在试验早期准梯形型 *F-D* 曲线表现出明显的滑移特征，位移随循环周次的增加迅速降低，磨痕呈非对称的彗星状，可明显观察到磨粒磨损和粘着现象。微动白层、平行裂纹和磨屑（第三体）已在该阶段形成。

② 阶段Ⅱ（椭圆形型 *F-D* 曲线）：当 F_1 增加到某临界值时，*F-D* 曲线从准梯形型突变到椭圆形型，此时变形处于弹塑性范围。平行和垂向裂纹相遇，导致片状颗粒按剥层机制脱落。第三体聚集在接触界面间，两体接触转变为三体接触。

③ 阶段Ⅲ（直线型 *F-D* 曲线）：界面间不发生滑移，在外加载荷作用下接触副只发生弹性变形。由于三体层的调节作用，使磨损速率大大降低。疲劳裂纹的形成是该阶段最重要的特征。

在一定条件下 3 种微动区域（滑移、混合和部分滑移区）可在同一次试验中观察到。混合区的形成是反复的裂纹形成、扩展和颗粒剥落的结果。在分析微动白层、第三体行为和磨损与疲劳竞争关系的基础上，提出了复合微动损伤的物理模型。本文为解释复合微动过程中位移和接触状态的变化规律，提出了一种位移协调机制。

（五）随接触副相对倾角的变化，研究了切向、径向和复合微动损伤机理的变化规律。

从切向微动到复合微动再到径向微动（倾斜角度从 0°连续变化到 90°）的变化过程中，切向微动分量减少，径向微动分量增加；在磨损和疲劳的竞争关系中，滑动磨损特征逐渐减弱，径向接触疲劳的特征逐渐占据优势。同时研究提出了微动白层形成的控制参数的表达式，为微动白层的塑性变形形成机制提供了有力证据。

对 MoS_2 涂层，随着倾角的增加，MoS_2 的氧化效应逐渐减弱，涂抹层的形成也越困难。当达到径向微动条件时，涂层几乎没有损伤，MoS_2 的氧化也不再发生。

ABSTRACT

【Keywords】 Fretting damage Radial fretting Tangential fretting Composite fretting

Tangential, radial, rotational, and torsional fretting are four basic types of fretting running modes. Presently, the absolute majority of researches have been focused on tangential fretting, and the research concerning composite fretting compounded of two basic modes has not been reported so far. Studies on radial and composite fretting, showing a broad prospect of engineering application in many fields such as railway, automobile, airplane, nuclear reactor, telecom, electric power, and artificial implantation, etc., not only have science significance of exploring the unknown, but also have important guidance to palliate fretting damages in industry. The main research works and obtained conclusions in this dissertation are as follows:

(1) A new radial fretting apparatus has been developed to really simulate the case of radial fretting, laying an experimental foundation to investigate radial fretting.

The new hydraulic radial fretting test rig has been successfully developed by modifying the clamps and the control programs from the tangential fretting apparatus with high precision. Fretting tests can be done on mode of imposed load or of imposed displacement. The speed of relative movement between contact pairs can be controlled by changing the speed of loading or frequency. The apparatus can really simulate the case of radial fretting. Results showed a better comparable characteristics and repeatability.

(2) The running and damage mechanisms of radial fretting have been studied systematically.

Under the ball-on-flat contact, the dynamic behaviours of radial fretting have been investigated by varying loads applied to different materials including Fe-C alloys (industrial pure iron, 1045 steel and 52100 steel), 2091 aluminium-lithium alloy, TiN coating, MoS_2 coating and

$TiN + MoS_2$ composite coating. Variations of normal load *vs* displacement between two contact surfaces have been analyzed as a function of cycles. The tests results showed that two basic styles of load-displacement curve (*F-D* curve), i. e. open cycle and close cycle, appeared in radial fretting. Three parameters of deformation rigiditiy (R), dissipated energy (E_d), and open displacement (?) can be introduced to describe the *F-D* curves of radial fretting. The process of radial fretting was dependent strongly upon the load levels and characteristics of materials, while the radial displacement decreased and trended to a limit with the increase of number of cycles. The radial deformation rigidities, dissipated energies and open displacements, which have different values for different materials, changed with the increase of number of cycles.

The effects of different loading speeds and surface roughness have also been studied in the case of radial fretting. The results showed that the loading speed obviously affected the deformation processes of radial fretting. Decreasing of the loading speed resulted in the increase of radial displacement, accompanying with increasing of the values of deformation rigidities, dissipated energies and open displacements in *F-D* curves. As the increase of the surface roughness of specimens, the radial displacements, deformation rigidities and open displacements all increased obviously, but the dissipated energies were not changed evidently.

On the basis of analyses of elastic mechanics, in combination with microscopic examinations by profilometer, optical microscope, scanning electricalmicroscope (SEM) and energy dispersive spectroscope (EDX), it can be deduced that: a) for the contact pairs made of same materials, it is impossible for the relative micro-slip between contact interfaces to happen under the oscillatory normal load because of the coordination of elastic deformation; b) for the different materials of contact pairs, the micro-slip inducing radial fretting failures took place on the contact interface between the maximum and minimum contact radii that varied with the oscillatory normal load. In other words, the damages of radial fretting occur between the surfaces of two contact pairs which consist of different materials.

The investigations on damages of radial fretting showed that the

damages generally occurred in the zones where the second phases or defaults of materials existed. Although different materials are damaged to different extents, the mechanism of failure mainly appears as contact fatigue of the contact surfaces, i. e. the particles detached by delamination.

The running behaviours and damage mechanisms of three coatings have been studied. The results indicated that TiN coating with high hardness and elastic modulus clearly improved the deformation rigidity of its substrate material, and reduced the dissipated energy and lasting time of the open *F-D* curves. MoS_2 coating, which is in possession of low friction coefficient and hardness, was obtained an inverse result. It illuminated that the TiN coating enhanced the load bearing capacity, and enlarged the using range of substrate material. MoS_2 coating and TiN+ MoS_2 composite coating both possessed the good capability for palliating radial fretting damage. The microslip increased in radial fretting when the solid lubrication coating was used on the contact interfaces. More system energy can be absorbed in this process in favor of reducing vibration. For TiN+MoS_2 composite coating, a compound feature of two individual coatings can be observed.

The damages of contact fatigue of hard coatings were mainly dependent upon the test parameters and characteristics of coatings. Therefore, the experimental method of radial fretting can be proposed as one of new and potential methods to evaluate life of contact fatigue of hard coatings.

(3) The combination of two basic fretting modes of radial and tangential fretting was successfully fulfilled for the first time.

On the basis of radial fretting, the combination of radial and tangential fretting was successfully fulfilled for the first time though a delicate and simple design, i. e. obliquely placing the flat specimens. The features of radial and tangential fretting modes have been strongly reflected in the *F-D* curves of composite fretting. It is a significantly important for studies of composite fretting to palliate complex fretting damages in actual engineering applications.

(4) The running and damage mechanisms of composite fretting have been studied systemically.

The composite fretting tests have been carried out for different

materials, such as 1045 steel, 52100 steel, 2091 aluminium-lithium alloy, TiN coating and MoS_2 coating, under two inclined angles of 45 and 60 . The results indicated that there were three basic types of *F-D* curves, i. e. qusi-trapezoid cycle, elliptic cycle and linear cycle. The variations of the *F-D* curves as function of number of cycles were strongly dependent upon the load levels, inclined angles, characteristics of materials and test procedure. According to the three kinds *F-D* curves, the processes of composite fretting can be divided into three stages. The features of runningand damage behaviours were as follows:

a) Satge Ⅰ (qusi-trapezoidal *F-D* curves): The parameters of F_l、F_s and δ_c can be introduced to describe the qusi- trapezoidal *F-D* curves. During the early stage of testing, the *F-D* curves of qusi-trapezoid cycles obviously displayed the features of slip. With the increase of the number of cycles, the displacements dropped down quickly. Some phenomenon of abrasion and adhesion can be obviouslyobserved in wear scars with an asymmetry shape of the comet-like. The white layers of fretting, cracks parallel to surface and debris (the third body) have been formed during this stage.

b) Satge Ⅱ (elliptic *F-D* curves): When the parameter of F_l increasedto a certain critical value, the *F-D* curves transformed suddenly from qusi-trapezoid cycle to elliptic cycle. The deformation entered into the range of elasto-plasticity during this stage. When the parallel and verticalcracks encountered, the plate-like particles detached by delamination mechanism. The third bodies were accumulated between the contact surfaces during this stage, and subsequently the two-body contact transformed to the three-body contact.

c) Satge Ⅲ (elliptic *F-D* curves): There is no sliding between the interfaces. Only elastic deformation of contact pairs occurred under the imposed loads. Because of accommodation of the third-body bed, the ratio of wear greatly decreased. The formation of fatigue cracks became the most important features in this stage.

Three fretting regimes (slip, mixed and partial slip regimes) can be observed in one test procedure under certain conditions. The formation of mixed regime was the results of repetitious processes, in which cracks

formed, cracks propagated and particles detached. On the basis of the analysesconcerning the fretting white layers, the third body behaviours and the competition between wear and fatigue, a physical model of compositefretting damages were proposed. A displacement accommodation mechanism was also proposed to explain the variations of the displacements and the contact conditions during the processes of composite fretting.

(5) With the change of relative inclined angle between contact pairs, the variations of fretting damage mechanisms of tangential, composite and radial fretting have been studied.

During the transition from tangential fretting to composite fretting, and to radial fretting (inclined angle changed from 0o to 90o), the decreasing of componentof tangential fretting was accompanied with the increasing of component of radial fretting. In the competition relation between wear and fatigue, the features of sliding wear reduced gradually, the features of radialcontact fatigue held the predominance step by step. The formula for the controlling parameters of white layer formation of fretting has been built up at the same time during this research, which strongly supported the plastic deformation mechanism of the white layer formation.

For MoS_2 coating, the oxidation effect became weakened gradually with the increase of number of cycles, while the flow layers of MoS_2 coating were more and more difficult to form. When the condition of radial fretting achieved, the MoS_2 coating hardly damaged and oxidized as well.

目录