Development and experimental research of a test bench for sliding friction and bending fatigue

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Abstract. In order to research the fatigue damage characteristics of components under the coupling of sliding friction and bending fatigue, a test bench of the coupling of sliding friction and bending fatigue was developed based on the analysis of the principle of bending fatigue and friction experiment. The test bench mainly includes drive module, load application module, data collection and processing module. The single sliding friction test, single bending fatigue test, coupling test of sliding friction and bending fatigue can be carried out by this test bench. The three functions of test bench were carried out by 45steel experiment. The rationality and validity of the test bench were well verified by experimental measurement. The results show that the variation of life curve of coupling of sliding friction and bending fatigue is consistent with that of standard rotary bending fatigue life curve. The fatigue life of specimens is reduced on account of the effect of sliding friction. Under the low bending load, the influence of sliding friction effect on fatigue life is more significant. The fracture has typical characteristics of fatigue striations and dimples morphology.

1. Introduction
Fatigue damage is a design and analysis method widely used in Modern mechanical product design. Friction and wear effect can cause degradation or attenuation of system performance, and directly or indirectly lead to product failure. The active system is any mechanical system that transmits alternating workloads with simultaneous occurrence of the friction and wear process. This system exists widely in modern mechanical system, such as the gear pair system, the shaft/hub pair system, the rail transit wheel/rail pair system etc. It is impossible to evaluate the damage, life or limit state of mechanical system from single tribological view or from single mechanical fatigue view for the active system [1, 2].

Wang et al. [3-5] studied the interaction of fretting friction/wear and fatigue between the steel wires composed of steel wire rope subjected to stretching and bending in work. The evolution rule of fretting wear depth and its influence on fatigue life are obtained. It is found that the interaction between fretting friction and cyclic load leads to the crack initiation, propagation and fracture of the wire rope, and accelerates the fatigue failure of the steel wire rope. The results showed that the main failure of steel wire rope is caused by the interaction between fretting wear and fatigue fracture, the fatigue life of steel wire rope is inversely proportional to wear depth and contact load by Zhang et al. [6]. Benuzzi et al. [7] evaluated the stress intensity factors of type I and type II of inclined crack edge under cyclic loading by finite element method. It is found that the crack direction, crack length and Hertz contact...
area half width ratio, friction between crack surfaces and contact surface friction have obvious influence on the crack propagation mode and the crack propagation direction. Yan et al. [8] investigated the effect rule of friction coefficient, contact pressure, initial crack length and crack shape on the crack propagation by finite element method. It is found that the crack propagation is I- II compound crack because of the action of the friction effect. Abdelbary et al. [9] studied the effects of surface pre-crack polyamide materials on cyclic and static loads under non-lubricated sliding friction. It is found that the surface crack has a certain influence on the friction and wear, and the wear is more sensitive to the surface crack under cyclic load. A stable three-field equation is presented by the research on the multiaxial fatigue crack propagation rule considering the contact between the crack surface and the rail bending friction, the influencing characteristics of friction coefficient of the crack surface, crack position and track stiffness on crack propagation behavior are obtained by Mai et al. [10]. The interaction between contact pressure and sliding friction/wear characteristics of the Rails and wheels is investigated by Fletcher et al. [11]. It is found that there is a certain equilibrium relationship between crack propagation rate and surface wear rate under high contact cycle, and a shallow steady state crack depth is formed. The research of coupling of friction and fatigue is mainly focused on theoretical study and numerical analysis. However, experimental research has always been an important method of scientific research, which can effectively verify the correctness and availability of numerical analysis and theoretical research results. Therefore, it is very important to develop a test bench for coupling of friction and fatigue, and carry out experimental research.

In this paper, a test bench is developed based on the principle of sliding friction/wear test and fatigue test. The experimental measurement of single sliding friction/wear test, single bending fatigue test and coupling test of sliding friction/wear and bending fatigue can be carried out by the test bench. The experimental research under the same test conditions with comparable results was carried out. The development of the test bench is successful by the experimental results. It provides a foundation for the experimental study of tribo-fatigue.

2. Design of test bench

2.1. Design principle of test bench

According to the china national standards GB/T4337 [12] and GB/T12444 [13] and the purpose of coupling test of sliding friction and bending fatigue, the test bench is required to perform the following functions: (1) For the single sliding friction experiment. The effects of various factors on the friction/wear characteristics can be investigated by this test bench. (2) For the single bending fatigue experiment. The fatigue damage characteristics and fatigue life can be carried out by this test bench under different bending loads. (3) For the coupling experiment of sliding friction and bending fatigue. The interactional damage characteristics and fatigue life can be investigated by this test bench under coupling of sliding friction and bending fatigue. In order to achieve the design objectives of the test bench, this test bench mainly includes driver module, main bearing box module, load imposed module, measurement and analysis module. The rotary motion of the specimen is driven by the driving module. The fixed clamping end of the rotary specimen is connected with the driving motor through the main bearing box. The driving motor does not bear the bending load in the process of experiment by this connection. The experimental bending load and the contact load are applied to the experimental specimen by the load module. The collection and processing of measurement data is completed by measurement and analysis module.

2.2. Structural design of test bench

2.2.1. Total design. The Schematic diagram of coupling test bench of sliding friction and bending fatigue is showed in Figure 1. The test bench should be able to complete the experimental measurement of a certain range of experimental conditions. The variable-frequency and variable-speed motor is selected to drive the rotary specimen for realizing the regulation of the experimental speed
range. The contact load is applied to the friction pair by means of the contact load mechanism. The contact position of the specimen can be adjusted in a certain range according to the experimental requirements. The purpose of the position change is to realize the experiment of different bending stress positions. The bending load is applied by bending load mechanism. The damper spring is added at the joint of weight plate in order to reduce the influence of vibration on the experiment results. The friction force is measured by the pressure sensor. The friction coefficient is calculated by contact load and friction force measured. The experimental status is monitored by the vibration sensor, and the vibration signal is used as the criterion of the end of the experiment.

Figure 1. Schematic diagram of test bench.

Figure 2. Contact load mechanism.

Figure 3. Bending load mechanism.

2.2.2. Key structure design. The Figure 2 shows the contact load-imposed mechanism. The contact load is applied to the sliding friction pair by the leverage and weights. The load mechanism includes leverage, disc specimen, lock nut, pin, sensor seat and damper spring. According to the experimental scheme, a certain mass weight is applied to the weight plate. After the test starts, the friction force between the disc specimen and the bar specimen drives the disc specimen to rotate, and the pin fixed on the disc specimen is drove to rotate. At the moment, the pin is in contact with pressure sensor. The friction force is measured, and the friction coefficient is obtained by calculation.

Figure 3 shows the bending load-imposed mechanism. The bending load is applied by cantilever beam single point bending load. The load mechanism includes fixture, II shaft, spacer bush, rolling bearing, cover, clamp spring, joint bearing and damper spring. The right end of II shaft is supported by joint bearing, and the weight plate is connected to end of joint bearing by damper spring. The bending
load was applied to the bar specimen by bending load-imposed mechanism. After the bending load of experiment is applied, the joint bearing is fixed by a locking device in Figure 1. So the bending load remains constant during the experiment. The fixed chuck of bar specimen is ER20-12 elastic collet produced by HUARUI precision machinery limited company. The joint bearing is the PHSC14A with internal thread produced by MISUMI, and its maximum load is 20.6kN. Then the relationship between stress and load on the bar specimen is as follow [12]:

\[ S = \frac{16F (L - x)}{\pi d^3} \]  

Where \( S \) is the stress of bar specimen, MPa. \( F \) is the bending load, N. \( L \) is the arm of force, mm. \( x \) is the distance between the fixed load plane and the stress measuring plane, mm. \( d \) is the diameter of bar specimen, mm.

2.3. Measurement system

It is necessary to obtain the friction force, friction coefficient and vibration signal in the experiment. The friction force is obtained by the pressure sensor. The kinetic friction coefficient can be obtained by timing sampling function of measurement system. The vibration signal is obtained by the vibration sensor, and is used as the criterion of the experiment end. The threshold value of vibration signal is set by preliminary test. During the experiment, the experiment will be stopped when the experimental vibration signal reaches the preset threshold. The friction coefficient is calculated by friction force and contact load. Then, the friction coefficient \( \mu \) can be described as

\[ \mu = \frac{F_f}{P} \]

Where \( F_f \) is the friction force, N. \( P \) is the contact load, N.

The function of the measurement system includes the data collection, data transmission, data processing and data storage. The analog signals are converted into digital signals by the NI USB-6009 data acquisition card. And then the data are input computer by USB bus. The graphic programming software LabVIEW is used to develop the measurement system based on the test bench function, data display, data storage and selected data acquisition card [14]. The functions of experimental parameters setting, data acquisition and processing, data real-time display and record and data storage are realized in measurement system. The program chart of data acquisition and processing is showed in Figure 4. The main technical parameters of the test bench are shown in Table 1.

![Figure 4. Program chart of data acquisition and processing.](image)
3. Experimental investigation

3.1. Experimental project

In order to verify the rationality and availability of the test bench, the single sliding friction experiment, the single fatigue experiment and coupling experiment of sliding friction and bending fatigue are carried out by the test bench in Figure 5. All experiments are carried out in the rotary speed 600 r/min at room temperature under no-lubrication condition. The specimen material is 45 steel. The bar specimen size is $\phi 10 \times 130$mm, and the disc specimen size is $\phi 50 \times 5$mm. The contact load is 20N, the bending load is 0 and the experimental time is 30 minutes in single friction experiment. The bending load is 200N, 220N, 240N and 250N in single fatigue experiment, respectively. To the coupling experiment of sliding friction and bending fatigue, the contact load is 10N and 20N, respectively. The bending load is the same as that of the single bending fatigue experiment. The fatigue fracture of bar specimen is taken as criterion in the single bending fatigue experiment and coupling experiment. Three sets of effective test data are measured under each experiment, and then the average is taken as an experimental result.

| rotary speed (r.min⁻¹) | bending load (N) | contact load (N) | bending load form | load method |
|------------------------|-----------------|-----------------|------------------|-------------|
| 0~1000                 | 0~350           | 0~80            | cantilever single point | weight     |

![Figure 5. Test bench of sliding friction and bending fatigue.](image)

![Figure 6. Variation of friction coefficient and vibration.](image)

![Figure 7. Relationship between fatigue life and bending load.](image)

3.2. Analysis and discussion

Figure 6 shows the variation of friction coefficient and vibration signals under single sliding friction experiment. The friction coefficient fluctuates slightly with the experimental time, and its average value is 0.1707. The variation of vibration velocity with experimental time is obtained, and fluctuates...
within the range of 1.41mm/s. There is not the fatigue failure of the specimen by the variation. It can be seen that the test bench has fully realized the single sliding friction experiment and the collection and processing of experimental data. The experimental status can be monitored by the measurement system. Figure 7 shows the relationship curve between fatigue life and bending load under the conditions of single bending fatigue experiment. It can be seen that the fatigue life of bar specimen decreases gradually with the increase of bending load. The fatigue life of 250N bending load is 1.26×10^5, only 14% of that of 200N bending load. The relationship between fatigue life and bending load conforms to the variation rule of material load life curve in the GB/T4337. The test bench has realized the function of rotary bending fatigue experiment and achieved the design goal.

Figure 7 shows the relationship curve between fatigue life and bending load under the conditions of single bending fatigue experiment. It can be seen that the fatigue life of bar specimen decreases gradually with the increase of bending load. The fatigue life of 250N bending load is 1.26×10^5, only 14% of that of 200N bending load. The relationship between fatigue life and bending load conforms to the variation rule of material load life curve in the GB/T4337. The test bench has realized the function of rotary bending fatigue experiment and achieved the design goal.

Figure 8 shows that the life curve of the coupling experiment of sliding friction and bending fatigue. It can be seen that the variation of the fatigue life of the bar specimen is basically the same as that of the single bending load, and it has the characteristics of the life curve of single bending fatigue. However, the fatigue life decreases with the increase of contact load under the same bending load. The influence of friction effect on fatigue life is more significant under the lower bending loads. The fatigue life of bar specimen is reduced by 26% compared with that of single bending load under 200N bending load and 20N contact load. The fatigue life of bar specimen with contact load of 20N is decreased by 10% compared with that of 10N contact load. The fatigue life of single bending load is 1.15 times of that of 20N contact load and 250N bending load. The comprehensive analysis shows that the sliding friction effect has a significant influence on the fatigue life. The bar specimen bears the shear stress caused by friction force on account of contact load. Thermal fatigue damage may occur due to frictional heat. At the same time, the specimen surface is damaged because of wear, and the initiation crack source more likely to appear. The fatigue life of coupling experiment is lower than that of the single bending fatigue experiment. The reason may be the composite action of shear stress, contact stress and wear damage. So, the friction effect has obvious influence on the fatigue life of metal materials.

**Figure 8.** Life curve of coupling experiment.

Figure 9 shows the morphology of fatigue fracture of bar specimen under the coupling experiment. It can be observed that the fatigue fracture occurs at the position where the bending stress is greater at the edge of wear track. The fracture surface is relatively flat. The instantaneous failure zone is located in the center of the fracture surface. The multiple crack sources of the bar specimen are observed in the specimen surface because of the composite action of bending load, contact load, friction heat and wear damage, the obvious plastic deformation is not observed in Figure 9(a). After the crack source is formed, there is the fatigue crack propagation with the repeated action of sliding friction and bending fatigue. There is alternate action between cleavage propagation and plastic passivation of the crack tip. The fatigue propagation zone with obvious fatigue fringe feature is observed in Figure 9(b). The multiple fatigue cracks converge together as the crack propagating towards the central area of the specimen section. The bar specimen break, when the carrying capacity of the remaining section size of the bar specimen is lower than the external load. The typical dimple morphology of the transient fracture zone is observed in Figure 9(c).
Figure 9. Fracture morphology: (a) Fracture section; (b) Fatigue zone; (c) Transient zone.

4. Conclusions

(1) A test bench of coupling of sliding friction and bending fatigue is developed according to the principle of rotary bending fatigue experiment and friction/wear experiment. A high efficiency and high precision measuring system are exploited by using the LabVIEW virtual software, PCI data acquisition card and dynamic sensor. The measurement system has the functions of signal conversion, data acquisition and processing and input of experimental parameters.

(2) The functions of test bench are proved by the single sliding friction experiment, the signal bending fatigue experiment and the coupling experiment of sliding friction and bending fatigue. It is proved that the design of test bench is reasonable and effective.

(3) The variation on fatigue life of the coupling of sliding friction and bending fatigue is basically the same as that of single bending fatigue damage. The experimental results show that the friction effect reduces the fatigue life of the specimens and has a significant effect on the fatigue life.

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