Friction coefficient and error test via micro-rotation mechanics model

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Abstract An air pressure-loading mode incorporated into the friction apparatus is firstly applied to coatings tribology involving large load, automation, stepless and continuous loading processes. A novel measurement principle is proposed and a micro-rotation mechanics model was developed for high precision measurement of friction coefficient. By properly designing and locating two sensors real-time monitoring the normal and friction forces, the troublesome influences in friction measurement is considerably relieved which come from surface characteristics of coatings of the samples in traditional friction test processes. By calculation and analysis, the max rotation angle $\theta_{\max} = 0.001\,8^\circ$ is gained, which indicates that the measurement error of the apparatus is greatly reduced. The whole system error is about 1.15% given by finite element method and indication error of the least square fitting of measurements. [doi:10.1063/2.1202107]

Keywords air pressure-loading, measurement principle, micro-rotation, friction, error analysis

Friction apparatus is a professional equipment testing and evaluating tribological characteristics.[1,2] With the development of friction testers, different types of loading and corresponding measurement principles emerge consecutively.[3–5] Development of computer technology also is beneficial for the test operation of high-precision testers.[6] Traditional load methods are commonly adopted in testers, such as weight, servo systems, hydraulic systems, and so on. Most of the existed testers consider the positive pressure as a constant, ignoring the influences of the coatings, surface characteristics.[7] While testers run at high speed, the traditional loading type of standard weight would produce vibration, and the error would amount up to 25% according to statistics.[8] To reduce the impact of fluctuations, air pressure-loading is introduced and sensors are used to monitor simultaneously the changes of pressure and friction in a real-time manner, obtaining an instantaneous coefficient of friction.

The results show that the friction was measured by mechanical amplification, such as torque amplification pendulum rod amplification. Amplification principles measure the friction coefficient with certain error.[9] Meanwhile, with development of coatings technologies, analysis of the behavior of surfaces in contact and theoretical basis for the prediction of surfaces characteristics are needed.[7] There are few studies focused on tribological behaviors of coatings with real-time simultaneous monitoring of normal and friction forces.[10,11] So a new mechanics model is proposed in the present paper for micro-rotation measurement based on the air pressure-loading method. The system error of apparatus was analyzed by model calculation and indication error of the least square fitting of measurement. Furthermore, given the fluctuation error, collecting error and other factors, comprehensive calculations give the overall system error.

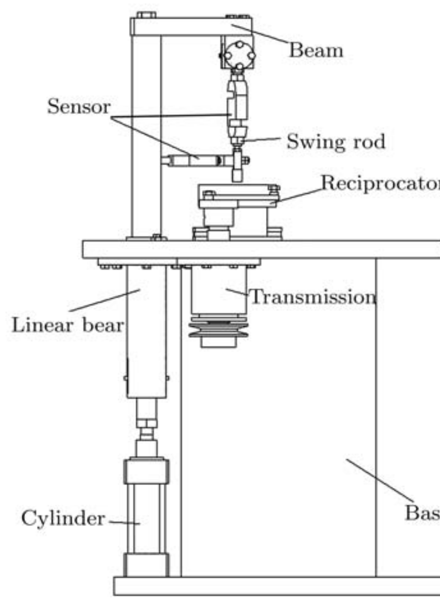

Fig. 1. Schematic diagram of the air pressure-loading friction apparatus.

Figure 1 shows the schematic diagram of the air pressure-loading friction apparatus. The apparatus includes five main parts: loading part, transmission part, clamping part, signal acquisition and data processing. Measurement system consists of two sensors monitoring pressure and friction, respectively. The range of senor is 0–500 N and accuracy is 0.001 N. The accuracy of electronic valve is 0.002 MPa and the loading gradient is 0.05 N.

As shown in Fig. 1, two sensors are rigidly hinged on the loading beam, which is directly connected to the cylinder. A variable frequency motor is used to drive

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the sample holder via belt. In testing process, the electronic valve controls the cylinder, and the computer applies loads via the electronic valve. Driven by the motor, the sample holder can rotate or reciprocate, producing signal pressure and friction. The computer collects signals and changes the mode signals into digital signals. The experiment process is monitored through closed-loop control.

Surface roughness and mechanical factors of parts resulted in micro-fluctuation under normal operation of apparatus. In order to reduce the influence of surface, two sensors were adopted to monitor and execute dynamic adjustment of the air pressure-loading, which could accurately collect instantaneous changes of normal and friction forces, giving precise friction coefficient under the help of computer. Influences of surface roughness and mechanical factors on friction coefficient were greatly relieved by incorporating micro-rotation measurement mechanics model with advanced measurement technology.

Among traditional friction testers, the normal force was considered as a constant force (weight load). However, this situation could not reflect the changes of normal force resulting from contact surface characteristics. Figure 2(a) shows a scanning electron microscope surface morphology of CrAlSiN coating. It's easy to understand that surface characteristics of the structure film must affect the evaluation of normal force. Figure 2(b) shows tribological mechanism of a contact involving CrAlSiN coating surface. The assumption of constant force can not reflect the existence of micro-contact in the friction process and thus cannot meet the requirement of the development of modern micro-mechanics.

Most traditional measurement principles were used for the existent apparatus measured friction by magnifying angle, torque, beam distortion and so on. The friction force was measured by amplification principle with certain inherent errors.[12] Figure 3 shows a comparison between the weight load and the real-time measured load, revealing a clear difference between them. There was a difference δ between weight load and measured load so that the importance of real-time measured load for deriving friction coefficient in micro-tribology could be understood. And thus our apparatus used real-time monitored normal and friction forces to relieve the troublesome influence on friction measurement which came from coatings surface characteristics of the sample in traditional friction test processes.

Figure 4 shows the schematic diagram of the micro-rotation measurement mechanics model. The dotted line is diagram of a pendulum rod which exhibits tiny deflection under loading. When the apparatus worked, friction from the upper and lower samples made the pendulum rod exhibit very tiny rotation. The pressure and friction were directly monitored by sensors, because the deformation of sensors themselves and the rotation of the pendulum rod were extremely tiny.

As can be seen from Fig. 4, the equilibrium of pendulum rod was affected by three forces (friction force f, tensile force P and reaction force N'). The rotation angle of pendulum rod is θ. From the moment balance theory we can get

$$(f\cos\theta + N'\sin\theta)(l_1 + l_3 - \Delta l) = P(l_1 - l_2\tan\theta)\cos\theta. \tag{1}$$

Equation (1) can be written in the following form

$$f = \frac{P(l_1 - l_2\tan\theta)}{l_1 + l_3 - \Delta l} - N'\tan\theta, \tag{2}$$

where $l = N/\lambda$, N is pressure from apparatus, λ is deformation constant of the sensors. $l_1 = 120$ mm, $l_2 = 80$ mm and $l_3 = 30$ mm are structure parameters of the apparatus. From $\lambda = 7.8 \times 10^4$ N/mm and $N_{\max} = 300$ N, the maximum deformation of sensor is $l_{\max} = N/\lambda = 3.8 \times 10^{-3}$ mm $(l_1, l_2, l_3 >> l_{\max})$. The maximum deformation $l_{\max}$ is substituted into the following equation

$$\begin{aligned} & l_1^2 + (l_1 + l_2\tan\theta)^2\cos^2\theta - 2l_1 \cdot \\ & \quad (l_1 - l_2\tan\theta)\cos^2\theta = a^2, \\ & l_2^2 + (l_2 + \Delta l_{\max})^2 - 2l_2(l_2 + \Delta l_{\max})\cos\theta = a^2. \end{aligned} \tag{3}$$

By software of Matlab 7.0, we can get $\theta_{\max} \approx 0.001\,8°$ from Eq. (3). Sites of sensors were optimized and sensors were very sensitive to the rotation of pendulum rod, therefore, errors of the mechanical part and the collection part are directly reduced.

As l, $l_2\tan\theta$ and $N'\tan\theta$ can be ignored and $\theta_{\max} = 0.001\,8°$, Eq. (2) is simplified to

$$f = \frac{Pl_1}{l_1 + l_3}. \tag{4}$$

So the formula of friction coefficient can be written in the following form

$$\mu = \frac{Pl_1}{N(l_1 + l_3)}, \tag{5}$$

where tensile force P and normal force N were simultaneously measured by the two sensors.

Amplification principles of rotating angle or torque were applied in the existed friction testers, meanwhile they also amplified errors. Our apparatus adopted micro-rotation measurement principle ($\theta_{\max} = 0.001\,8°$), and thus the error was extremely small. Accurate friction coefficient could be obtained by data processing. The maximum rotation angle ($\theta_{\max} = 0.001\,8°$) was very small, by calculation we knew that the neglection of l and $l_2\tan\theta$ did not affect the accuracy of friction coefficient.

Error of apparatus includes error of measurement principle, mechanical parts, deformation, signal acquisition and external disturbance.[9] In the present apparatus, the error of data acquisition system is main. The indication error of the least square method was used to analyze the error of acquisition system. In the least square method, the measurement value of sensor was selected as the fitting object, and then the indication

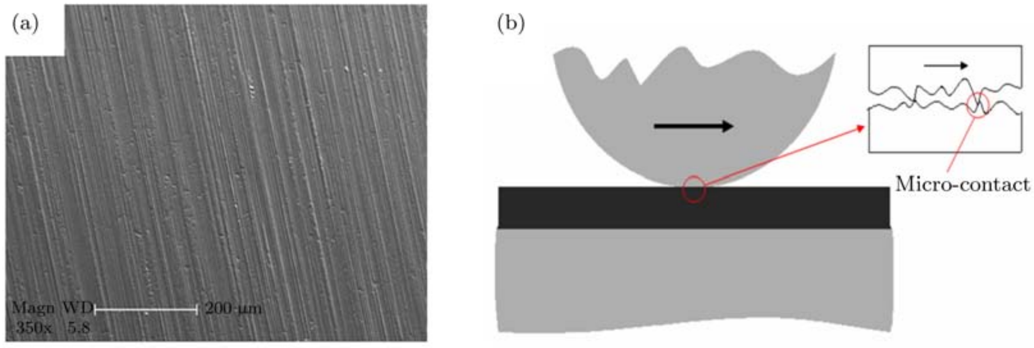

Fig. 2. (a) Scanning electron microscope surface morphology of CrAlSiN coating and (b) tribological mechanism of a contact involving CrAlSiN coating surface.

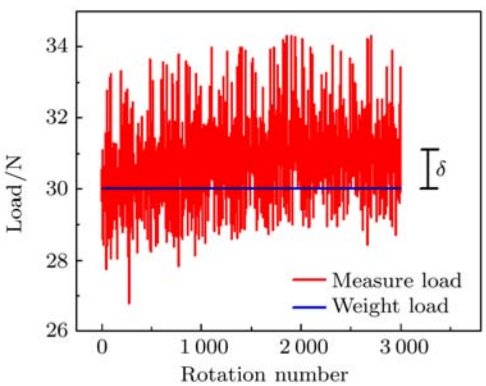

Fig. 3. Comparison of real pressure load with constant pressure load.

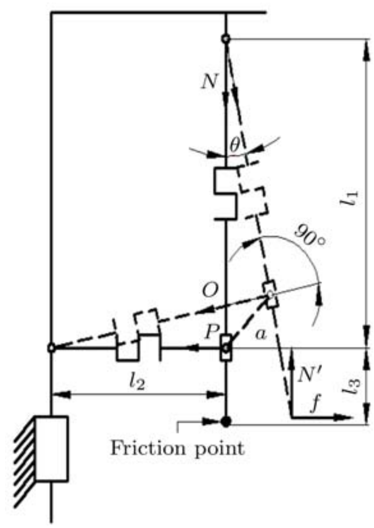

Fig. 4. Schematic diagram of the micro-rotation measurement mechanics model.

error of the fitting curve was properly transformed, and finally errors calculation gave acquisition system's errors. x_n is the standard value of input, y_n is the corresponding measurement value and $f(y)$ is set to be the fitting curve of the measurement values. According to the least square method, the least square formula for fitting $f(y)$ was $\varepsilon = \sum_{i=1}^{n} [f(y_i) - (y_i - x_i)]^2$. The essence of the least square method was to minimize ε. Therefore, we could seek the first-order partial derivatives of all undetermined coefficients of $f(y)$ on ε and set all values to 0. Equations composed by all undetermined coefficients of $f(y)$ were got and then the equations were solved to obtain all undetermined coefficients, finally the exact expression of $f(y)$ was obtained. We also got relative error (%), which was defined as $(y_n - f(y_n) - x_n)/x_n \times 100\%$. By using the above method to calibrate acquisition system and using Matlab software, the maximum error of the acquisition system was calculated to be 0.26%. To sum up, the system's overall error was about 1.15% when the apparatus was under normal operation conditions.

The friction apparatus could achieve large load, high precision and automation, stepless and continuous load process which was optimized by integrating air pressure-loading, micro-rotation measurement principle, advanced control technology and the ball-disc friction apparatus. The new measurement principle could significantly reduce the troublesome influence in friction measurement which came from the sample fluctuations in traditional friction test processes. Adoption of micro-rotation measurement principle in design resulted in a max rotation angle of $\theta_{\max} = 0.0018°$, and thus the measurement error of apparatus was greatly reduced. The overall system error was about 1.15%, derived from analysis of finite element method and indication error of the least square fitting of measurements. The results showed that the apparatus had much higher reliability and better repeatability, and provided a new and effective test way to study tribology.

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