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A new method for measuring stress inside movable element in contact

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Abstract

The subsurface stress plays an important role in the damage of the movable contact element, but most subsurface stresses are obtained with numerical calculations according to the contact mechanics. In the present paper, a new method to measure the subsurface stress of the movable element is proposed with using photoelastic technology. Although the technology has been widely used in measuring the stress of the static elements, it is seldom used in the moving body because the observed point is moving. After the experimental tester is introduced in detail, the principles of the photoelastic technology are presented. The tester is designed to be able to working in the three conditions, the static, the rolling and the sliding in the line or surface contacts. The experimental results, that is the interference fringes, of the three states are then presented in the different loads and the rotational speeds. Because the fringe figures indicate the maximum shear stress distribution in the body of the moving element, we can find what the real stress distribution in the rolling or sliding element is alike.

Keywords: rolling; sliding; contact; subsurface stress; photoelastic

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Nomenclature

a : Half-width of contact

C : Optical constant of material

d : Thickness of sample

f_{α} : Stress fringe coefficient of photoelastic material

h : Thickness of photoelastic material

I_0 : Incident light intensity

I : Interference light intensity

n : Rotational speed

N : Order of isochromatic fringes

p : Surface normal pressure

R : Radius

U : Velocity

w : Load

Δ : Optical path difference

λ : Wavelength of incident light

μ : Friction coefficient

ω : Angular velocity

σ_1, σ_2 : Two principal stresses in plane stress field

σ_H : Hertzian stress

τ : Surface friction stress

$\tau_{\max}$: Maximum shear stress

1 Introduction

The stress distribution in different contact states is the key factor to understand how the element is failure. The acting force and the frictional force on the contact surface will bring about the normal and shear stresses in the body of the contact elements. The stresses, especially the maximum shear stress, are very important for predicting the fatigue of the element [1, 2]. Therefore, how to obtain a real stress field of a contact element, especially as the element is kinematic, is of great significance for studying the failure of mechanical parts.

In tribology research, rolling friction and sliding friction are two basic contact states which has attracted the attention of many scholars. There has been a large amount of theoretical study on the subsurface stress in contact, Hertz must be mentioned first [3]. Hamilton and Goodman solved the analytical solution of the full-field stress inside the material when the sphere is in contact with the normal force and the tangential force [4]. In the rolling contact, Kalker studied the non-Hertzian contact problem with the numerical method, and he studied the three-dimensional rolling contact problem under dry friction [5-9]. Johnson, Popov and et al. proposed the theoretical distribution of the contact and tangential stresses [10,11]. In the sliding contact, the stress under the surface tends to shift upwards [12]. Hariprasad et al. concluded that the stress is no longer asymmetrically distributed under friction[13]. The theoretical researches have revealed most of the contact stress field already [14]. Therefore, the subsurface stress distributions can have been precisely calculated based on the contact mechanics

The observation of the plane stress field under the static condition mostly adopts the photoelastic experiment method, which can directly observe the distribution of the principal stress difference inside the object. Brewster discovered the phenomenon of stress optics [15, 16]. Many studies have applied this method to contact stress analysis [13,17-20]. Zhan et al. used numerical calculation combined with photoelastic experiment to solve the distribution of rolling contact pressure and describe the evolution of contact stress field in the wear process [19,21]. Bryant used the photoelastic technology to measure the photoelasticity experimental images between the contact interfaces with or without sliding [22]. In the study of viscoelastic rolling contact, Yoneyama et al. used the photoviscoelastic technique of elliptically polarized light to calculate the variation of principal stress, principal strain and their direction with time [23].

Although the experimental results of the subsurface stress of the elements in the static are consistent with the theoretical ones, those in motion have not been seen. In order to study the stress in a movable (rolling or sliding) element to compare with the numerical results, a photoelastic tester is developed for the static and kinematic friction pairs in the present paper. The experimental testers is modified from the researches of He [24], Fang [25] and Hoang [26].

Based on their studies, the principal stress difference, which is proportional to the maximum shear stress, can be obtained by the tester, which can work in static or kinematic situation under different loads and speeds by using the photoelastic method. With the tester, the comparison between the photoelastic experiment result and the

numerical calculation result will help us to verify the validity of the theoretical analysis of the subsurface stress of a moving element.

2 Construction and principles of the tester

For the photoelastic stress measurement method, it can be used in a surface contact. According to the principles of photoelasticity, the sample must be made of the transparent photoelastic material. Then, a polarized light source irradiates from one side of the sample in the contact area and a camera is used to observe the divided and magnified lights behind the polarizer on the other side of the sample. Since the photoelastic material may change the refractive index under the different stresses, the different refractive indexes will cause the light through the sample with different velocity. Therefore, as a same source light passes through one point of the sample and is divided to two different polarized lights in the directions of the two principal stresses, they will form an interference image because of the optical path difference. Then, the photoelastic fringes will appear in the contact area. The brightness of the fringes show the intensity of the principal stress difference, which is two times proportional to the maximum shear stress in the contact area. So, when the fringe image has been obtained, the distribution of the maximum shear stress in the element has been known.

2.1 Construction of experimental device

The diagram of the experimental device is shown in Figure 1. Along the direction of the optical path, it consists of a collimating light source, a polarizer, two quarter-wavelength plates, a photoelastic sample, an analyzer and a CCD camera. The

contact pairs consists of a steel disc which is a rolling bearing on the top and the photoelastic plate which is made of epoxy resin on the bottom. The photoelastic plate is driven by a motor through a synchronous belt. When the steel disc contacts the photoelastic plate, the speed of the steel disc and the photoelastic plate is the same under the action of frictional force as the rolling friction is formed. The steel disc can be braked so that the steel disc will be stationary so that the two plates will slide relatively. Therefore, the device can realize three states, static, rolling and sliding, as shown in Fig.2. Different weights are applied on the top of the steel disc so as to change the load. By controlling the speed of the motor and the load of the weight, we can form a variety of experimental working conditions.

Fig.1 Schematic diagram of experimental platform for measuring subsurface stress by photoelastic method

The photoelastic disc and steel disc are placed on the photoelastic experimental platform and the servo motor is controlled to achieve different rotational speeds. The monochromatic light generated by the collimating light source reaches the CCD

camera device through the polarizer, the quarter-wavelength plate, the photoelastic plate, the other quarter-wavelength plate and the analyzer. The contact area is left in the camera's field. The image can be adjusted by the distance between the lense of the camera and the contact area. The imaging and recording device captures the enlarged photoelastic image of the contact area. The fringe order of the photoelastic image represents the change of the pressure in the contact area and the subsurface stress.

Fig.2 Schematic diagram of three different working states in line contact

2.2 Principles of experiment

The samples used in the experiment are unlubricated at the room temperature. The upper contact pair is the deep-groove ball bearing 6900-2Z. Its inner diameter is 10 mm, the outer diameter is 22 mm and the width is 6 mm. The lower contact pair is a photoelastic disc which is assembled on a shaft to be able to rotate.

The load is applied from the top of the rolling bearing. Although the load can be changed, the material is always kept in the elastic state. The load will be measured by a sensor. The loaded sample is placed in a circularly polarized dark field.

In the current experiment, a monochromatic laser light with a wavelength of 623 nm is mainly used, which can be regarded as parallel light and used directly. Although the other light, such as white light, can be used as the light source, a convex lens is usually needed to make the light to be parallel. Finally, an industrial camera is used to capture the fringe images. The camera was set to record at a speed of 120 f/s.

The photoelastic disc used in the experiment is made of epoxy resin. The material fringe value of the specimen is 14.6 N/(mm·fringe) which is determined by a four-point bending test, and its outside diameter is 50mm, the inside diameter 10 mm, and the width 4mm.

The lower photoelastic disc rotates is driven by a motor. As mentioned before, there are three states shown in Figure 2, which are : (a) static, (b) rolling ($U=R\omega$) and (c) sliding ($U>R\omega$). For the rolling, the upper rolling bearing rotates synchronously with the photoelastic disc. When the upper steel plate is braked, it is in the stationary so that the sliding occurs. Adjusting the brake force the state may be between the rolling and the sliding ones. In the current experiment, no lubricant is used between the contact region.

3. Photoelastic method and principles

The photoelastic experimental method is suitably used in a plane stress field. The isotropic and transparent photoelastic materials have no birefringence property without external forces. However, under external forces, the light passing through the material will become anisotropic if the stress varies so as to produce the birefringence phenomenon. Birefringence will cause the light to pass through the

sample for a different time because the same light source will produce an optical path difference. This will cause the light interference. The distribution of stress on the surface area of the sample can be determined by collecting interference images in response to the principal stress difference (iso-chromatics) and its direction (iso-clinics) in the photoelastic material.

3.1 Acquisition of interference images

In experiments, the photoelastic sample subjected to an external force is placed between a polarized light field. Due to the temporary birefringence effect of the material, when a beam of plane-polarized light enters the loading sample disc vertically, it will be decomposed into two plane-polarized light beams along the principal stress directions at a point. Because of their different propagation velocities, the phase difference will occur after passing through the loaded disc. According to the stress-optics law, the basic formula of the photoelastic experiment is obtained:

$$\Delta = \frac{2\pi Ch(\sigma_1 - \sigma_2)}{\lambda} \quad (1)$$

where, Δ is the optical path difference (retardation), C is the optical constant of the material, h is the thickness of the photoelastic material, σ_1 and σ_2 are the two principal stresses in the plane stress field, and λ is the wavelength of the incident light.

Figure 3 is a schematic diagram to show how to use the photoelastic method to obtain isochromates. The tester includes a light source, a polarizer, a galvanometer, two quarter-wavelength plates, a photoelastic plate and a CCD camera. The light source can be monochrome or white light source. Set the optical axis of the polarizer to be perpendicular to the reference axis OX . The angle between the fast axis of the

first quarter-wavelength plate and OX is 45° . The sample is placed between two quarter-wavelength plates. The angle of the second quarter-wavelength plate between its fast axis and OX is 135° . Then, set the optical axis of the analyzer is horizontal. Finally, a CCD camera is used to obtain the interference images.

Fig.3 Schematic diagram of photoelastic experiment

3.2 Relationship between interference image and stress

The light passes through the polarizer and the first quarter-wavelength plate, circularly polarized light is incident on the photoelastic plate. Then, optical path difference is resulted in while the polarized light will undergo birefringence under different stresses in the dark field. Therefore, the interference due to the optical path difference occurs. The intensity of the interference light can be expressed as follows.

$$I = I_0 \sin^2 \left(\frac{\Delta}{2} \right) \quad (2)$$

where, I_0 is the incident light intensity and I is the interference light intensity.

The interference image obtained by the above optical device reflects the principal stress difference.

According to Equation (1), the relationship between the principal stress difference and the optical path difference in the interference image can be deduced as follows:

$$\sigma_1 - \sigma_2 = \frac{\lambda \Delta}{2\pi Ch} \quad (3)$$

According to Equation (2), the light intensity of the interference image changes periodically with the optical path difference. Because the principal stress difference continuously varies, the interference image changes alternately between light and dark. If the light level changes for N times, the principal stress difference will appear dark as $I=0$. If $\Delta=2N\pi$ ($N=0, 1, \dots$), Equation (3) can be written as:

$$\sigma_1 - \sigma_2 = N \frac{f_\sigma}{d} \quad (4)$$

where, N is the order of isochromatic fringes, d is the thickness of the sample, and f_σ is the stress fringe coefficient of photoelastic material.

The stress fringe coefficient f_σ only depends on the type of birefringence material and the wavelength of the incident light, but has nothing to do with the size and shape of the sample. If the principal stress difference is an integer multiple of f_σ/d , then the dark streaks appear the isometric lines.

According to the theory of elasticity, the relationship between the maximum shear stress and the principal stress difference in the stress plane can be expressed as:

$$\tau_{\max} = \frac{\sigma_1 - \sigma_2}{2} \quad (5)$$

It can be seen from Equation (5) that the larger the value of fringe order N is, the larger the value of the principal stress difference will be. Therefore, the position where the maximum shear stress appears can be judged according to the order of the

photoelastic fringe. From the knowledge of material fatigue damage, it is known that the main cause of fatigue usually happens at the position of the maximum shear stress. Therefore, the acquisition of photoelastic images is of great significance to find the real damaged position in rolling or sliding contact, and to moreover check whether the theoretical analysis is accurate or not.

4. Experimental results of rolling and sliding in line contact

In the process of photoelastic experiment, the load borne by the specimen can be loaded with different loads by increasing or decreasing the number of weights, and different speeds can be obtained by adjusting the speed of the servo motor. Then, a CCD industrial camera is used to capture the fringe image. The light source can be a common light focused into a parallel light by a convex lens or it can be directly a parallel light such as the laser. In Fig.4, there is a fringe image of photoelasticity obtained with white LED light. For convenience, the following analysis figures are obtained with a laser light source used in the experiments under different loads and speeds.

Fig.4 Photoelastic experiment result with a white LED light lamp in rolling contact
(load $w=99$ N, linear velocity $U=44$ mm/s)

4.1 Influence of load on distribution of principal stress difference

As shown in Table 1, the load w is equal to 94.8, 114.5 or 142.7 N in the static contact (the rotation speed $n=0$), and in the rolling contact or the sliding contact ($n=25$ rpm). Corresponding the different loads, the maximum Hertzian stress σ_H and the experimental results are shown in the table.

Table 1 Photoelastic experimental results of three states under different loads

	$w=94.8\pm1$ N ($\sigma_H=50.11$ MPa)	$w=114.5\pm1$ N ($\sigma_H=54.96$ MPa)	$w=142.7\pm1$ N ($\sigma_H=59.81$ MPa)
static

By using Equation (3), it can be determined that when the fringe order of the photoelastic principal stress difference distribution diagram is $N=1$, the value of the principal stress difference is 3.6MPa. It can be seen from Table 1 that the principal stress difference is symmetrically distributed in the static and rolling states. The number of stripes near the surface is the largest, which is quite similar to the solutions of Hertzian contact theory. At the same time, it can be seen that with the increase of the load, the fringe order in the photoelastic principal stress difference distribution diagram increases significantly. The more fringe order, the greater the stress on the contact pair. It is consistent with the theoretical results. At the same time, as the load increases, the friction force experienced by the contact pair also increases.

Since the photoelastic plate rotates counterclockwise, it can be seen that the photoelastic principal stress difference fringe distribution under the sliding state deflects toward the direction of rotation, and the degree of deflection of the stripes in the sliding state is more obvious than that in the rolling state, which shows that the friction force in the sliding state has more significant influence than that in the rolling state.

4.2 Influence of rotational speed on principal stress difference in rolling and sliding

When considering the influence of the speed on the subsurface stress, adjust the motor speed to make the contact pair roll or slide under a certain load. Table 2 shows the photoelastic interference fringes at different rotational speeds to keep the load as a constant, that is, $w=142.7\pm 1$ N ($\sigma_H=59.81$ MPa).

Table 2 Photoelastic experimental results of rolling and sliding under different rotating speeds under $w=142.7\pm 1$ N ($\sigma_H=59.81$ MPa).

	$n=0$ rpm	$n=25$ rpm	$n=75$ rpm	$n=125$ rpm
rolling
sliding

It can be seen from Table 2 that without rotation, the images have no deflection. As the disc rotates, there is no obvious change in the rolling, but there is some deflection of the photoelastic fringes in the sliding although the effect on the magnitude of the stress and the degree of deflection are not much significant. The difference between the stationary and rotated images lies in the different degrees of deflection, which indicates that under the action of friction, the photoelastic fringes will deflect and the stress field will deflect along the direction of motion. The effect of sliding friction on fringe deflection is greater than that of rolling friction because the

sliding frictional force is larger than that of rolling friction so that the shear stress is larger than that of rolling friction too. Therefore, the effect of the frictional force in sliding must be considered on fatigue of elements, but not in rolling.

5. Relative sliding results in surface contact

The tester can also be changed slightly to be used for measuring the subsurface stress of a relative sliding element in surface contact. However, since the study region may move away from the scope, the movement can only be limited in a short distance. The relative sliding model in surface contact is shown in Fig.5, where the fixed block and movable block are made of the photoelastic material. The observed region is at the bottom of the block. And, the bottom base can move while the transverse force is large enough.

Fig. 5 Model of relative sliding in surface contact

The results of the interference patterns corresponding to the distribution of the principal stress difference in the block are shown in Fig. 6. It can be seen that the fringes change over time as the transverse the force driving the movable block increases under different loads.

Fig. 6 Principal stress difference of relative sliding in surface contact with varying time under different loads

We can see that without transverse force (that is, $t=0$ s), the fringes (stresses) are nearly symmetrical and concentrated at the two edges because there is a large number of interference fringes. As the transverse force increases, the fringe images gradually change. The stresses are severely distorted, that is, the stress at the front (left) edge increases while the stress at the back (right) edge decreases. The images at the last column in Fig. 6 indicate that the movable block starts to slide.

6 Conclusions

In the present paper, a method for measuring the subsurface stress of a rolling element is presented by means of photoelasticity. The images of the principal stress difference, that is, equal to twice of the maximum shear stress, are obtained under the rolling and sliding contacts. The main conclusions are as follows.

- (1) The photoelastic method for measuring the shear stress inside the element can

used in the kinematic states, rolling or sliding, as well as the static one for the plane stress field.

(2) The interference fringes obtained during photoelastic experiment indicate the maximum shear stress, which may be used to find the position where fatigue occurs. The friction has an effect on the sliding situation.

(3) For the relative sliding in surface contact, the stress at the front (left) edge increases, but the stress at the back (right) edge decreases.

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FIGURE CAPTIONS

Fig 1. Schematic diagram of experimental platform for measuring subsurface stress by photoelastic method

Fig 2. Schematic diagram of three different working states in line contact

Fig 3. Schematic diagram of photoelastic experiment

Fig 4. Photoelastic experiment result with a white LED light lamp in rolling contact (load $w=99$ N, linear velocity $U=44$ mm/s)

Fig 5. Model of relative sliding in surface contact

Fig 6. Principal stress difference of relative sliding in surface contact with varying time under different loads

Highlights

- The photoelastic method for measuring shear stress inside the element can be used in the kinematic states, rolling or sliding, as well as the static one for the plane stress field.
- The position of the maximum shear stress can be determined by interference fringes.
- During the sliding process, the stress in the front part of the movement direction increases, and the stress in the back part decreases.
- This work provides a valuable strategy for measuring stress inside movable element in contact.