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Temperature field analysis of pin-on-disk sliding friction test

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ABSTRACT

Heat flux of friction and the convective heat transfer coefficient were initially calculated accurately according to the theory of heat transmission. Then a pin-on-disk temperature field model was established via the finite element method, and the steady-state temperature distributions for the pin and the disk were analyzed. Due to the influence of the surrounding media on convective heat transfer, the center temperature in any section of a disk or pin specimen was highest and the temperature dropped gradually from inside out. The position farther from the disk center was found with smaller temperature difference from the lubricating oil and smaller temperature dropping gradient. Under the impact of friction heat flow and convective heat transfer, the temperature of the pin-on-disk rose rapidly at the initial stage of friction, then increased at a slower rate, and finally reached a thermal equilibrium. Comparison between simulations and experiments for the average temperature rise at the disk bottom were in good agreement, which proved the correctness of the temperature model. This study provides references for temperature prediction in studying the pin-on-disk friction pair and verifies the feasibility of simulation method for studying the temperature field of friction pair.

1. Introduction

Friction is a complicated phenomenon that is accompanied with energy conversion. About 85%–95% of friction-induced energy is converted to heat energy, besides surface energy, optical energy and acoustic energy [1]. The change of the motion state such as normal load, relative velocity and friction factor can cause variation in friction heat and temperature field. The friction heat and temperature field also have counteractive effects on the friction pair and thereby affect tribological behaviors. The research on friction heat plays an important role in the tribology development.

Le et al. studied the heat transfer over the curved surface of NACA0012 micro-airfoil and the sharp 25–55-deg. biconic by the computational fluid dynamic (CFD) and Montecarlo (DSMC) method. The CFD simulation of heat transfer considering sliding friction agreed well with the DSMC data [2]. Liu et al. analyzed the temperature field of disk-pad friction pair by using FE simulation and LM algorithm regression. The simulated peak temperatures of brake disk at different working states agree well with the regression analysis [3].

Belyakov and Nosko studied the non-stationary heat conduction in two sliding layers with consideration into the time-dependent heat-generation coefficient and contact heat transfer coefficient. They found the time-dependent friction conditions considerably influenced the partition of the friction heat between the sliding layers [4]. Gui et al. developed a numerical method to study the mechanical, thermal and tribological characteristics in dry sliding systems. The simulations of the wear distribution, stress and temperature are all consistent with the experimental results [5].

Many friction and wear mechanisms of materials are still not solved due to the very complexity of tribological phenomena. Tribological studies mainly rely on laboratory tests [6–8]. The pin-on-disk test is a common method to study tribological properties,

Massaq et al. applied pin-on-disk tribometer test to study the tribological properties of woven glass-fiber- reinforced polyamide composites, and found frictional phenomena were more severe when the fibers were vertical to the frictional direction [6]. Through pin-on-disk tests under dry sliding conditions at a constant velocity and different normal loads, Kumar et al. studied the tribological performances of aluminum-based composites containing either SiC or a combination of MoS_2 and SiC [7]. Bahri et al. investigated the mechanical and tribological behaviors of Titanium-nitride coating by the pin-on-disk friction and wear tests [8].

There are many studies on the temperature field of the friction pair. As a widespread and basic method, the thermal tribological characteristic analysis of the pin-on-disk friction pair is especially

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important. However, the pin-on-disk temperature field is seldom studied. Yevtushenko et al. developed an analytical model to study the friction heat distribution between a rotating disk and a vertical stationary cylindrical pin [9]. But there is no comparative analysis of research results.

With the development of the finite element method, numerical simulation of friction pair plays an increasingly important role in the temperature research. Pin-on-disk was studied here based on the theory of heat transmission. A numerical model was then built with consideration into the actual size of the pin-on-disk. The heat transfer coefficient and the friction heat flux were calculated. Steady-state temperature field of the pin-on-disk was determined using the finite element method and the temperature distribution was analyzed. The simulation results and the test results of average temperature rise at the disk bottom were compared, which verifies the correctness of the temperature model and the feasibility of simulation in solving the temperature field problem of the friction pair.

2. Pin-on-disk sliding friction test

Pin-on-disk sliding friction test was performed on UMT-3 Universal Tribometer Test machine by using pin-on-disk samples and at an alternating motion mode. The pin of the upper sample was fixed, and the disk of the lower sample was made in an alternating motion in the range of 1.5 mm in the right and left areas of lower surface of pin sample.

The lubricating system of the UMT-3 test machine is shown in Fig. 1. The disk specimen was placed in the small oil pool located in a large oil pool. The small oil pool was installed with vertically-crossed grooves. The pins passed through the pin pores drilled in advance on the disks, and then were embedded into the grooves. Before the test, the disk specimen was adjusted at the appropriate position. The small oil pool was filled with #150 lubricating oil until the disk specimen was fully soaked and was moving in an oil-rich state.

As the pin-on-disk sliding friction test would guide the research on tribological properties of the locomotive traction gear material, the pin specimen was made of 42CrMo (dimensions showed in Fig. 2) into the driving gear. The disk specimen was made of 17CrNiMo6 into the driven gear. The lower specimen is a $43.2 \times 30.3 \times 5\ \text{mm}^3$ rectangular disk. The material parameters and chemical components of the specimens are given in Tables 1 and 2, respectively.

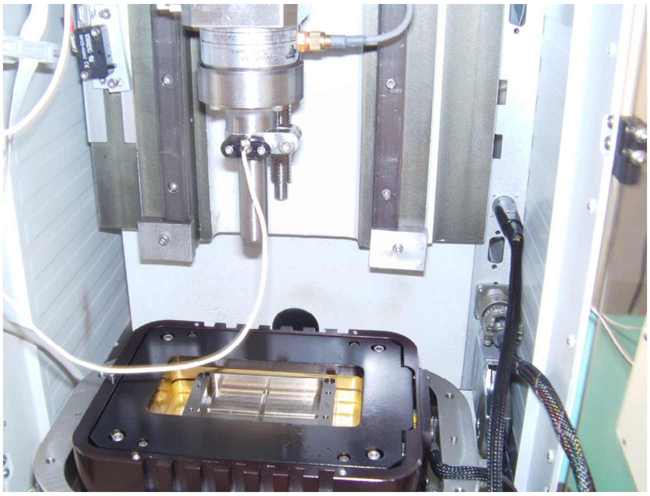

Fig. 1. Lubricating system of UMT-3 test machine.

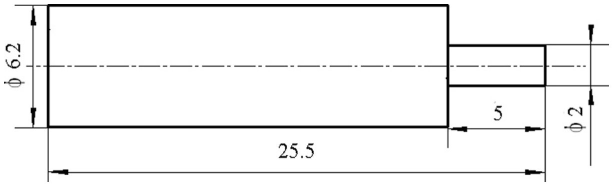

Fig. 2. Dimension drawing of pin.

Table 1
Material parameters of specimens.

Items	Upper specimen (pin)	Lower specimen (disk)
Materials	42CrMo	17CrNiMo6
Hardness/HRC	62.5	61.7
Roughness/μm	0.6	0.6

Pin-on-disk friction tests were carried out under dry sliding conditions at different normal loads of 200, 400, 600, 800 and 1000 N and at different sliding speeds of 30, 120, 210 and 300 mm/s. The loads and velocities were randomly combined to generate 20 groups of test conditions. Tests under each condition were repeated three times to obtain the corresponding average friction coefficient, which was regarded as the friction coefficient under that condition. The results are listed in Table 3.

By regression analysis and significant test, the friction coefficient of the pin-on-disk friction pair (μ) is obtained in [10] as follows:

$$\begin{aligned}\mu = {} & 0.1012 - (4.9635 \times 10^{-5})F_N - (5.9768 \times 10^{-5})\upsilon \\ & + (5.1106 \times 10^{-8})F_N^2 + (7.0669 \times 10^{-9})F_N\upsilon + (2.0189 \\ & \times 10^{-8})\upsilon^2 - (2.0103 \times 10^{-11})F_N^3 - (3.3028 \times 10^{-12})F_N^2\upsilon \\ & - (3.1578 \times 10^{-13})F_N\upsilon^2 - (2.2932 \times 10^{-12})\upsilon^3 \end{aligned} \tag{1}$$

where F_N is the normal load and υ is the relative velocity.

The correctness of Eq. (1) was verified by some groups of pin-on-disk friction test [10]. As indicated by Eq. (1), the friction coefficient is significantly influenced by the normal load and the relative velocity of the friction pair. In the temperature field research, the corresponding friction coefficient under the working condition of the different loads and relative velocities was calculated. Therefore, the friction coefficient in the simulation is closer to the experimental value.

3. Related theories

3.1. Differential equations of temperature field analysis

The temperature field of an object is defined as the sum of instantaneous temperature distributions or temperatures at all points inside the object. The temperature T in a three-dimension nonstable temperature field is mathematically expressed as $T = f(x, y, z, t)$, where x, y, z are the coordinates in a rectangular coordinate system and t is time.

According to the law of energy conservation, a three-dimensional unsteady conductive differential equation for a micro-body is expressed as:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) + q_v \tag{2}$$

where ρ is the density of a micro-unit, c is its specific heat, λ is the heat conduction coefficient of material, and q_v is the generating heat per unit time and volume.