Dynamic correction of IR emissivity for temperature measurement of rubbing surface

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Infrared thermometer could provide IR radiance information to get the corresponding temperature as the machine is working. But the emissivity coefficient, which converts IR radiance to temperature, would vary with change of surface properties during rubbing, and this would bring dynamic error in measurement. In this study, we introduced a special tester, in the side of which compact IR thermometer are mounted. The thermometer enables us to measure contact surface temperature directly during tests of a rotating ring and a flat block which had a laser diode fixed under its contact surface. Based on Kirchhoff theory, the calculate model of the spectral emissivity is constructed. The normal emissivity at target region are measured through trigonometric ray consisted of InGaAsP laser source, PbSe detector and objective surface. So the temperature value from the IR thermometer could be corrected dynamically according to the real-time emissivity. The structure and the principle of the apparatus are described. The key technologies and the corresponding solution methods are briefly discussed. The error due to the rapid variations of emissivity value with change in contact conditions was shown, and it must be taken into consideration in radiometric temperature measurement in rubbing and could be especially useful in the verification of friction surface temperature predictions.

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NOMENCLATURE

L_1 = radiation of rotating ring
L_2 = radiation of known material A
L_3 = radiation of known material B
L_λ = standard blackbody radiation
γ = reflectivity of rotating ring
β = optical reflection correction coefficient
E_λ = radiation of rotating ring
ε_λ = emissivity of ring at wavelength λ

1. Introduction

The parts used in the fields of modern manufacture generally work under the extremely severe service conditions, such as high speed, high temperature and heavy load, which cause friction and wear unavoidably in these conditions. Least material and energy consumption is needed, and this requires a better understanding of the rubbing interface. Damage to either parts or work pieces can occur during such solid-solid contact, but not enough is known about the actual contact conditions. It is very desirable to be able to estimate the surface temperature that is generated by contact heat between a rotating rubbing ring and a flat block. The high temperature in interface, are suspected of softening the binder of harden-layer coated parts and reducing the effectiveness of lubricants on the surface of either oil film or boundary film coated disks. Because of the importance of this problem, some theoretical and empirical studies have been done [1,2], but theoretical analysis could not be applied to numerous or rapid changed rubbing conditions. In practical studies, especially in the examination of limit conditions of materials, such as high temperature, high pressure and micro-scale, it is the best way to acquire the true temperature under the limit working conditions and to analyze the testing results based on the accurate simulation and reproduction of the sliding contact conditions.

Infrared thermography(ITG), sometimes called IR imaging system, provides a quantification of the degradation in thermal performance as the machine are working and can be used to identify degrading parts for replacement before failures become immanent. However, the main difficulty of IR measurements is the necessity of the specimen emissivity knowledge, which varies during rubbing with the surface state and temperature [3-5].

The purpose of this paper is to provide information on the variations of emissivity for more accurate measurement of transient surface temperature during rubbing than other end-face temperature measurement using only thermography [6,7]. The ring surface temperature was studied by using a set of reflecting radiometric detector developed for emissivity variations obtain and an ITG. Thermal phenomena of ring-block in rubbing are correlated to the evolution of normal and tangential frictional force. Finally, the values of the surface emissivity are reintroduced in the measures obtained by the ITG which allows estimating the measurement errors of surface temperature due to the variable emissivity.

2. Experimental

2.1 Conditions

Surface friction experiments were carried out on an end-face friction and wear test machine which having a load resolution of 0.1N along the vertical axe and speed resolution of 1 rpm in rotation. A steel ring, with hardness of HRC 45, was used to slide on a copper block. The block diameter (Φ27 mm) was designed to be larger than the diameter of the ring (outer: Φ25 mm and inner: Φ20mm) in order to ensure the contact between the ring and the block extended to the block edge. Ring speed was kept constant at a range of 100~1000 rpm, while the maximum linear speed is 1.31 m/s. All rubbing experiments were done under dry condition.

In this study, the surface temperature field was measured dynamically to assess friction temperature. Forces were measured continuously during experiment to estimate the heat generated in the friction zone and to explore the dependences of temperature on both normal pressure and relative speed.

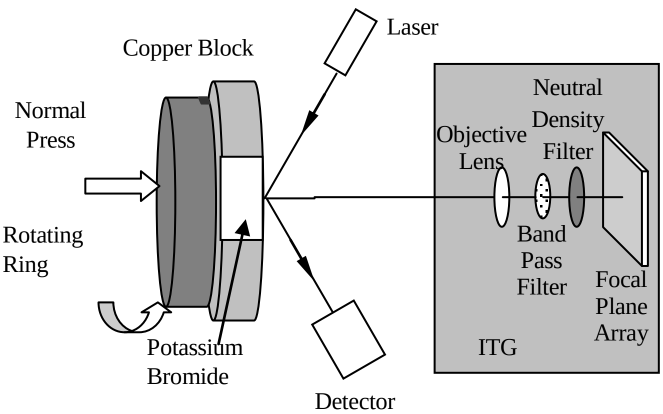

Fig.1 Schematic of the set-up used for friction temperature measur ement.

2.2 Set-up

A schematic of the experimental set-up is shown in Fig. 1. During rubbing experiments, temperature measurements on the ring surface were performed through this potassium bromide (HW-7) transparent 'window'. The HW-7, which was polished along with the block surface, also prevented the accumulation of wear debris, thereby making the disc surface accessible for measurements during rubbing. Potassium bromide was chosen for two main reasons: first is its high transparency in infrared spectra (94% for 1-3 μm); second is its suitable capacity for wear, which ensured that the whole block surface would wear down at the same average rate to prevent the heterogeneous load distributions. Indeed, the HW-7 occupied less than 8% of the total rubbing area. Also, its thickness of 5 mm was chosen as a compromise between the capacity to absorb infrared radiation and mechanical strength.

A medium wavelength, high-speed ITG (made by FLIR Systems) was used to measure the radiation being emitted from the window. The ITG consists of a CCD detector array and an infrared micro-scope assembly. The objective lenses were made of semiconductor materials viz. silicon (Si) and germanium (Ge). These lenses focus the infrared radiation onto a two-dimensional focal plane array (FPA) of 320×240 detectors, effectively creating an image of the source on the FPA. The FPA is a two-dimensional CCD array of indium antimonide (InSb) detector elements (pixels) that are highly sensitive to radiation in the medium-wavelength infrared range, allowing a temperature change as small as 0.025℃ to be detected in a black body. The size of single pixel is 30μm×30μm, with a total field range of 6.1 × 4.6 mm. The pixels of the FPA have a time constant low enough to enable system operation at shutter speeds as small as 50μs, which allows observation of transient events. A band-pass filter (Fig. 1) is fitted into the microscope assembly to cut off radiation outside the spectral range of 3.16-3.80μm. A neutral density (ND) filter is also incorporated into the optical path at the rear of the lens assembly (Fig. 1) to attenuate the amount of radiation incident on the FPA. The increase of the maximum temperature can be measured by ITG. The ND filter used in the experiments allowed 1 percent of the radiation incident on it to pass through, enabling a maximum temperature of approximately 700℃ to be measured when the paint-coated specimens was in friction. This maximum temperature value can be increased to well over 1000℃ by using an ND Filter of lower transmissivity (0.1%). The ITG could be operated at framing rates of up to 100 frames per second by sacrificing either the field of view or the spatial resolution. An integration time of 6 ms and a frame rate of 50 frames per second were used to capture a full-Field image of 6.2 × 4.6 mm with 18μm spatial resolution. Details of the measurement set-up are shown in Fig. 1.

The normal emissivity at target region are measured through trigonometric ray consisted of InGaAsP laser source, PbSe detector and objective surface. The reflection spot was placed on the average sliding radius (11.3mm) at the ring-block contact centre of the ITG observed area. When the laser source emit constant wavelength beam, the detector will give the ring radiation [8].

$$L_1 = \varepsilon_\lambda L_\lambda + \gamma\beta E_\lambda \quad (1)$$

Where the $\varepsilon\lambda$ is the emissivity of ring at wavelength λ, $L\lambda$ is blackbody radiation at wavelength λ, γ is the reflectivity of ring, β is optical reflection correction coefficient and $E\lambda$ is the energy on ring surface from laser. Use two known emissivity material (A and B) as reference objects, prior to experiments, to get the radiations from detector:

$$L_2 = \varepsilon\lambda L_\lambda + \gamma A\beta E_\lambda \quad (2)$$

$$L_3 = \varepsilon\lambda L_\lambda + \gamma B\beta E_\lambda \quad (3)$$

From the above three simultaneous equations, the reflectivity of ring could be determined:

$$\gamma = \frac{L_1 - L_2}{L_2 - L_3}(\lambda_A - \lambda_B) + \lambda_A \quad (4)$$

Based on Kirchhoff theory[8], the ring emissivity can be calculated with:

$$\varepsilon = 1 - \gamma = \frac{L_2 - L_1}{L_2 - L_3}(\lambda_A - \lambda_B) - \lambda_A + 1 \tag{5}$$

with $\lambda_A=1-\varepsilon_A$ and $\lambda_B=1-\varepsilon_B$.

Knowing the transient emissivity, it is possible to correct the temperature value at each pixel in image observed by the ITG. Furthermore, the temperature at the subsurface can be obtained by extrapolation from the surface values.

3. Conclusions

Fig. 2 illustrates the evolution of the emissivity on the average radius of the sliding track. This emissivity is calculated from the signals obtained by detector. It can be observed that emissivity decreases rapidly from a value of ~0.55 at begin to ~0.4 at t=6 min. The emissivity then increases and stabilizes around 0.55 with fluctuations of ~0.25.

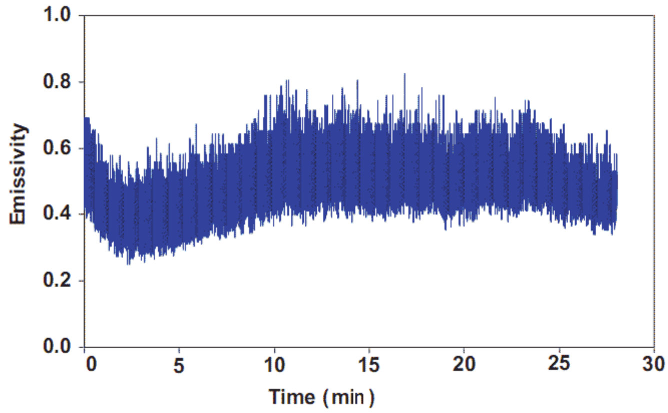

Fig.2 Evolution of the surface on the average radius of the slidi ng track emissivity

In order to correct the temperature measured by the ITG, the v alue of the surface emissivity is reintroduced in the post-treatment of measurements obtained by the ITG. Fig. 3 gives the two corre sponding temperature profiles on the average radius of the sliding track; one was calculated with emissivity 1 (blackbody behavior o f the ring) while the second was calculated with emissivity equal t o 0.44 (value measured and calculated by the laser and detector). It can be clearly seen that the correction of the ITG temperature, by using the corrected emissivity value, allows one to significantly reduce the error on measured temperature. The corrected visualiza tion of the thermography film shows the temperature of ring at ti me 15min from HW-7 window (Fig. 4).

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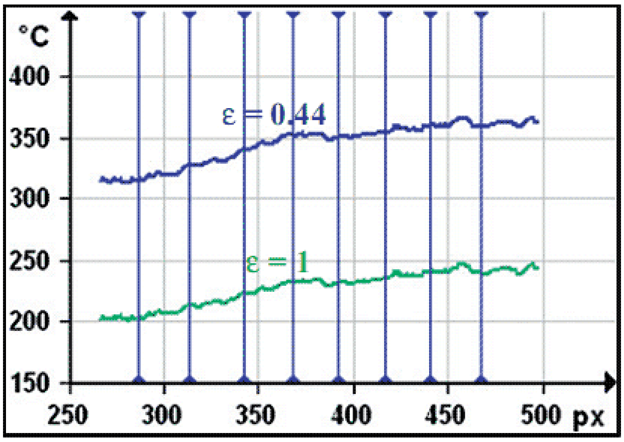

Fig.3 Temperature profiles with different emissivities

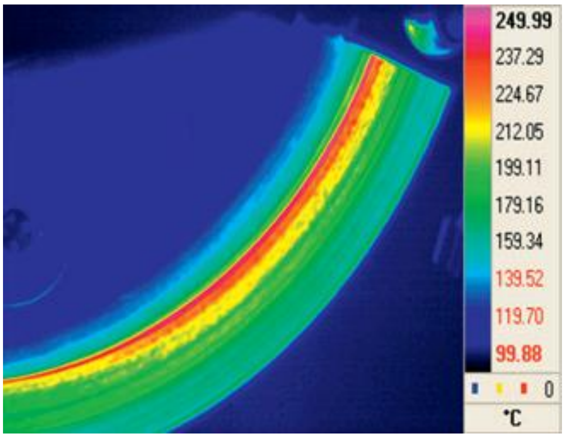

Fig.4 Corrected flase color ITG image of ring

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