Quantitative measurements of sliding friction coefficients of tribological interfaces with a new differential infrared radiometric instrument

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Experimental sliding friction coefficient (SFC) measurements using a mechanical friction rig and infrared radiometric emission data from a novel instrument monitoring radiant heat generation at the tribological interface of the rig are described. The infrared radiometric (IRM) system features thermal-emission-intensity harmonic modulation with background-radiation-compensating wave forms, leading to differential signal operation mode and suppression of ambient radiation. The mechanical friction rig was used to generate friction between pairs of moving and stationary samples and to provide reference normal-force and friction-force measurements. Correlations between the lock-in amplifier readouts and the SFC data obtained simultaneously from the mechanical system have been established. The ratio of SFCs from adjacent steel surfaces with and without a lubricant film was accurately measured by the IRM instrument. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1517163]

I. INTRODUCTION

A high-detectivity infrared radiometry-based thermometric instrument, which features background-radiation suppression through the use of a differential mechanical chopper, has been developed.[1] The signal generation principle of this instrument depends on thermal (blackbody) emission of Planck radiation from a heated interface or neighboring locations. Friction can cause a temperature rise at the contact points or surfaces and through heat conduction to the bulk of tribological interfaces, it can generate a measurable radiation heat transfer field at the sample surface exposed to the ambient according to Stefan's law. For small temperature increments, a linearized form of Stefan's law may be used.[2]

II. INSTRUMENTAL DESIGN FOR SLIDING FRICTION COEFFICIENT MEASUREMENTS

Figure 1 is an overview of the differential infrared radiometric (IRM) thermometric instrument, as modified from our earlier report[1] in order to monitor moving tribological interfaces. In the system, two ellipsoidal-arc mirrors were focused on two spatially separated spots on a sample surface, and were used to collect the radiation flux emitted from each spot. The upper mirror was focused on a reference spot on the same sample, approximately 5–6 mm above the friction-heated interface. This distance was assumed (and experimentally proven) to be sufficiently remote from the moving interface, so that any temperature rise from conduction heat transfer from the heated area was negligible for the duration of each frictional motion experiment (~5 min). Thus, infrared (IR) signals collected from the reference location were only due to the background (ambient) temperature and surface thermal fluctuations of the moving sample when both frictioning materials were at rest or in relative motion.

A specially designed differential mechanical chopper blade allowed radiation from one spot to enter the IR detector during 50% of the selected intensity-modulation period through an opening (slot) subtending an arc of 180°. During the remaining 50% of each period, radiation from the other spot entered the detector through a second slot, which also subtended an arc of 180°.[1]

The output of the IR detector was preamplified and fed into a lock-in amplifier (LIA) for demodulation and the output signal was stored in a personal computer (PC). A characteristic figure-of-merit was defined for the background thermal IR emission suppression efficiency of the radiometric temperature-measuring instrument as the ratio of the LIA signal from the single-slot mechanical chopper to that obtained with the double-slot (differential) chopper and was estimated to be 159.9 ± 8.5.[1]

A mechanical friction rig, on the side of which the IRM system was mounted, was used as the friction-generating assembly for testing the friction-measuring capabilities of the IRM instrument.

III. EXPERIMENT AND RESULTS

All components of the IRM instrument were mounted on an optical breadboard, which was attached to one side of the moving sample carriage in the friction rig system. In this manner, the entire IRM system assembly moved along with the moving interface, so that both ellipsoidal-mirror foci remained fixed with respect to the observation coordinates on the (upper) moving sample to detect the IR radiation from

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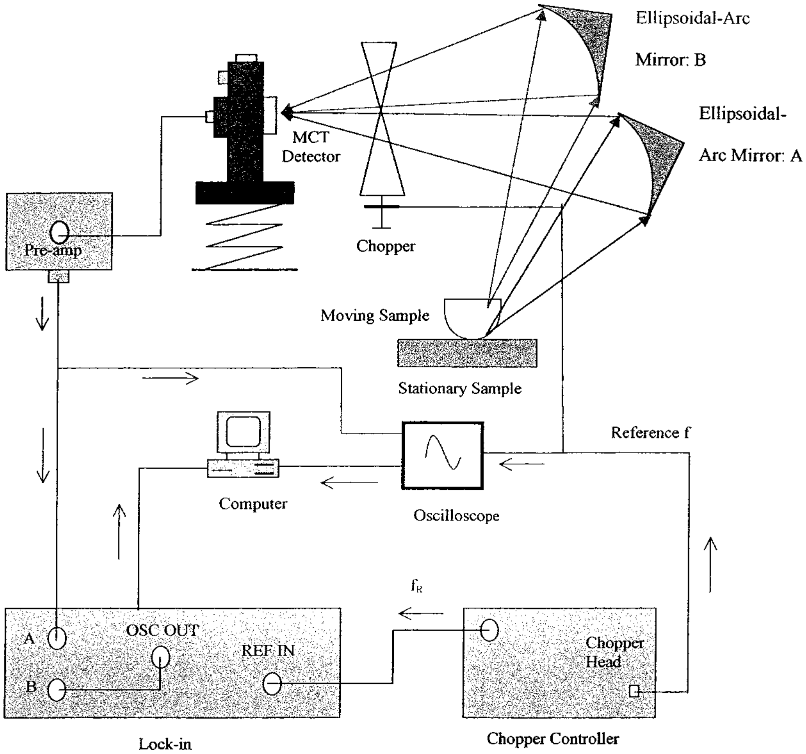

FIG. 1. Experimental setup of the differential infrared radiometric thermometer.

the relative temperature rise produced by friction. The temperature of the reference point, Fig. 1, barely (~0.05 °C) rose above the ambient base line, thus validating the use of that coordinate point for differential IRM measurements. The motion speed selected for the experiments was 5.0 mm/s. The normal loads were fixed at 10, 20, 40, and 50 N. The differential thermal IR signal from the interface and reference points was fed into the LIA (filter time constant $\tau_{RC} = 1$ s) and the time evolution of the demodulated amplitude was recorded and stored in the PC. Frictional heat was generated by the flat-strip contact of the curved side of the cylinder on the flat stationary sample surface. For generating frictional heat with a nominally homogeneous interface, both moving and stationary samples were made of commercial aluminum 6061-T6. In order to assess the IR base line signal level, the LIA amplitude was recorded during the 10 s prior to the onset of the mechanical motion of the frictioning parts.

The friction coefficient was measured using the load-cell readings at various normal-force loads. Typical results using a fresh sample surface (i.e., with no prior frictional contact) for $F_N = 20$ N are shown in Fig. 2. From that figure in can be seen that the LIA amplitude increases immediately after the onset of frictional contact at $t = 0$, although not always monotonically, and eventually saturates within the time scale shown in the figure after the end of the frictional motion. At long time scales (~5 min) the transient curve slowly returns to the base line value. The spikes observed in the rising portion of the transients are unique to each frictional run and, therefore, cannot be associated with instrumental effects. Furthermore, it is important to note that, upon reversal of the frictional motion, from the end point to the starting point, the fast rise time of the LIA signal was followed by rapid decay with time constant on the order of the rise time (not shown here). Postscan visual and microscopic inspection of the contacted surfaces showed evidence of mechanical deformation ("grooving") of the flat stationary sample already after the first frictional run for all values of F_N. Some material accumulation or deformation on the cylindrical moving surface was also visually evident. This type of wear has been reported previously by Blau[3] and was given the designation "*highly deformed layer due to subsurface ductile fracture*."

Additional experiments were performed to monitor the IRM instrumental sensitivity to abrupt changes in the sliding friction coefficient (SFC) across the tribological interface. Steel type 52100 was used for both stationary and moving samples. Part of the surface of the stationary sample was coated (lubricated) with Teflon. Figure 3 shows a typical ex-

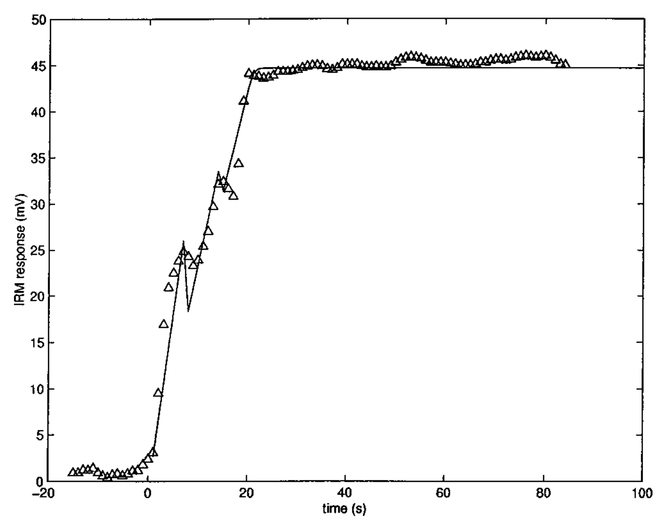

FIG. 2. (△): Experimental IRM time transients from an Al 6061-T6 tribological interface with $F_N = 20$ N. (−): Theoretical fits using thermal diffusion model. Duration of frictional motion: $\tau = 20$ s.

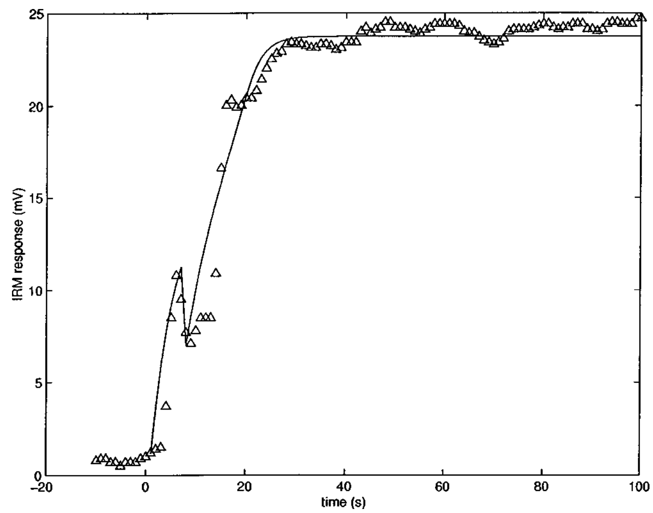

FIG. 3. (△): Experimental IRM time transients from a steel 52100 tribological interface with $F_N = 50$ N. (−): Theoretical fits using thermal diffusion model. Time to crossing the steel–Teflon interface: $t_i = 7$ s. Duration of frictional motion: $\tau = 17$ s.

perimental time record similar to that in Fig. 2, at normal force of 50 N and motion speed $V = 5$ mm/s. Here the smoother Teflon surface was reached at $t_i = 7$ s from the onset of the frictional motion. A sharp decrease in the IRM signal is shown right after the upper surface crossed over onto the Teflon-coated steel. Unlike the spikes of Fig. 2, the sharp feature of Fig. 3 was reproducible and can be definitely associated with an abrupt change in the sliding friction coefficient across the steel–Teflon interface. Figure 4 shows the mechanical-rig generated time record corresponding to the

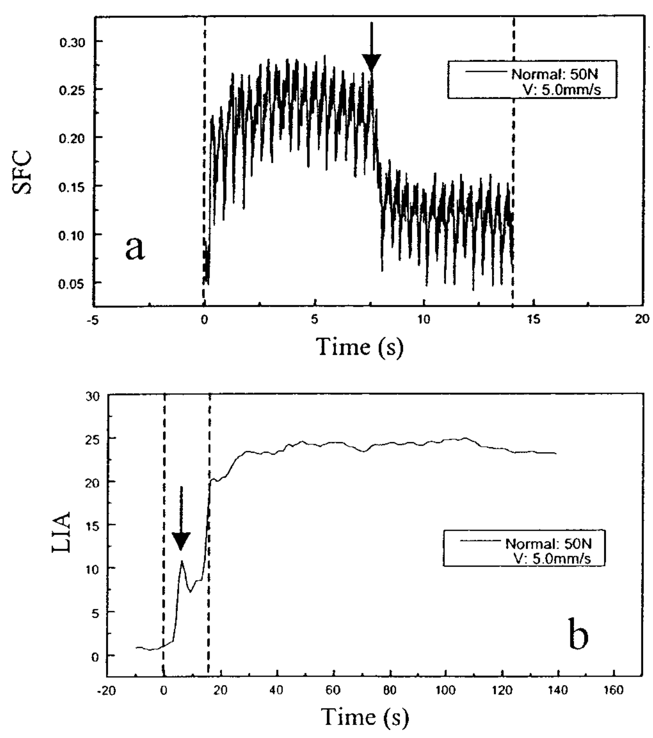

FIG. 4. Comparison of the mechanically measured SFC (a), and the IRM LIA amplitude time record (b) of a 52 100 steel-lubricated-steel interface at $F_N = 50$ N. The steel–Teflon-coated-steel interface is indicated by the arrows (lubricated steel lies to the right of the interface).

TABLE I. Average values of the SFC between two Al 6061-T6 surfaces measured at various normal forces and speed $V = 5$ mm/s.

F_N (N)	10	20	40
$\langle \mu(t) \rangle$	0.63±0.13	0.54±0.09	0.47±0.11

IRM trace of Fig. 3. The record is that of the time-dependence of the SFC and was derived in real time from ratios of the horizontal and normal force-monitoring load-cell outputs at a normal-force load of 50 N. That is, $\mu(t) \equiv F_F(t)/F_N(t)$ is the SFC. The trace on Fig. 4 is the simultaneously recorded IRM LIA amplitude time-record corresponding to Fig. 3. The duration of the frictional motion is indicated with dashed vertical lines and the crossover instant from the steel surface onto the Teflon-coated surface is indicated with upside down arrows. In Fig. 4, a sharp decrease in the sliding friction coefficient following the crossover onto the lubricated surface is clearly seen and is correlated with the simultaneous decrease in the IRM signal. Similar correlations between mechanically measured $\mu(t)$ and IRM transients were observed for other values of the motion speed V (not shown). The correlated signal drops were absent from comparison time records from nominally uniform interfaces, such as those of Fig. 2.

IV. IRM SFC DATA ANALYSIS AND DISCUSSION

The sliding friction coefficient between two contacting surfaces of Al 6061-T6 has been reported to be 0.34,[4] a number, which is in good agreement with the time-averaged values $\mu \equiv \langle \mu(t) \rangle$ obtained from the mechanical-rig measurements of F_N and F_F in this work, considering the usual difficulties in comparing data from different tribological surfaces even between nominally the same materials.[5] The values of SFC under the full range of normal-force values, averaged over the duration of the motion of the mechanical platform, are given in Table I. A thermal diffusion model of the moving interface which includes an advancing interface layer was developed and used to fit the experimental data. Figure 2 shows the best fit of the thermal-diffusion model to the experimental IRM data transients.

For the $F_N = 50$ N case of Fig. 4, the rising transient was best fitted (while ignoring the early sharp spikes), by assuming that a layer of average thickness $z_i = 0.7$ mm was built up essentially from the onset of the frictional motion. The thickness of this compact layer had to remain constant throughout the motion. This picture of the sudden "appearance" of an interfacial layer upon the onset of the frictional motion is physically plausible and consistent with the well-known effects of mechanical impact with "asperities" between nonideal metallic surfaces.[6,7] It is also consistent with visual inspection of the smoothened groove left behind the cylindrical moving part onto the stationary underlayer, and with a small accumulation of metal left at the far end of the frictional travel.

The flexibility of the theoretical model to allow for arbitrarily many and different linear growth rates, during the tribological motion of the two surfaces was found to be very useful toward a sort of reconstruction of the interface thickness growth history, including taking account of the observed sharp spikes. In Fig. 2 we were able to adequately reproduce the two major spikes during the motion.

Let μ_2, μ_1 be the SFCs of the second and first stationary surface, respectively. A sharp IRM signal slope change is expected as the moving surface crosses over to the second stationary underlayer due to the thermal flux discontinuity. Then if $\mu_2 > \mu_1$, a signal increase is anticipated. If $\mu_2 < \mu_1$, a corresponding decrease is expected, thus leading to a local IRM signal peak, as shown in Fig. 3 at $t = 7$ s. From the ratio of the SFCs on the steel and on the Teflon-lubricated steel side of the interface at $t = \tau_{21} = 7$ s in Fig. 4, it is found that $\mu_2/\mu_1 = (0.12 \pm 0.2)/(0.24 \pm 0.2) = 0.5 \pm 0.28$, in agreement with the IRM value. The measurement of the IRM value of μ_2/μ_1 is, however, improved by a much higher signal-to-noise ratio over the mechanical value, as easily seen from a comparison of the noise levels in Fig. 4. Although the discontinuity feature in Fig. 3 is capable of yielding accurate ratios of SFCs between two consecutive spatial regions, the absolute value of μ can only be inferred from knowledge of the values of F_F and F_N.

V. CONCLUSIONS

In conclusion, a novel infrared thermometric instrument (IRM) based on radiometric detection of thermal radiation was adapted to the measurement of sliding friction coefficients at tribological interfaces in conjunction with a mechanical friction rig. The IRM experimental data from contacting Al–Al 6061-T6 surfaces were fitted with a theoretical heat conduction model, which includes an advancing interface layer, in order to simulate the compact metal layer thickness generated by mechanical friction at the contact interface. As a result of the theoretical fits, the time-dependent thermal properties of the growing interfacial layer were determined and the maximum signal level was found to be consistent with the average value of the frictional force $F_F = \mu F_N$, as measured by the load cells of the mechanical friction rig. Using the combined theoretical and experimental methodology, the quantitative monitoring of the otherwise difficult or impossible-to-observe kinetics of interfacial material changes under frictional motion has become possible. Furthermore, the IRM was shown to be sensitive to tribological changes across the stationary material interface between surfaces with different SFCs, yielding the ratio of the SFCs on both sides of the interface. The theoretical model predicted the SFC ratio fairly accurately and with higher signal-to-noise ratio than the simultaneous load-cell measurements by the mechanical rig. Appropriate calibration curves of the IRM system can be produced through knowledge of the normal force, F_N, and can be used to yield quantitative values of the SFC.

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