Determination of interfacial temperatures under extreme pressure conditions

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Interfacial temperatures attained in a pin and v-block apparatus under extreme pressure (EP) conditions were measured using pins made from either copper or an aluminum alloy from the asymptotes in the curve of removal rate versus applied load since these have been shown to correspond to the temperatures at which the interfacial material melts. The interfacial temperature rise was proportional to the applied load, where the proportionality constant $\alpha = A\mu$ where μ is the interfacial friction coefficient and A a geometrical constant which has been previously measured for steel pins and v-blocks lubricated by chlorinated hydrocarbons dissolved in a poly α-olefin as 2.3 ± 0.3 K/N. Values of A measured when using the aluminum alloy (2.4 ± 0.1) and for copper (2.1 ± 0.2) were in good agreement with this measurement and indicated that interfacial temperatures in excess of 1000 K can be attained during EP lubrication. Finally, the rate of material removal in the pin and v-block apparatus can be related to the metallurgical properties of the pins.

Keywords: extreme pressure lubrication; pin and v-block apparatus; temperature measurement

1. Introduction

It has been demonstrated previously that chlorinated hydrocarbon extreme-pressure (EP) lubricant additives operate by thermally decomposing at the hot solid–solid interface to deposit a layer that consists of either an iron chloride that incorporates small carbonaceous particles [1,2] or, at higher interfacial temperatures, an iron carbide film [3,4]. This layer is continuously formed by reaction of the

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chlorinated hydrocarbon additive with the lubricated interface and also removed due to the relative motion of the two surfaces, the resulting steady-state film thickness arising from a balance between these two processes [5]. A simple theoretical calculation [6] shows that the interfacial temperature during a pin and v-block experiment should vary linearly with the applied load as:

$$T = T_0 + \alpha L, \tag{1}$$

where T_0 is the ambient temperature, L the applied load and α a constant. It can be shown [6] that the constant α is given by $\alpha = Kr\mu\omega$, where K is a constant that depends on the thermal conductivity near the interface, r the pin radius, μ the interfacial coefficient of friction and ω the angular velocity of the pin. Lubrication failed, i.e., the pin and v-blocks seized together, when the interfacial temperature reached some critical value T_c, as determined from measurements of the temperature *close* to the interface. This occurred at some critical load L_c (the seizure load) so that this temperature and load are related by:

$$T_c = T_0 + \alpha L_c\,. \tag{2}$$

Since the critical temperature is a well defined quantity, measuring the variation of the seizure load as a function of the ambient temperature, T_0, can be used to determine both the constant α and the critical temperature. Such measurements led to a value of $\alpha = 2.5 \pm 0.3$ K/kg and a value of T_c of about 940 K, the melting point of iron(II) chloride [13,15].

Other strategies have been used to measure the temperature at the interface during lubrication. Early work used a pin-on-disk configuration where the pin and the disk were made from different materials with relatively large thermoelectric constants so that the temperature could be measured directly [7]. The results of these experiments showed that the interfacial temperature rise indeed varies in direct proportion to the applied load and reaches a plateau at the melting temperature of the lowest-melting-point material. In this case, since the softer material is continuously deposited onto the harder material, care was taken to ensure that the desired thermocouple junction and the tribological interface are identical. This was done in the pin-on-disk configuration by measuring the temperature using different parts of the disk. Note that this strategy is inherently impossible in the pin and v-block apparatus.

Another strategy that has been applied to the measurement of interfacial temperature involved monitoring the infrared emission from near the interface and to apply black-body radiation laws to determine the temperature. This strategy has been successful in measuring temperatures during machining and, in some cases, a maximum temperature was attained corresponding to the melting temperature of a fully hardened AISI D3 steel using cubic boron nitride tooling [8]. This strategy, although in principle possible in the pin and v-block apparatus, is rather difficult since the apparatus is immersed in a hydrocarbon fluid (a poly α-olefin) so that careful corrections must be made for fluid absorption. A different strategy for further confirming the interfacial temperature during extreme pressure lubrication has therefore been adopted. It has been shown that the wear rate during extreme pressure lubrication is strongly dependent on the applied load and tends asymptotically to infinity when the interface reaches the melting point of one of the major components of the interface [9]. This is relatively easy to understand, since the removal rate per unit sliding length has been given by Archard (and modified by others) as:

$$r = BL/S\,, \tag{3}$$

where B is a constant, L the applied load and S the shear strength at the interface [9,10]. S depends on temperature and its dependence is given by:

$$S = S_0 \ln(T_{\mathrm{m}}/T)\,, \tag{4}$$

where T_{m} is the interfacial melting point and S_0 a constant [11]. Combining eqs. (3) and (4) shows that the removal rate becomes infinite as the interface melts. Clearly, this is because the liquid formed at the melting temperature is extremely rapidly removed from the surface. This phenomenon is exploited in this work by using pins of known material (with known melting point) which are softer than the steel of the v-block so that this soft material is deposited onto the v-block. The removal rate is then measured as a function of the applied load and any asymptote in this curve corresponds to the melting temperature of the material of the pins. In the following both pure, "electrolytic" copper and an aluminum alloy (5052 H32; 95.7% aluminum minimum) are used for this purpose. Note that, in the case of aluminum especially, the surface is likely to consist initially of an aluminum oxide. This will, however, be rapidly removed under the typical high loads used here, exposing an aluminum surface. Finally, it should be noted that calibrating the interfacial temperature using the melting point of a known material most closely corresponds to the physical processes occurring during extreme-pressure lubrication. Lubrication often fails when the interfacial lubricating film melts.

2. Experimental

Experiments were performed using a pin and v-block apparatus where a pin which rotates at 290 rpm is clamped between two v-shaped blocks. In this study, pins were made from either copper or an aluminum alloy and the v-blocks are in all cases made from AISI 1137 steel and therefore harder than both the aluminum alloy and copper pins [12]. The pin and v-blocks were immersed in a poly α-olefin lubricating fluid and run for a period of 600 s at a constant applied load [6]. In previous cases, when steel pins were used, the amount of wear was measured from the width of the wear scar formed on the face of the v-block. In this case, since the pins are of much softer material than the v-blocks, the v-block wear was negligible, whereas the pin suffered significant wear. The amount of wear was evaluated in this case from a change in diameter of the pin after each experiment using vernier calipers. The experiments were repeated for various applied loads. The surface of the v-blocks was also analyzed using Auger spectroscopy after loading at 1010 N for copper and 2350 N for the aluminum alloy to confirm that either copper or aluminum had been transferred onto the face of the v-block. In the case of copper, such material transfer could also be determined visually. Finally, since the temperature coefficient α in eq. (1) depends on the coefficient of friction of the interface, the μ value was determined directly from the slope of the plot of torque versus applied load.

Auger spectra were collected using a Varian vacuum chamber equipped with a single-pass, cylindrical-mirror analyzer incorporating a normal-incidence electron gun. Spectra were collected using an incident current of $\sim 6\ \mu$A with a 3 kV beam energy.

3. Results

Fig. 1 displays a plot of the rate of material removal when a copper pin in an pin and v-block apparatus is used. Wear rates were determined from the change in the pin diameter. The surface of the v-blocks was covered with a copper film as detected both by an Auger analysis of the surface and also from visual inspection. It

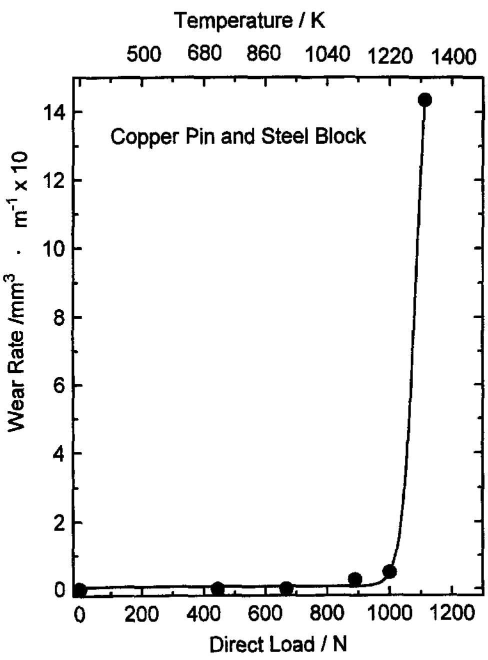

Fig. 1. Plot of removal rate (amount of material removed in 600 s) versus applied load when using a copper pin immersed in poly α-olefin.

is clear that the rate of removal of material is rather low for low applied loads and increases extremely rapidly as the load increases, reaching an asymptote at a value of about 1150 ± 25 N applied load. The corresponding plot of torque versus load when using the copper pin is shown in fig. 2 indicating a clear linear relationship. The slope of the plot yields the interfacial coefficient of friction as 0.44 ± 0.04 (slope $\times$ 117 m^{-1}, [14]). A corresponding set of data when using the aluminum alloy as the pin are shown in fig. 3 indicating again that the wear rate at low loads is relatively small and increases rapidly with applied load to reach an asymptote at a value of 2500 ± 100 N. The corresponding plot of torque versus load is shown in fig. 4 and leads to a value of 0.093 ± 0.003 for the coefficient of friction. Auger analysis again indicated transfer of aluminum from the pin to the v-blocks.

4. Discussion

The constant α in eq. (1) has been measured previously to be 0.25 ± 0.03 K/N for steel pins lubricated by a fluid consisting of a chlorinated hydrocarbon dissolved in a poly α-olefin [13]. This value is given theoretically by $\alpha = Kr\mu\omega$ (see above) so depends on the interfacial coefficient of friction. The values K, r and ω are kept essentially constant during the experiment so that the equation can be written as $\alpha = A\mu$ where the constant A is approximately the same for all materials. Note that slight differences may be expected in the value of K, depending on the

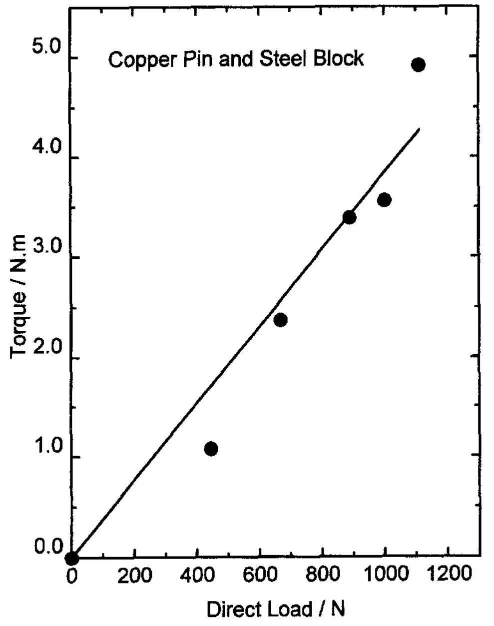

Fig. 2. Plot of torque versus load when using a copper pin immersed in poly α-olefin.

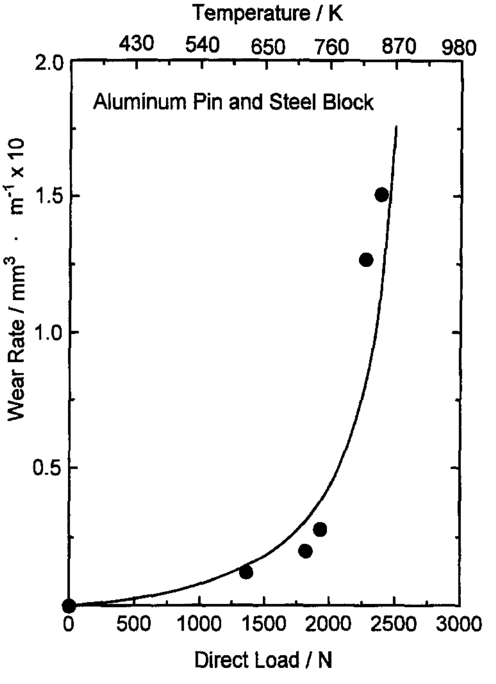

Fig. 3. Plot of removal rate (amount of material removed in 600 s) versus applied load when using an aluminum pin immersed in poly α-olefin.

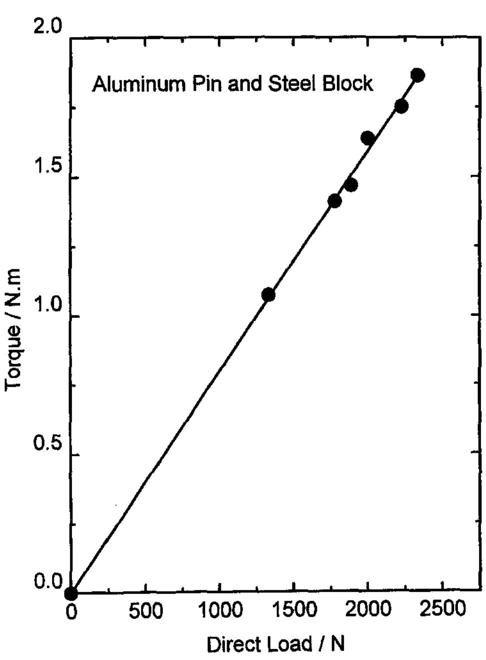

Fig. 4. Plot of torque versus load when using an aluminum pin immersed in poly α-olefin.

thermal conductivity in the region of the interface but this should only have a slight effect on this constant. A value of A is calculated from previous results [14] as 2.3 ± 0.3 K/N for interfaces lubricated by an iron chloride layer.

The data of fig. 1 for a copper pin and steel v-block show an asymptote at 1150 ± 25 N so that the interfacial temperature at this applied load corresponds to the melting point of copper, 1358 K [15]. This directly yields a value of α (eq. (1)) for the copper pin of 0.090 ± 0.02 which must be corrected for differences in the interfacial coefficient of friction measured from the data of fig. 2 to yield a value for A. Using the value of α measured above yields $A = 2.1 \pm 0.3$, a value consistent with that measured previously.

A similar strategy for the data obtained with the aluminum pin, which has a melting point of 880–920 K [12], yields a value of α of 0.23 ± 0.01 and similarly, using the corresponding coefficient of friction (fig. 4), leads to a value of $A = 2.5 \pm 0.2$, again in very good agreement with previous values. These results suggest that the calibration used to measure the interfacial coefficient of friction for the interface lubricated by an iron chloride film is valid.

Note that, paradoxically, the highest direct load for aluminum (2500 N, fig. 3) results in a lower interfacial temperature than when using copper. This arises from the much higher interfacial coefficient of friction for copper than for aluminum. A similarly high and relatively constant value for copper (0.42) has also been observed by others under extreme pressure conditions using a heated-ring compression test where the interface attained the elevated temperatures proposed here [16]. Similar testing on another aluminum alloy (7075) shows a range for coefficient of friction of 0.04–0.15 under various conditions [17]. Note that this range spans the value of 0.093 found in our pin and v-block experiments. The variation in the internal coefficient of friction for aluminum with temperature [16] as well as the compositional differences from our 5052 alloy make direct comparisons difficult, however. The formation of at least some thermodynamically allowed carbide [18] or the presence of some other hydrocarbon reaction film or polymer which lowers μ and prevents some adhesive wear cannot be ruled out. Note, however, that the higher initial wear rate for this aluminum alloy compared with copper suggests that this is a minor effect, which is strongly dependent on the shear strength of the metal (see below).

The data can be treated more fully to take account of the shape of the curve. The wear rate is proportional to L/S (eq. (3)), where S varies as $\ln(T_m/T)$ (eq. (4)) and the interfacial temperature varies with load as $T_0 + \alpha L$ (eq. (1)). These can be combined to yield an overall variation in wear rate W with applied load as:

$$W = BL/\ln(T_m/(T_0 + \alpha L)) \,. \tag{5}$$

The value of T_0 is fixed at the ambient or bath temperature (322 K) and T_m is the melting point of the pin material so that the data are fitted using a non-linear least-squares program with two parameters, B and α [19]. The resulting fits are plotted as solid lines on the data of figs. 1 and 3. This leads directly to values of α for the copper pin of 0.92 ± 0.02 and for the aluminum alloy pin of 0.22 ± 0.01, in good agreement with those measured from the asymptote except that these now use all of the data and therefore are likely to lead to more accurate results. Using the values of interfacial coefficients of friction (figs. 2 and 4) gives $A = 2.1 \pm 0.2$ (Cu) and 2.4 ± 0.1 (Al), in good agreement with values measured from the asymptote and also in good agreement with the values measured previously for an iron halide layer (2.3 ± 0.3). The resulting temperature scales are marked on the top axes of figs. 1 and 3.

Further confirmation of the importance of the interfacial shear strength is found by comparing either the curvature or the initial slopes of the curves of wear rate versus applied load. The theoretical initial slope for the removal-rate curve $R_r = \mathrm{d}W/\mathrm{d}L|_0$, where W is the wear rate and L the applied load, is given by [10]:

$$\frac{\mathrm{d}W}{\mathrm{d}L}\Big|_{L=0} \propto \frac{w}{H}, \tag{6}$$

where w is the dimensionless wear coefficient and H the material's hardness. If w is considered to be identical for the two metals (since this represents a probability of wear particle generation due to adhesion) as proposed by others [20], and assuming that $H \propto \sigma$, the yield strength of the materials, then the ratio of the initial slopes of the copper and aluminum wear curves is given by:

$$\frac{R_r(\mathrm{Al})}{R_r(\mathrm{Cu})} = \frac{\sigma(\mathrm{Cu})}{\sigma(\mathrm{Al})}. \tag{7}$$

A range of values of $R_r(\mathrm{Al})/R_r(\mathrm{Cu})$ from 0.63 to 0.68 can be calculated using nearly the entire range for σ, from partially to fully work-hardened, for these metals [12]. The corresponding experimental values can be found by differentiating eq. (5) and calculating the value at $L = 0$ yielding $\mathrm{d}W/\mathrm{d}L|_0 = B/\ln(T_m/T_0)$, where T_m is the melting point of the pin material (1357 K for Cu; $\sim$ 900 K for the Al alloy). T_0 is the bath temperature (322 K) and the values of B are obtained using the fit to the experimental data (figs. 1 and 3) yielding $(2.28 \pm 0.05) \times 10^{-5}$ mm^3/(N min) for copper and $(2.52 \pm 0.05) \times 10^{-5}$ mm^3/(N min) for aluminum. The ratio of these values then is 0.645 in excellent agreement with metallurgical predictions above for these metals (0.63–0.68).

In order to further verify the validity of the use of shear strength and its temperature dependence in eq. (4), the ratios of S_0 for the aluminum alloy and copper from the experimental data were compared with calculated values of this quantity. In the derivation of eq. (4) [11], it is shown that $S_0 \propto \rho \Delta H_f$, where ρ, the density, and ΔH_f, the heat of fusion, are the only material-dependent parameters. For the A1100 alloy, the values of these parameters are $\rho = 2.68$ g/cm^3, $\Delta H_f = 397$ J/g and $T_m = 930$ K, and for copper the corresponding values are $\rho = 8.92$ g/cm^3, $\Delta H_f = 208.7$ J/g and $T_m = 1357$ K. This yields a theoretical ratio of the shear strengths for the alloy to copper at 298 K of 0.429. The experimental value varies between 0.33 and 0.43 [12] depending on the degree of work hardening, with the latter value representing the most work-hardened surfaces. This value would be the most appropriate under the conditions encountered in these experiments [10,11].

Finally, the dimensionless wear coefficient was calculated for the copper pins for comparison with literature values [20]. Using the value determined above for the initial slope of the wear curve, $R_r(\mathrm{Cu})$, the total distance slid during the experiment (5.58×10^4 mm) and the hardness of work-hardened copper (80 $\mathrm{kgf/mm^2}$) yields a value of 2.2×10^{-6} for the dimensionless wear coefficient. This is within the range found for copper [20].

5. Conclusions

The interfacial temperature can be calibrated in a pin and v-block apparatus using pins of known melting point to establish the temperature at which the wear rate tends asymptotically to infinity. Both copper and aluminum alloy pins yield values of the temperature that are in good agreement with those measured for an interface lubricated by an iron chloride layer, once this scale has been properly corrected for the interfacial coefficient of friction. These data can also be obtained more accurately by fitting the entire curve of removal rate versus applied load to a theoretical formula. Both of these analytical strategies yield essentially identical results.

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