CORRELATING THERMAL DILATATION TO PROTECTIVE LAYER FORMATION IN FRETTING WEAR

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ABSTRACT
This paper studies the effects of the heat dissipation capacity of a rubbing material on wear resistance at high temperatures with a special focus on the dilatation of the thermal energy. The results suggest a connection between the transition in wear and the change in the heat dissipation capacity of the rubbing material. Examination of the wear data suggests that a critical ratio between the effects of the conductivity and those of the effusivity has to be established for favorable wear resistance at elevated temperatures. © 2001 Elsevier Science Ltd

Introduction

The idea that tribo-failure is related to the efficiency of heat removal is not new to tribo-analysis. For example, Blok [1] and [2], used it as a basis for his proposal concerning the constancy of scoring temperatures. Many investigators supplied experimental evidence supporting the connection between the accumulation of frictional heat within the mechanically affected layer of a rubbing material and wear regime transition. Wang [3] performed abrasion experiments on hardened 35 Mn2 steel specimens on a dry sand rubber wheel tester at a variety of loads and speeds. The author considered the appearance of tongues on the worn tracks as evidence of frictional heat accumulation on the steel specimen surface. Due to heat accumulation, the hardness decreased and wear regime transition, from soft-abrasive to hard-abrasive, took place. Singh and Alpas [8] observed that the surface temperature of a wrought aluminum alloy (6061AL) worn against an SAE 52100 steel counter face reached a constant value of 395 °K ± 10 °K at the onset of mild-to-severe wear transition. This observation was equally valid for both velocity induced and load induced transitions. Therefore, Singh and Alpas suggested that attainment of a critical temperature is a necessary condition for wear transition.
The conjecture that an equilibrium between frictional heat generation and the heat dissipation capacity of a wearing material is a necessary condition for high temperature wear resistance was examined by Abdel-Aal [13, 14]. It was found that the balance between heat generation and heat dissipation by a rubbing pair is, in essence, an equilibrium between the influence of the diffusivity and that of the conductivity (and their respective variation with temperature) on frictional heat transfer. Moreover, it was established [13] that the equilibrium between the effects of the thermal properties is strongly correlated to the self-repairing properties of the oxide layers. That is, the intrinsic ability of the material to sustain an oxidative reaction of a controlled rate. So that, the glaze oxide layers are formed at a rate that continuously compensates for the removed oxide layer. The equilibrium between thermal property effects bears on the dilatation of the frictional heat due to thermal diffusion within the contacting layers of the material. The dilatation is also a measure of the intensity (concentration) of heat within the contact area and its' immediate vicinity.

Thermal dilatation is a function of the thermal conductivity, thermal diffusivity and, their respective variation with temperature. Therefore, this paper investigates the role of the thermal transport properties on thermal dilatation within the mechanically affected layer of a rubbing material; and the effect of this dilatation on protective oxide formation during rubbing. The first part of the paper examines the individual role of each of the thermal properties, and their respective variation, on dilatation. Whereas, the second part examines the conjecture that thermal dilatation is related to protective layer formation. This is achieved by examining the fretting wear data of two alloys: a nickel-based alloy (Ni-20Cr-2Al) and a Cobalt-based alloy (Haynes-188) in light of the thermal dilatation-temperature curve.

**Heat Dissipation Through the Contact Spot**

Heat flow within the contacting layers is predominantly one-dimensional. As such the amount of heat penetrating through a nominally flat contact spot in the X-Y plane, is adequately calculated from:

\[
q_a = -k \frac{\partial U}{\partial Z} \bigg|_{z=0}
\]  

(1)

In a sliding solid, the thermal properties of the material at the surface, depending on the temperature difference between the surface and the bulk, will be different. To incorporate the effect of the temperature-induced variation of the thermal properties on the surface temperature the so-called Kirchoff Transformation is applied. As detailed elsewhere [16]. This transformation acts as a correction to the constant property solution of the heat equation. Thus if the constant conductivity surface temperature is given by
\[ U_s(t) = 2 \frac{q_{gen}}{k_o} \left[ \frac{\alpha t}{\pi} \right]^{1/2} \]  

the variable thermal conductivity solution will be given as,

\[ \Theta_s(Z,t) = \frac{1}{\beta} \left[ \{1 + 2 \beta U_s(Z,t)\}^{1/2} - 1 \right] \]  

Differentiating equation (3) with respect to the depth \( Z \) we may write,

\[ \frac{\partial \Theta}{\partial Z}(Z,t) = \frac{\partial U}{\partial Z}(Z,t) \bigg|_{Z=0} \{1 + 2 \beta U(Z,t)\}^{-1/2} \]  

Substituting from equation (3) into equation (4), in equation the temperature dependent amount of heat penetrating through the contact spot may be written as,

\[ q_s(\theta) = \{1 + \beta \Theta(Z,t)\} \frac{\partial \Theta}{\partial Z}(Z,t) \bigg|_{Z=0} \]  

Equation (5) may be rewritten, for one dimensional heat conduction,

\[ q_s(\theta) = \{1 + \beta \Theta\} \left[ \frac{\Theta}{Z_{thick}} \right] \]  

Where, \( Z_{thick} \) represents the thickness of the thermal layer and is proportional to \((\alpha t)^{1/2}\). Now, assuming a linear variation in the diffusivity with temperature of the form \( \alpha(\theta) = \alpha_o (1 + \delta \theta) \), the amount of heat dissipated through the surface of true contact may be written as:

\[ q_{thc} = -k_o \frac{4 \sqrt{\alpha_o}}{4 \sqrt{\alpha_o}} \left[ \frac{1 + \beta \Theta_s}{(1 + \delta \Theta_s) t_s} \right]^{1/2} \]  

Plotting equation (7) as \( q_{thc}/A_c \) versus temperature \( \theta \), results in a curve that represents the variation in the HDC with temperature. As pointed out elsewhere [18], the maximum HDC may not necessarily be equal to the amount of heat generated at the surface.

To investigate the influence of the transport properties, the change in the slope of the HDC is evaluated, this is written as [19],
\[
\frac{1}{A_c} \frac{\partial q_{dan}}{\partial \theta_s} = F_1 + F_2 \theta_s + F_3 \theta_s^2
\]  
\tag{8}

Where,

\[
F_1 = \frac{k_o}{\sqrt{\alpha_o t}} \frac{1 + 2 \beta \theta_s}{\left[1 + \delta \theta_s^{3/2}\right]^{3/2}}
\]  
\tag{8-a}

\[
F_2 = \frac{k_o}{2 \sqrt{\alpha_o t}} \frac{\delta}{\left[1 + \delta \theta_s^{3/2}\right]^{3/2}}
\]  
\tag{8-b}

\[
F_3 = \frac{3 k_o}{2 \sqrt{\alpha_o t}} \frac{\beta \delta}{\left[1 + \delta \theta_s^{3/2}\right]^{3/2}}
\]  
\tag{8-c}

The preceding analysis may be extended to accommodate the presence of an oxide film on the contact surface by replacing the thermal conductivity by an effective thermal conductivity given by:

\[
k_{eq} = k_m \left[1 + \frac{\zeta}{l_f} \left(\frac{k_m}{k_{ox}} - 1\right)\right]^{-1}
\]  
\tag{9}

Where \(\zeta\) is the thickness of the oxide layer, \(l_f\) is the diffusion length in the metal, and the subscripts \(m\) and \(ox\) denote the thermal conductivity of the metal and the oxide respectively. Note that \(k_{eq}\) is inversely proportional to the thickness of the oxide layer.

Thermal dilatation, according to equation (8), has three components. The first, represented by \(F_1\), is due to the variation in the thermal conductivity of the material with temperature. The second, expressed as \(F_2\), is due to the variation in the thermal diffusivity with temperature. While the third component, the function \(F_3\), represents a non-linear contribution due to the interaction of the diffusivity and the conductivity coefficients. It is noted that the dilatation is a strong function of the temperature coefficients \(\beta\) and \(\delta\).

**Results and Discussion**

To examine the proposed connection between the thermal properties and wear transition, two alloys
were studied: a Nickel-based alloy (Ni-20Cr-2Al) and a Cobalt-based alloy (Haynes-188). Each alloy was tested for fretting wear against like material by Bill [21, 22] under the following conditions: frequency 80.0 Hertz, peak-to-peak amplitude \(75*10^{-6}\) m and, a nominal applied load of 1.47 N. Physical properties of the alloys are summarized in table 2 [23] and the wear volumes are supplied in table 2.

**TABLE 1**
Thermo-physical Properties of the Studied Alloys

<table>
<thead>
<tr>
<th>Alloy</th>
<th>(e \times 10^{-3})</th>
<th>(k_v)</th>
<th>(\alpha_v \times 10^6)</th>
<th>(\beta)</th>
<th>(\delta)</th>
<th>(T_m)</th>
<th>(\sigma_y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haynes-188</td>
<td>6.182</td>
<td>10.4</td>
<td>2.83</td>
<td>0.00161</td>
<td>0.00075</td>
<td>1374</td>
<td>640</td>
</tr>
<tr>
<td>Ni-20Cr-2AL</td>
<td>5.744</td>
<td>11.3</td>
<td>3.87</td>
<td>0.00157</td>
<td>0.00037</td>
<td>1400</td>
<td>570</td>
</tr>
</tbody>
</table>

**TABLE 2**
Experimental Fretting Wear Scar Volumes

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature °C</th>
<th>(W(mm*10^{-5}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>23</td>
<td>216</td>
</tr>
<tr>
<td></td>
<td>327</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>540</td>
<td>650</td>
</tr>
<tr>
<td></td>
<td>816</td>
<td>100</td>
</tr>
<tr>
<td>Haynes-188</td>
<td>28</td>
<td>3</td>
</tr>
<tr>
<td>Ni-20Cr-2AL</td>
<td>19</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1500</td>
</tr>
</tbody>
</table>

For each of the examined alloys the three functions \(F_1\), \(F_2\) and, \(F_3\) were calculated. These are shown in figures 1-a (for the Ni-based alloy) and figure 1-b (for the Co-based alloy). The plots represent the normalized values of the respective functions. The normalization is done by dividing the value of each function at the particular temperature by the value of the respective function at room temperature. It is noted that for both alloys the dominant function is \(F_1\) which represents the relative effects of the conductivity variation on thermal dilatation. As such, for the purpose of this work only the normalized values of the function \(F_1\) will be correlated to the wear data.

The analysis starts by calculating the difference between the Heat Dissipation Capacity (HDC) of the material and the generated heat \(q_{gen}\). This quantity, termed the residual heat \(q_{res}\), is then used to construct a Ratio of Residual Heat (RRH), \(q_{res}/q_{gen}\), versus temperature plot. The heat generated at the interface is calculated from:

\[
q_{gen}(\theta) = 2.7 \, \mu \, \alpha_v(\theta) \, U \, A_r
\]  

(10)
Variation in the components of thermal dilatation (functions F1, F2 and F3) with temperature.

a- Variation of the functions for Ni-based alloy Ni-20Cr-2AL

b-Variations of the functions for a Co-based alloy (Haynes-188)

where, $\sigma_y(\theta)$ is the temperature dependent yield strength in MPa. This is calculated by interpolation between the room temperature value and the value at the melting temperature ($\sigma_y = 0$). Whence, $\sigma_y(\theta) = \sigma_y^0 (1 - \theta/\theta_m)$. The RRH plot is then inspected for points where it is equal to zero (implying that the HDC is equal to the generated heat) or where a change in the slope takes place. The temperatures associated with each point are then correlated to the transition temperatures extracted from the literature. Thermal aspects of the transition in wear are then examined by analyzing the trends of RRH, the thermal effusivity and the function F1 before and after the calculated transition temperatures.

Figure 2 depicts the variation in the RRH (solid lines, left scale) and the function F1 (dashed lines, right scale) with temperature. The curves denoted I, and II were calculated using the value of the coefficient of friction at room temperature (see table 2) and at the respective temperatures. The RRH values corresponding to the temperature at which the friction coefficient changes are plotted as discrete values. Curves III, are schematics sketched to indicate the anticipated behavior of the RRH in the presence of an oxide layer. Transition points pertaining to the Co-based alloy are marked by the letter T while those pertaining to the Ni-based alloy are identified by the letter S. Transition points that are located within the discrete points on the plot are reported as intervals. Thus, the graphically extracted transition temperatures for the Co-based alloy are 230°C, 560°C, 790°C < $\theta$ < 825°C. Whereas, those associated with the Ni-based alloy are 435°C, 500°C < $\theta$ < 525°C, 600°C < $\theta$ < 625°C and, 800°C < $\theta$ < 830°C. Those values are in good agreement with the experimentally determined temperatures (see table 2).

Initial wear reduction is associated with a change in the sign of the RRH from a negative (indicating
The variation in the Ratio of Residual Heat RRH (solid lines, left scale) and the function F1 (dashed lines, right scale) with temperature.

that HDC<Q to a positive (indicating that HDC> Q). This change corresponds to an initial growth period where the oxide tries to overcome the energy barriers exerted by pressure, temperatures, and chemical composition of the alloys. The protective film starts discontinuous and as its thickness and area grow, partial separation between the rubbing materials will take place and a decrease in wear volume will follow. The zone of oxide formation is at the gas-oxide interface. The diffusion of oxygen in oxides is lower than that of the metal in oxides. Protective layer formation, therefore, requires the metal ions from the matrix to diffuse outward through the oxide layers. Since there is an abundance of oxygen at the surface, the diffusivity of the material in the oxides determines the growth rate. This means that the temperature (or synonymously the available thermal energy) at the formation front, and the length of the time through which this energy is available will control the distance the material atoms can travel. Thus, an abundant thermal energy in combination to longer times of energy availability will aid the growth of a protective oxide.

The secondary transition range for the Co-base alloy entails further reduction in wear volume. This is associated with a decrease in the available thermal energy (RRH is positive). The energy decrease is compensated by an increase in the intensity of frictional heat (i.e. concentration of thermal energy) within the contacting layer as indicated by the increase in F1. Additionally, the effusivity of the alloy continues to increase with temperature. This implies an increase in the time interval through which heat is retained within the contacting layer. In contrast, through the same interval the Ni-base alloy exhibits an increase in the wear volume. Interestingly, at θ and θ the RRH is equal to zero. This indicates a balance between the HDC and the generated heat. Concurrently, heat intensity increases (note the considerable increase in F1). The increase in F1 is also accompanied with an increase in the effusivity whence implying, again, an increased specific time of thermal energy availability. Therefore, the opposite wear behavior noted in this region may be attributed...
to nature of change in the function $F_1$ with temperature. The change in $F_1$ for both alloys promotes oxide growth through focusing the frictional heat within the true area of contact. However, the high intensification effect in the case of the Ni-base alloy will aid the growth of a thicker oxide film. The growth of that film will cause the effective conductivity of the film-substrate combination to drop (see equation 9). The drop in the conductivity will tend to insulate the substrate. This will cause a considerable temperature difference between the film and the substrate. Now, since the oxide has a different coefficient of thermal expansion considerable stresses will develop at the boundary and wear debris will detach from the material. The detachment of wear debris will expose the underlying metal. The freshly exposed material being of higher effusivity and HIC than the oxide will admit a greater amount of heat. This, in turn, will be retained within the contacting layers for a longer period and an oxidative reaction will be sustained and the oxide layer will be repaired. The rate by which the oxide is repaired depends on the optimal combination of $F_1$ and effusivity (the determination of that combination is a subject for future research). It is worth noting that this self-repair characteristic was observed by Bill [21] for the Haynes-188 alloy.

**Concluding Remarks**

This work suggests a connection between wear transition and the change in the heat dissipation capacity of a rubbing material. The nature of change in the thermal properties before and after the transition influences the thermal environment within the contacting layers. This controls the kinetics of oxide formation and thereby controls wear.

An important factor is the function $F_1$, which indicates the intensity of thermal energy available within the contacting layers. A high $F_1$ value and a high effusivity will promote the growth of a protective layer. The protective layer will affect the effective conductivity of the interface and may alter the thermal environment at the contact zone.

**Nomenclature**

- $A_a$ area of conduction $m^2$
- $A_s$ real area of contact between the sliding solids $m^2$
- $B$ initial coefficient of heat penetration $W/m^2\cdot sec^{-1}$
- $P$ average contact pressure $N/m^2$
- $Q_{\text{das}}$ rate of total heat dissipation away from the surface $W$
- $Q_{\text{gen}}$ rate of total heat generation at the surface $W$
- $U_{\text{slid}}$ sliding speed $m/sec$
- $Z_p$ diffusion length $m$
depth from the surface at which a temperature rise 1% of that at
the surface is felt

$$Z_{\text{max}}$$

reference thermal conductivity

$$k_0$$

c_{\text{a}}$$^\prime$$

rate of instantaneous heat dissipation by an individual pair
of contacting asperities

$$q_{\alpha}$$

radius of the contact spot between two contacting asperities

$$r_0$$

duration of a single contact cycle

$$t_c$$

Greek symbols

$$\alpha$$

thermal diffusivity of the material

$$\beta$$

temperature coefficient of the thermal conductivity

$$\eta_0$$

efficiency of an asperity pair to dissipate heat

$$\Theta_b$$

bulk temperature rise

$$\Theta_i$$

instantaneous temperature rise at the center of contact spot
between two asperities

$$\Theta_{\text{max}}$$

maximum potential temperature rise at the end of the contact cycle

$$\Theta_s$$

temperature rise at a depth Z from the surface

$$\mu$$

nominal coefficient of friction

References


5. Abdel-Aal, H. A., The correlation between thermal property variation and high temperature wear transition of rubbing metals, *WEAR* forthcoming


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