Short communication

Hierarchically constructed metal foam/polymer composite for high thermal conductivity

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Abstract

Most polymeric tribological components are inherently insulative, resulting in susceptibility to failure from frictional heating at the PV limit, which is typically reported as a product of the heat flux terms pressure (P) and sliding speed (V). This letter reports on the design of a tribological composite for increased thermal conductivity and PV limit. The control sample is an unfilled compositionally graded sample, consisting of a PEEK bulk with an integral PEEK/PTFE tribological solid lubricant surface layer. One composite sample is a compositionally graded PEEK bulk containing 10 vol.% aluminum foam, and the other is a 10 vol.% indium filled PEEK/PTFE bulk sample. Tribological experiments are conducted on a thrust washer tribometer instrumented with 13 thermocouples. At failure, the unfilled sample had a temperature rise of 170 K. Under the same conditions, the aluminum and indium filled samples had temperature rises of 37 K and 115 K, respectively. They also had 250% and 40% higher PV limits, respectively than the unfilled sample. As designed, the continuity of the aluminum foam was found to be substantially more effective than the particle dispersion of the indium at dissipating thermal energy.

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1. Introduction

Solid lubrication has a number of advantages including reduced cost, simplicity, cleanliness, ease of implementation, range of operational temperature and in general, performance in applications where the use of fluid and boundary lubricants is precluded. Many solid lubricant systems are created through various coating techniques. Under such situations, the substrate provides load support with the coating providing tribological protection. Coatings experience wear during operation and thus have finite life. For many practical applications bulk polymeric solid lubricants extend operational life by providing a greater amount of sacrificial material to the tribological contact. Unfortunately, bulk materials often do not provide the required engineering performance in terms of strength, toughness, electrical and thermal conductivity, creep and thermal expansion.

Thermal failures are particularly problematic in tribology; they are difficult to foresee, occur rapidly and in most cases, lead to complete failure of the system. These failures occur when a critical surface temperature, such as $T_g$, is exceeded as a result of frictional heating. At the critical temperature a transition from mild to severe wear occurs; this is usually accompanied by a several order of magnitude increase in the wear rate [1–6]. For a given system design, the temperatures developed at the tribological interface are proportional to the heat flux (µPV) and the thermal resistance of the materials. The PV limit is considered an important design parameter and is an indicator of material performance. Polymers have inherently poor thermal conductivity, and consequently, also have relatively low PV limits. The goal of this work is to design multifunctional tribological composites for higher thermal conductivities and PV limits. This article presents a building block in the design of multifunctional composites, specifically, those for tribological and engineering applications.

2. Modeling

Long term success of the solid lubricating components requires that the frictional power developed in a tribological system must be conducted away from the interface; otherwise,
polymeric solid lubricants can fail under even modest conditions. A thrust washer is a common tribological configuration that can have elevated temperatures from frictional heating, and generally consist of a flat, annular ‘thrust washer’ that is continuously rotated and loaded about its axis against a flat counterface. The experimental apparatus used in this study is representative of a typical thrust washer and is shown schematically in Fig. 1.

An upper bound of the temperatures that may be developed during operation can be obtained by treating the thrust washer as a stationary heat source on an infinite half space. All of the frictional power is conducted through the half space as the thrust washer and surroundings are assumed to be perfect insulators. The differential temperature rise of any point in the half space is

\[
\frac{d\theta}{2\pi K r} = \frac{q'' dA}{2\pi K r}
\]

where \(q''\) is the heat flux of the stationary point source, \(dA\) the differential area of that point source, \(K\) the conductivity of the half space and \(r\) is the distance from the location of interest to the point heat source. The heat flux is \(\mu P \omega s\), where \(\mu\) is the friction coefficient, \(P\) the normal pressure (assumed to be constant), \(\omega\) the angular velocity of the thrust washer and \(s\) is the radial distance of the point source from the axis of the thrust washer. Eq. (1) can be integrated to give the temperature rise at any location in the half space (axisymmetric):

\[
\theta(r, a) = \frac{\mu P \omega}{2\pi K} \int_{s_i}^{s_o} \int_0^{2\pi} \frac{s^2 d\beta ds}{\sqrt{a^2 + (s \cos(\beta) - r)^2 + (s \sin(\beta))^2}}
\]

where \(r\) is a radial distance from the axis of the thrust washer, \(a\) is an axial depth into the half space, \(s_i\) and \(s_o\) the outer and inner radii of the thrust washer, respectively, and \(\beta\) is the angle from the plane of interest to the point source. A typical thrust washer system may have a Polytetrafluoroethylene (\(\mu = 0.1\), and \(K = 0.2\) W/mK) counterface with inner and outer thrust washer diameters of 25.4 and 28.6 mm, and tribological conditions of \(\omega = 34\) RPM (\(V_{\text{mean}} = 50.8\) mm/s, \(A_{\text{nom}} = 136\) mm\(^2\)) and \(P_{\text{nom}} = 6.5\) MPa. Solving Eq. (2) for the maximum temperature gives \(T_{\text{max}} \sim 430\) °C, a value well above the melt temperature of PTFE at a very low value of PV.

From a materials design standpoint, it is desirable to achieve the highest values of PV for a system of given dimension without overheating the material. Since the primary function of a solid lubricant is to provide a low friction coefficient, it cannot, in general, be reduced. Then, according to Eq. (2), thermal conductivity must be increased if the interfacial temperatures are to be reduced.

Fillers are often incorporated into polymer matrices to improve upon matrix properties. For a given filler material, the size, shape, loading, dispersion and orientation of the filler can result in a wide range of properties. Two particularly interest-
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Fig. 2. (a) Equal pressure composite (b) equal strain composite (c) random dispersion of particles within a composites. Counterface samples for temperature measurement in thrust washer experiments: (d) compositionally graded control sample; unfilled PEEK with an integrated solid lubricant surface layer, (e) a compositionally graded 10 vol.% aluminum foam-PEEK sample with an integrated solid lubricant surface layer, and (f) a 10 vol.% indium filled PEEK/PTFE bulk solid lubricant component.

In the case of equal strain, top and bottom temperatures are prescribed and the temperature rise is the same for each constituent, and the total power is the sum of the power in each constituent:

\[
q'' A_c = K_{ES} A_c \frac{\Delta T_{ES}}{L_c} = K_f x_f A_c \frac{\Delta T_{ES}}{L_c} + K_m (1 - x_f) A_c \frac{\Delta T_{ES}}{L_c}
\]

which yields the equal strain conductivity:

\[
K_{ES} = K_f x_f + K_m (1 - x_f)
\]

Eqs. (6), (8) and (9) can be used to find the normalized temperature rise of the equal strain composite:

\[
\Delta T^{*}_{ES} = \frac{1}{1 + \frac{K_m}{K_f}}
\]

If a normalized conductivity is defined, \(K^* = K_f/K_m\), Eq. (7) reduces to

\[
\Delta T^{*}_{EP} = 1 - x_f \left(1 - \frac{1}{K^*}\right)
\]

And Eq. (10) reduces to

\[
\Delta T^{*}_{ES} = \frac{1}{1 + x_f (K^* - 1)}
\]

For aluminum filler in a PTFE matrix, \(K^* = 1000\). At 10 vol.% filler, the temperature rises for equal pressure and equal strain composites are 90% and 1% that of the matrix alone, respectively. There are major opportunities to improve in composites by hierarchically structuring the filler domains.
3. Experimental

PTFE is a well known solid lubricant and has one of the lowest friction coefficients of any bulk polymer; it’s poor wear resistance limits its use. PEEK is a strong, tough engineering thermoplastic with high wear resistance, but suffers from a high coefficient of friction. The multifunctional composites in this study are based on a unique PEEK/PTFE blend discussed previously by the authors in [7] At the optimal composition, the solid lubricant has a lower friction coefficient and 1000× lower wear than either constituent for the conditions tested; a 30 wt% PEEK-PTFE blend is used here as the solid lubricating material. The mechanical attributes of the PEEK filler are used to improve the bulk mechanical properties of the composite through a compositional grading. Both PEEK and PTFE are extremely poor thermal conductors, and the 140 °C \( T_g \) of PEEK further limits the operational range of the components. Aluminum has excellent strength, stiffness and thermal conductivity, and is available in the form of continuous open cell foams with varying densities, pore sizes and properties. But, the high strength of aluminum requires it to be mechanically, and consequently, thermally isolated from the interface to avoid detrimental effects to the tribological properties. Indium is slightly less conductive than aluminum but has extremely low shear strength making it a suitable material for use at the interface. The disadvantage of indium is that it is available only in pellet or powder form making it unlikely to form the continuous structure necessary for efficient dissipation of thermal energy.

Three components are tested here: (1) an unfilled PEEK sample compositionally graded to a solid lubricant surface layer, (2) a 10 vol.% aluminum foam filled PEEK sample compositionally graded to solid lubricant surface layer, and (3) a 10 vol.% indium filled solid lubricant component. Optical cross-sections of the samples are shown in Fig. 2. Each sample is compression molded in a 1.25 in. diameter cylindrical mold. The compositional grading process is discussed in detail in [8], but briefly, consists of a sacrificial layer of PTFE followed by a layer of the solid lubricant and successive layering of powder ensembles increasing in 10 wt% increments. The remainder of the mold is filled with PEEK powder for the unfilled graded sample. The metal foam is infiltrated with PEEK at approximately 400 °C, by slowly pressing the foam into a relatively low viscosity PEEK melt. This material, once cooled, fills the remainder of the mold after the compositional grading. The indium composite is prepared by combining 10 vol.% indium powders with 90 vol.% solid lubricant powders. The powder ensemble is mechanically mixed in a Hauschild high speed mixer. The parts are consolidated at 50 MPa and compression molded at 360 °C for 3 h with 2 °C/min ramps at approximately 2 MPa.

After molding, the samples are machined to 10 mm thickness. The samples are then mounted into a fixture on a computer numerically controlled stage. A series of four 3.3 mm deep, 250 μm holes are drilled radially at axial locations of 0.76 mm, 2.54 mm, 4.32 mm and 6.10 mm as measured from the surface. The sample is rotated about its axis and two additional sets of holes are drilled at radial depths of 5.3 mm and 7.3 mm. These holes receive thermocouples for temperature measurement and estimation of the 2D temperature field in a region beneath the contact. An additional thermocouple measures the temperature at the base of the sample for temperature rise calculations. The locations of these measurements with respect to the center of the thrust washer are shown in Fig. 1.

Experiments are conducted on a custom thrust washer tribometer shown schematically in Fig. 1. A 1 HP DC motor drives a spindle connected to an annular Polyimide thrust washer. Polyimide was chosen because it is thermally insulating and has a higher \( T_g \) than PEEK. It is kinematically mounted to the spindle to retain axisymmetric conditions for slightly misaligned or nonparallel samples. The outer and inner diameters are 23.3 mm and 17.6 mm, respectively, producing 180 mm² of nominal contact area. The tribological counterface sample is located beneath the thrust washer and is mounted to a 15 °C water chilled heat transfer plate. A 6-channel load cell is mounted to a linear thruster below the heat exchanger and is the only source to ground for loads and moments on the sample. The sample, load cell and thruster are loaded against the rotating thrust washer via a pneumatic cylinder and software controlled electro-pneumatic valves. Friction coefficients are calculated by dividing the moment about the normal axis by the mean radius of the thrust washer and the normal load. Friction coefficient and temperature measurements are made continuously and are averaged and saved in 10 s intervals. A more detailed schematic of the tribometer is in [8].

Initially, the experimental conditions consist of a normal load of 180 N and a spindle speed of 50 rpm. This corresponds to a normal pressure of approximately 1 MPa and a maximum speed of 61 mm/s. When the sample reaches thermal equilibrium, the spindle speed is increased in 50 rpm increments. When the maximum spindle speed of 350 rpm is reached, normal load is increased in 90 N increments. When the PV limit is reached, wear accelerates, friction coefficient and temperature become erratic and the test is stopped.

4. Results and discussion

The experimental results are summarized in Table 1, and graphically illustrated in Fig. 3. Fig. 3a–c shows the maximum temperature and base temperature of each sample plotted as a function of time. While the operational PV is fixed as the sample develops a steady state, the heat flux changes with the developing tribological system and causes the temperature to change even after the system is determined to be at thermal equilibrium. At 305 mm/s and 1 MPa the unfilled sample failed after operating briefly at a temperature rise of 170 °C. At these conditions, the aluminum and indium samples had temperature rises of 37 °C and 115 °C, respectively. The indium filled sample failed at a sliding speed of 427 mm/s and a normal pressure of 1 MPa, and the aluminum filled sample failed at 427 mm/s and 2.5 MPa. The measured temperature rise at failure is reduced due to increased base temperature.

Contour plots of temperature rise for a 6 mm × 4 mm area of each sample is shown in Fig. 3d–f for a sliding speed of 305 mm/s.
Table 1

Results of temperature measurements for thrust washer experiments with an unfilled PEEK sample with an integrated solid lubricant surface coating, a 10 vol.% aluminum foam filled PEEK sample with an integrated solid lubricant surface coating, and a 10 vol.% indium filled solid lubricant bulk sample.

<table>
<thead>
<tr>
<th>rpm</th>
<th>F (N)</th>
<th>V (mm/s)</th>
<th>P (MPa)</th>
<th>Unfilled</th>
<th>Aluminum filled</th>
<th>Indium filled</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>μP (kW/m²)</td>
<td>ΔTmax (°C)</td>
<td>μP (kW/m²)</td>
</tr>
<tr>
<td>50</td>
<td>180</td>
<td>61</td>
<td>1</td>
<td>4.83</td>
<td>37.2</td>
<td>6.5</td>
</tr>
<tr>
<td>100</td>
<td>180</td>
<td>122</td>
<td>1</td>
<td>10.4</td>
<td>74.2</td>
<td>12.8</td>
</tr>
<tr>
<td>150</td>
<td>180</td>
<td>183</td>
<td>1</td>
<td>15.5</td>
<td>109</td>
<td>16.1</td>
</tr>
<tr>
<td>200</td>
<td>180</td>
<td>244</td>
<td>1</td>
<td>22.6</td>
<td>151</td>
<td>19.1</td>
</tr>
<tr>
<td>250</td>
<td>180</td>
<td>305</td>
<td>1</td>
<td>23.5</td>
<td>170</td>
<td>21.1</td>
</tr>
<tr>
<td>300</td>
<td>180</td>
<td>366</td>
<td>1</td>
<td>23.3</td>
<td>28.5</td>
<td>41.6</td>
</tr>
<tr>
<td>350</td>
<td>180</td>
<td>427</td>
<td>1</td>
<td>28.5</td>
<td>41.2</td>
<td>50.9</td>
</tr>
<tr>
<td>350</td>
<td>270</td>
<td>427</td>
<td>1.5</td>
<td>N/A</td>
<td>41.2</td>
<td>65.9</td>
</tr>
<tr>
<td>350</td>
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<td>427</td>
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<td>49</td>
<td>76.8</td>
<td>N/A</td>
</tr>
<tr>
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<td>450</td>
<td>427</td>
<td>2.5</td>
<td>80.3</td>
<td>92.3</td>
<td>N/A</td>
</tr>
</tbody>
</table>

The heat flux is the product of friction coefficient, pressure and maximum velocity averaged for a segment of steady state data. The maximum temperature rise is the difference between the maximum sample temperature and the temperature at the base of the sample. At elevated temperatures, wear, friction and temperature become erratic and the test is stopped.

and a normal pressure of 1 MPa; the condition at failure for the unfilled sample. The highest temperature rise and steepest temperature gradient occurred in the unfilled sample. The temperature gradient is visibly less steep for the indium filled sample and is significantly less steep for the aluminum filled sample. These isotherms are sloped and the gradients decrease with depth, indicating that power is flowing both radially, due to convection from the sides of the sample, and axially. It is also interesting to note that the highest temperature occurs inside the contact rather than under the contact zone near the point of maximum power input due to convection and the insulated condition of the interior.

Fig. 3. (a–c) Temperature plotted vs. test time for the unfilled, aluminum filled and indium filled samples, respectively. Only maximum and base temperatures are shown, (d–f) contour plots of the temperature rise in the unfilled, aluminum filled and indium filled samples, respectively, at 305 mm/s sliding speed and 1 MPa normal pressure. This point during each test is highlighted in (a–c). The point 0,0 is defined at the mean diameter on the face of the thrust washer.
Fig. 4a shows maximum temperature rise plotted versus the frictional power flux ($\mu PV$) for each of the samples. A regression of the data for the unfilled sample gives a slope $\Delta T/q'' = 7.0 \text{ m}^2\text{K/kW}$ with $R^2 = 0.99$; the linearity suggests that convection losses are proportional to the frictional power. The indium filled sample has a regression slope $\Delta T/q'' = 5.0 \text{ m}^2\text{K/kW}$, with $R^2 = 0.99$. The aluminum filled sample has a regression slope $\Delta T/q'' = 1.4 \text{ m}^2\text{K/kW}$, but the regression is poor with $R^2 = 0.86$. Examining only the portion of the data at constant load produces a slope $\Delta T/q'' = 1.7 \text{ m}^2\text{K/kW}$ and $R^2 = 0.99$. As load is increased, the slope decreases proportionally, decreasing to $\Delta T/q'' = 1.1 \text{ m}^2\text{K/kW}$ before failure. Various experiments were performed to investigate this load dependent phenomenon, including the addition of thermal grease to the base of the contact as well as constant $P-V$ experiments where sliding speed was reduced as load increased. From these experiments there is no clear hypothesis for the consistently observed behavior of increased conductivity with increasing load.

Estimates of thermal conductivity versus filler wt% for the samples in this study with analytical solutions for several idealized composites are shown in Fig. 4b. The conductivity envelopes for the analytical models are bounded by the equal strain (upper) and equal pressure (lower) composite structures. A bulk aluminum filled sample has the greatest potential with aluminum having higher thermal conductivity than indium, but because a solid lubricant surface layer was required, the conductivity is capped at approximately $2 \text{ W/mK}$. At 10 vol.% aluminum, analytical solutions for the capped equal strain and equal pressure composites are $K = 1.84$ and $0.27 \text{ W/mK}$, respectively. The thermal conductivity of the aluminum filled (10%) sample is estimated to be $1.6 \text{ W/mK}$. Because indium can be used at the interface, the indium composite has much greater potential than the insulated aluminum filled sample with analytical solutions for 10 vol.% indium equal strain and equal pressure composites being $K = 8.7$ and $0.22 \text{ W/mK}$, respectively. The indium composite has an estimated thermal conductivity of $0.35 \text{ W/mK}$. In general, it is very difficult to obtain connectivity of particulate filler at low loadings; this is reflected by the low conductivity of the indium sample and similarity to the equal pressure composite. The aluminum foam has a continuous thermal path resulting in a substantially higher conductivity and similarity to the equal strain composite.

5. Conclusions

Designed composites reduced the operating temperatures and extended the operational $P-V$ range of thrust washer components. At failure, the unfilled bulk component had an operational temperature rise of 170 K. Under the same operating conditions, aluminum filled and indium filled samples had operational temperature rises of 37 K and 115 K.

The conductivity of the composite is strongly dependent on the structure of the filler within the composite. The aluminum foam filled sample performed comparably to an equal strain composite while the indium particle filled sample performed comparably to an equal pressure composite.

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