Thermal Effects in Tribological Contacts.

by
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Wherever friction occurs, mechanical energy is transformed into heat. The temperature rise associated with this heating can have an important influence on the tribological behaviour of the contacting components. Apart from determining performance, thermal phenomena affect reliability and may cause failure of the contact.
In this paper results of numerical calculations of the contact temperature will be presented given a heat source distribution, e.g. by means of a measured coefficient of friction.
In order to calculate this contact temperature, a multilevel algorithm has been derived which allows for a non-uniform division of the heat generated in the contact and for different bulk temperatures.
Simulations for elliptic heat sources with uniform as well as semi-ellipsoidal distributions, which are of specific importance for contacts operating under conditions of dry and boundary lubrication, have resulted in acurate formulas for the average and maximum contact temperature. These formulas for arbitrary Peclet numbers, are based on asymptotic solutions for small and large Peclet numbers together with numerical calculated values.

Introduction

The concept of large and small scale heat flow restrictions by Holm (1948) and Tian and Kennedy (1993) has been applied, assuming that the contact temperature rise in a sliding contact is a superposition of two temperature rises i.e.: a local temperature rise and a bulk temperature rise, both originating from heat flow restrictions on a specific scale.

Suppose a rod, held at two different temperatures at its ends, is cut into two parts along z= 0 and the two parts are pressed together again. The real contact area now is much smaller than the apparent area because of surface roughness.
Only in the real contact area the temperature of both parts will be the same. In general this is not the case in the rest of the contact. So a temperature drop will take place in the contact, due to a small scale heat flow restriction, since this drop is limited to a very small region near the contact area.
Outside the contact area a linear temperature drop will prevail, caused by a large scale heat flow restriction.

Sliding Contacts.

In sliding contacts the surface temperature rise will be caused by two contributions:

- a local surface temperature rise due to a small scale heat flow restriction.
- a bulk temperature rise due to large scale heat flow restriction.

The bulk temperature rise depends on the geometry of the bodies and on the cooling conditions. The local surface temperature rise can be modeled by a concentrated heat source acting on a semi-infinite medium.

Local surface temperature rise by a moving concentrated heat source.

Much research has already been devoted to this subject:

- Blok (1937), band contact, high Peclet number
- Jaeger (1943), band contact, limited Peclet number
- Archard (1959), circular contact, partitioning problem
- Kuhlman- Wilsdorf, approximate solution elliptic contacts.

Bos [1] has solved this problem numerically by appliction of multilevel-multi-integration solution techniques, for elliptic contacts with uniform and semi-ellipsoidal heat source distributions.

The results of these calculations are presented as formulas based on asymptotic solutions for low and high Peclet numbers and for different heat sources.

The maximum or average temperature rise ϑ_f on the surface, when a heat source moves along a stationary surface, can be calculated according to:

$$\vartheta_f \approx \frac{F}{K\sqrt{ab}}\left[\{\theta_l \mathbf{S}(\phi)\}^s + \left\{\theta_r/\sqrt{\phi P}\right\}^s\right]^{1/s},$$

F: rate of heat supply, K: thermal conductivity, P: Peclet number, ϕ: aspect ratio contact ellipse b/a, a: semi-axis of the elliptic heat source in the direction of the velocity, $S(\phi)$: shape factor according to:

$$\mathbf{S}(\phi) = \frac{2\sqrt{\phi}}{1+\phi}\frac{2}{\pi}\mathbf{K}\left(\frac{|1-\phi|}{1+\phi}\right).$$

where K is the complete elliptic integral of the first kind. $S(\phi)$ can also be determined from the figure

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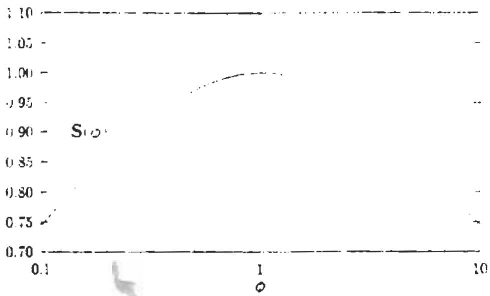
below.



The values for θ_l and θ_r follow from:

uniform heat distribution			
maximum temp.		average temp.	
θ_l^{um}	θ_r^{um}	θ_l^{ua}	θ_r^{ua}
0.318310	0.507949	0.270190	0.309955
semi-ellipsoidal heat distribution			
maximum temp		average temp	
θ_l^{em}	θ_r^{em}	θ_l^{ea}	θ_r^{ea}
0.375000	0.589487	0.281250	0.322991

Partition Problem.

When two surfaces are moving relatively with regard to its contact, heat will flow into both bodies, depending on speed, conduction properties, etc. of both bodies.

The conditions then are:
$Q_1+Q_2=Q$ and $T_1(x,y)=T_2(x,y)$, so the problem can be solved numerically.

Again curve fit formulas, for the general problem, have been derived from the numerical calculations. In these formulas the asymptotic solutions can again be recognised. The temperature rise ϑ_f reads:

$$\vartheta_f \approx \frac{F}{\sqrt{ab}}\frac{1}{\sum(K/\theta)} = \frac{F}{\sqrt{ab}}\frac{1}{\frac{K_1}{\theta_1}+\frac{K_2}{\theta_2}},$$

$$\theta_i \approx \left[\{\theta_l S(\phi)\}^s + \left(\frac{\theta_h}{\sqrt{\phi P_i}}\right)^s\right]^{1/s} \qquad (i=1,2)\ ;$$

with $s = 0.5 * \exp(1-\phi) - 2.5$.

$$\theta_h = \frac{\theta_r + t\theta_s}{1+t},$$

in which: $\theta_s^{um}=0.508$, $\theta_s^{em}=0.701$, $\theta_s^{ua}=0.406$, $\theta_s^{ea}=0.438$ and $t=\max\left(0, \frac{-q}{1+q}\right)$

with: $q=\operatorname{sign}(U_1\cdot U_2)\min\left(p, \frac{1}{p}\right)$,

and:

$$p \equiv \sqrt{\frac{P_2}{P_1}}$$

The heat fluxes entering bodies 1 and 2, respectively, can be approximated by

$$F_1 \approx \frac{1/\theta_1}{1/\theta_1+\lambda/\theta_2}F \qquad F_2 \approx \frac{\lambda/\theta_2}{1/\theta_1+\lambda/\theta_2}F$$

Bulk Temperature Differences.

When two bodies have different bulk temperatures, heat will flow from one body to the other via the contact and a certain contact temperature will be the result.

Also for this situation numerical calculations like before have been carried out.

Again a curvefit formula is presented based on asymptotic solutions, in this case for the following situations:

- velocities in same direction
- velocities in opposite directions
- two bodies at rest.

The general solution reads:

$$\bar{\vartheta}_m \equiv \vartheta_m \frac{K_1\sqrt{ab}}{F} \approx \frac{F_m}{F}(\psi_1 + \psi_2/\lambda),$$

with:

$$\psi_i = \left[\{\psi_l S(\phi)\}^s + \left\{\psi_h/\sqrt{\phi P_i}\right\}^s\right]^{1/s}$$

$$\psi_h = \frac{\psi_r + t\psi_s}{1+t}$$

where:
$\psi_l = 0.25$, $\psi_r = 0.358$, $\psi_s = 0.299$ and

$$t = \frac{1-q}{1+q}$$

with:

$$q = \operatorname{sign}(U_1 U_2)\min\left(p, \frac{1}{p}\right),$$

and:

$$p \equiv \sqrt{\frac{P_2}{P_1}}.$$

General sliding contact

For a sliding contact with two surfaces moving relative to the contact, and with different bulk temperatures, for instance because of different cooling conditions, the real maximum or average contact temperature can be determined by the sum of the temperatures calculated with the two above mentioned formulas.

References

Bos, J. "Frictional Heating of Tribological Contacts" thesis University of Twente, 1995, isbn 90-9008920-9.