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CONTACT TEMPERATURE IN A FRETTING CONTACT

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Abstract

Friction mechanisms for fretting contacts are the cause for the surface temperature. The determination of the sliding velocity is of primary importance in describing the thermal conditions in a contact. The tangential displacement for a ball- flat contact was expressed by assuming Mindlin hypotheses for an elastic ball on flat contact. The present paper argues that plastic deformation in the contact zone may contribute to relative displacement and to thermal heat flux. Temperatures in the fretting contact can be obtained by the integrating the fundamental solution of conduction. The integral function is solved in dimensionless form for divers parameters of fretting phenomena (friction coefficient, normal load and frequency).

Keywords: *Fretting; Partial slip; Heat flux; Friction temperature*

1. INTRODUCTION

Fretting is now fully identified as a small amplitude oscillation motion, which induces a harmonic tangential force between two solid surfaces in contact. It is related to three main loadings, i.e. fretting wear, fretting fatigue and fretting- corrosion [1].

The contact surface temperature is a dependent variable, being a function of the real contact area, the friction coefficient, normal load sliding and thermal propreties of the contacting body.The temperature rise in the fretting contact has been a subject of considerable interest.

Some authors reported very low contact temperature in fretting conditions, even below 10 ^oC, meanwhile the others reported temperature in the range from 500 to 1000 ^oC [2], [3]. For the fretting phenomena, it is necessary to define the slip and stick zones. In the circular contact (fixed sphere – oscillating plan- Fig.1), it is known the radius of the stick central area (*c*) (Mindlin's model)

$$\frac{c}{a} = \left(1 - \frac{F_x}{\mu F_z}\right)^{1/3} \qquad (1)$$

where *a* is the hertzian contact radius of sphere – plane, which are loading with the normal force F_z, μ is friction coefficient and F_x is tangential force.

The tangential displacement for a ball- flat contact was expressed by Mindlin through the relation

$$\delta_x = \frac{3\mu F_z}{16}\left(\frac{2-\nu_1}{G_1} + \frac{2-\nu_2}{G_2}\right)\left(\frac{a^2 - c^2}{a^3}\right) \qquad (2)$$

with: ν_1,ν_2, Poisson coefficients of the material 1 (ball) and 2 (plan); G_1 and G_2, shear elastic modulus of the materials 1 and 2.

The relation between δ_x and the applied tangential force F_x is

$$\delta_x = \delta_M\left[1 - \left(1 - \frac{F_x}{\mu F_z}\right)^{2/3}\right] \qquad (3)$$

where

$$\delta_M = \frac{3\mu F_z}{16a}\left(\frac{2-\nu_1}{G_1} + \frac{2-\nu_2}{G_2}\right) = a k_a \, .$$

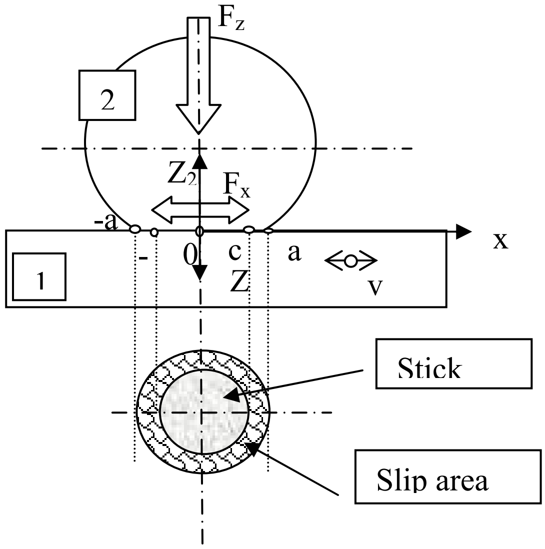

Figure1: *Sphere on plane in fretting*

We note $\delta_{ax} = {\delta_x}/{\delta_M}$, $k_a = {\delta_M}/{a}$ and $F_{ax} = \frac{F_x}{\mu F_z}$, thus $\delta_{ax} = 1-(1-F_{ax})^{2/3}$

The hertzian parameters of contact (the radius, the normal displacement and the maximum contact pressure) can be evaluated.

2. ANALYSIS OF HEATING FLUX

The tangential traction direction in the slip annulus takes the maximum value

$$\tau(r) = \mu p_o\left(1-\frac{r^2}{a^2}\right) \tag{4}$$

for $c \le r \le a$

The requirements of equilibrium in the tangential direction and continuity of the tangential traction component are satisfied by the tangential distribution in the stick circle, given by [3]

$$\tau(r) = \mu p_o\left[\left(1-\frac{r^2}{a^2}\right)^{1/2} - \frac{c}{a}\left(1-\frac{r^2}{c^2}\right)^{1/2}\right] \tag{5}$$

for $r \le c$

When the tangential force is increased from zero, microslip starts at the rim of the contact circle (r = a) and penetrates inwards to the radius c given by eqn. (1).

The tangential displacement will increase and may be decomposed into two components

$$\delta = \delta_e + \delta_s \tag{6}$$

where δ_e is the elastic (reversible) component and δ_s is the slip (irreversible) component.

During successive unloading, the slip tangential displacement starts at the rim and penetrates inwards. We analyze the case when the tangential displacement is imposed, but the tangential force amplitude ($F_x = F_o$) is inferior to friction force (μF_z).

The tangential displacement can be a perfect sine function

$$\delta = \delta_o \sin \omega t = \delta_0 \sin\left(2\pi\frac{t}{T}\right) \tag{7}$$

where δ_o is the amplitude of displacement, $\delta_o = \delta_M\left[1-(1-F_{ao})^{2/3}\right]$; ω - the angular velocity, T-the period of fretting cycle and t- the time.

The tangential force amplitude (F_o) and the displacement amplitude can be connected with eqn (3)

$$F_o = \mu F_z\left[1-\left(1-\frac{\delta_o}{\delta_M}\right)^{3/2}\right] \text{ or}$$

$$F_{ao} = \frac{F_o}{\mu F_z} = 1-\left(1-\frac{\delta_o}{\delta_M}\right)^{3/2} \tag{8}$$

The complete curve of fretting cycle in dimensionless parameters (tangential force and displacement) can be obtained and is equal to:

$$F_{axd} = F_{ao} - 2 + 2\left\{0.5\left[1+\delta_{ax}+(1-F_{ao})^{2/3}\right]\right\}^{3/2} \tag{9}$$

during unloading, when the dimensionless tangential force is gradually decreased at F_{ao} to - F_{ao} for the decreasing of displacement at δ_{ao} to -δ_a;

$$F_{axl} = \frac{2F_{ao}}{\delta_{ao}}\delta_{ax} - F_{axd} \tag{9'}$$

during loading, when the dimensionless tangential force is gradually increased at -F_{ao} to F_{ao} for the increasing of displacement at -δ_{ao} to δ_a.

The dimensionless elastic displacement δ_{aex} can be evaluated by the fretting cycle for the unloading and the loading curve

$$\delta_{aedx} = F_{axd}\,\frac{\delta_{ao}}{F_{ao}}$$ for unloading curve and

$$\delta_{aelx} = F_{axl}\,\frac{\delta_{ao}}{F_{ao}}$$ for loading curve.

The dimensionless slip displacement δ_{ap} is obtained as a function to total displacement and the elastic displacement eqn.(6).

For the variation of displacement, eqn.(7), it is possible to define the slip displacement and the slip velocity.

Thus, the slip velocity when the load is decreasing can be obtained

$$v_{sd} = \frac{\partial}{\partial t}\left(\delta_{pd}\right) = \delta_0 \omega f_v \qquad (10)$$

where f_v is a velocity function ;

and

$$v_{sl} = \frac{\partial}{\partial t}\left(\delta_{pl}\right) = v_{sd} - \delta_o \omega \cos \omega t = -v_{sd} \qquad (10')$$

for the slip cycle when the load is creasing.

The thermal flux in the slip annulus can be obtained with eqns (5) and (10), (10'):

$$q_d\left(r,t\right) = \tau(r) v_{sd}\left(t\right) \qquad (11)$$

for the decreasing load

and $$q_l\left(r,t\right) = \tau(r) v_{sl}\left(t\right) \qquad (11')$$

for the increasing load.

3. MAXIMUM AND AVERAGE TEMPERATURE IN FRETTING CONTACT

Temperatures in the fretting contact can be obtained by the integrating the fundamental solution of conduction [5],

$$\theta = \frac{Q}{8\rho c_t \left(\pi\kappa t\right)^{3/2}}\, e^{-\left[(x-x')^2+(y-y')^2+(z-z')^2\right]/4\kappa t} \qquad (12)$$

where Q is an instantaneous point source of strength at *(x',y',z')* at time $t = 0$; ρ - density; c_t –specific heat; κ - thermal difusivity of material.

We suppose that heat is emitted at a point of annular fretting contact ($z' = 0$) for $t > 0$ and that an semi-infinite medium moves past the instantaneous point with velocity v_s parallel to the axis of *x*.

In the element of time *dt'* at *t'*, Q *dt'* heat units were emitted at the mobile point *(x',y',0)*.

The point of the semi-infinite medium which at time t is at *(x,y,z)*, at time *t'* was at $\left\{x - v_s\left(t - t'\right) - x'\,, y - y'\,, z\right\}$.

Thus the temperature at *t* at *(x,y,z)* due to the heat Q *dt'* emitted at *t'* is

$$\theta_i\left(t,t'\right) = \frac{Q}{4\rho c_t \left(\pi\kappa\right)^{3/2}}\, f\left(x,y,z,x',y',t,t'\right)/\left(t-t'\right)^{3/2} dt' \qquad (13)$$

where

$$f = \exp\left[-\frac{\left\{x - v_s\left(t-t'\right) - x'\right\}^2 + \left(y-y'\right)^2 + z^2}{4\kappa\left(t-t'\right)}\right]$$

is a function which depends to point location of heat source (*x',y'*) and current point (*x,y,z*) and time.

The temperature at the *t* due to the heat emitted at the point *(x',y',0)* from time 0 to *t* is

$$\theta_t\left(t,t'\right) = \frac{1}{4\rho\, c_t \left[\pi\kappa\right]^{3/2}} \times \int_0^t Q\, f\left(x,y,z,x',y',t,t'\right)/\left(t-t'\right)^{3/2} dt' \qquad (14)$$

Temperature solution for different heat sources distributions can be obtained by integrating the above point heat source solution.

Figure 2 shows an annular heat source of radius *a* and *c* acting on the surface of semi-infinite medium. The *x*-axis is the sliding direction and there is an angle ψ between the *x*-axis and the *r*-axis [6]. The temperature rise at P caused by the heat flux over an infinitesimal element $s\, d\phi\, ds$ at C is

$$d\theta = \frac{1}{4\rho c_t \left(\pi\kappa\right)^{3/2}} \times \int_0^t q\, s\, f\left(x,y,z,x',y',t,t'\right) \frac{1}{\left(t-t'\right)^{3/2}}\, d\phi\, ds\, dt' \qquad (15)$$

where q is the source distribution of the slip region of the fretting contact.

The surface temperature rise at location $P(r,\psi)$, $z = 0$, due to a heat source acting over the slip fretting contact area is given by

$$\theta_f\left(r,\psi,t\right) = \frac{1}{4\rho\, c_t \left(\pi\kappa\right)^{3/2}} \times \int_0^t \left\{ \int_0^{2\pi} \left[\int_{s_1}^{s_2} q\left(s,\phi,t,t'\right) s\, f\left(s,\phi,t,t'\right) \frac{1}{\left(t-t'\right)^{3/2}} ds \right] d\phi \right\} dt' \qquad (16)$$

where s_1 and s_2 are the lengths between point *P* and inter and outer circumference respectively.

These lengths and the coordinates of some points can be evaluated by the geometrically conditions.

Some distances from current P point to A, A_1, C and C_1 points can be defined by geometrical conditions. The Cartesian point coordinates are:

$$x_P = r\cos\psi\,,\, y_P = r\sin\psi\,;$$

$$x_A = \frac{-mn+\sqrt{\Delta}}{1+m^2}, \qquad y_A = mx_A + n\,;$$

$y_{aA1} = y_A/a$; $x_{aC} = x_C/a$; $y_{aC} = y_C/a$; $x_{aC1} = x_{C1}/a$; $y_{aC1} = y_{C1}/a$; $n_a = n/a$; $\Delta_a = \Delta/a$; (18)

$\Delta_{ac} = \Delta_c/a$; $c_a = c/a$.

The geometrical parameters from the function f(x,y,z,x',y',t,t') (eqn13), in dimensionless form, are

$$x_a - x_a' = s_a\cos(\psi-\phi)\,;$$

$$y_a - y_a' = s_a\sin(\psi-\phi); \qquad \delta_{oa} = \delta_o/a\,;$$

$t_a = t/T$; $t'_a = t'/T$, where T is the period of fretting cycle.

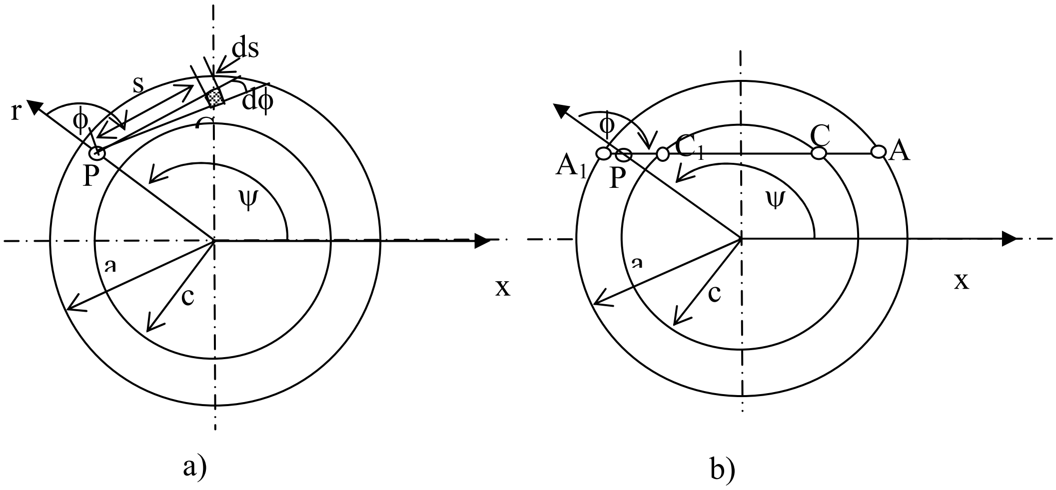

Figure 2: *Geometrical relation for an annular heat source.*

$$x_{A1} = \frac{-mn-\sqrt{\Delta}}{1+m^2}; \qquad y_{A1} = mx_{A1} + n$$

$$x_C = \frac{-mn+\sqrt{\Delta_c}}{1+m^2}, y_C = mx_C + n\,;$$

$$x_{C1} = \frac{-mn-\sqrt{\Delta_c}}{1+m^2}, y_{C1} = mx_{C1} + n\,, \qquad (17)$$

where $m = \tan(\psi-\phi)$; $n = r\dfrac{\sin\phi}{\cos(\psi-\phi)}$;

$$\Delta = (1+m^2)a^2 - n^2\,;\ \Delta_c = (1+m^2)c^2 - n^2$$

We adopt the dimensionless coordinates in comparison with the external radius of fretting circle, *a*.

Thus, $r_a = r/a$; $x_{aP} = x_P/a$; $y_{aP} = y_P/a$; $x_{aA} = x_A/a$; $y_{aA} = y_A/a$; $x_{aA1} = x_{A1}/a$;

To solve the integral equation (16) it is necessary to determine the coordinate of C and C_1 points as a function of the ψ and ϕ. In this case, can be evaluated an critical angle, $\phi_c = \arcsin(c/r)$, which delimitates five zones of the ψ angle contact as a function to variable length in the P point (fig.2):

$$(0,\phi_c);(\phi_c,\pi-\phi_c);(\pi-\phi_c,\pi+\phi_c);$$
$$(\pi+\phi_c,2\pi-\phi_c);(2\pi-\phi_c)$$

We note the dimensionless temperature

$$\theta_{af}(\psi,r,t) = k_\theta\theta_f(\psi,r,t)$$

where $k_\theta = \dfrac{2\rho c_t(\pi\kappa T)^{3/2}}{\pi\mu\, p_o a^3 k_a}$ is a thermal and loading parameter. (17)

The integral function (16) can be solve in dimensionless form for divers parameters of fretting phenomena.

Figure 3 shows the dimensionless temperature, θ_{af}, as a function to geometrical position of point for the ball-plane contact (steel-steel material). The maximum dimensionless temperature for first fretting cycle appears to center of contact circle($r_a = 0$).

Figure 4 shows that dimensionless temperature has a maximum as a function to normal load and frequency.

The variation of dimensionless temperature as a function to dimensionless axial load, F_{ad}, is shown in the Figure 5.

The thermal and loading parameter k_θ can be evaluated by some values of friction coefficient, normal load and frequency. Thus, for the steel-

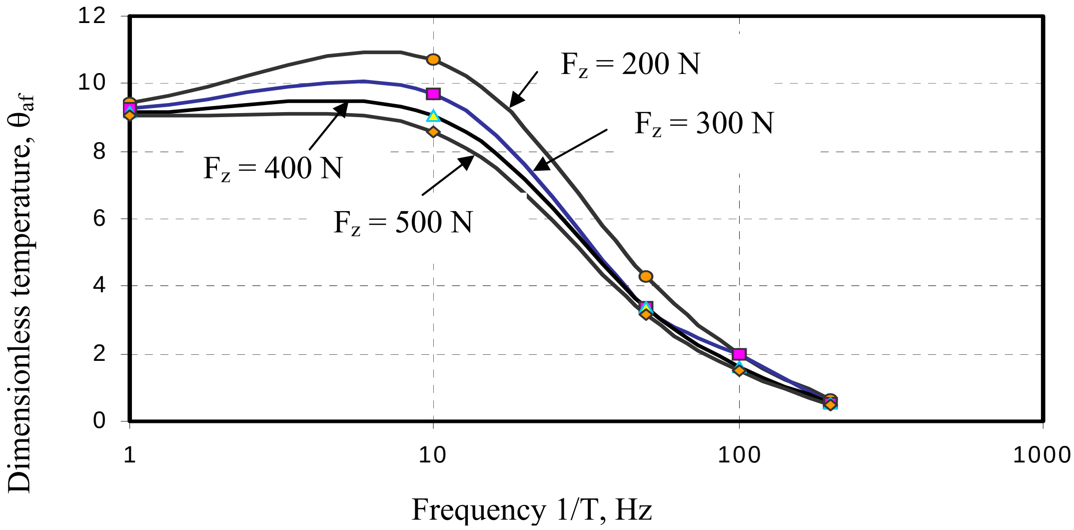

Figure 4: *Dimensionless temperature vs. frequency of fretting movement.*

The temperature decreases to rim of fretting contact and the maximum for every radius is placed to opposite axial load ($\psi = 3.14$ rad).

steel materials, this parameter has an interval very large 10^{-3} …. 10^{3}, when the friction coefficient $\mu = 0.9$, normal load $F_z = 500$ N, frequency $1/T = 1000$ Hz, rayon of ball $r = 12.5$ mm and, respectively, $\mu = 0.1$, $F_z = 200$ N, $r = 12.5$ mm, $1/T = 0.1$ Hz .

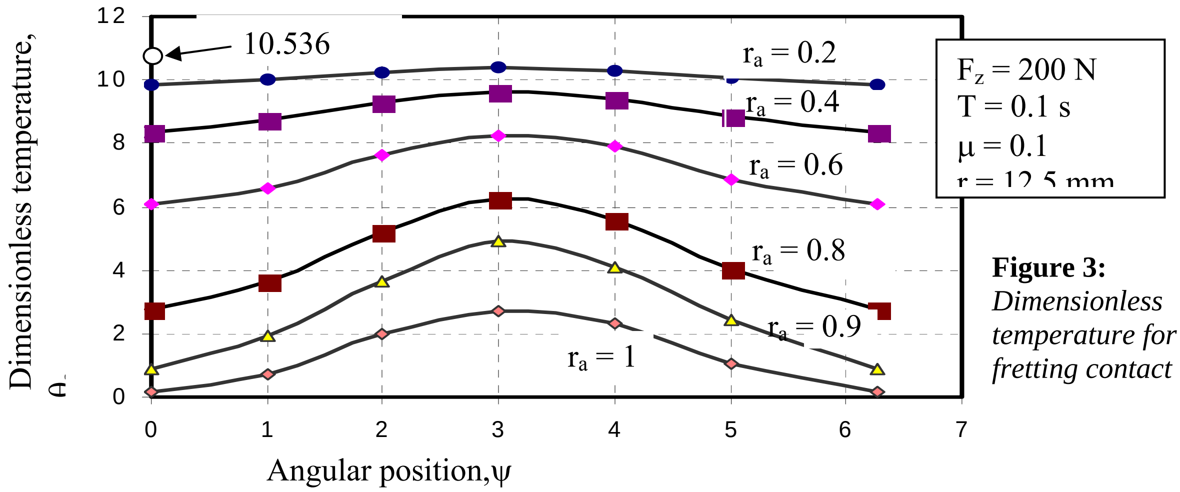

Figure 3: *Dimensionless temperature for fretting contact*

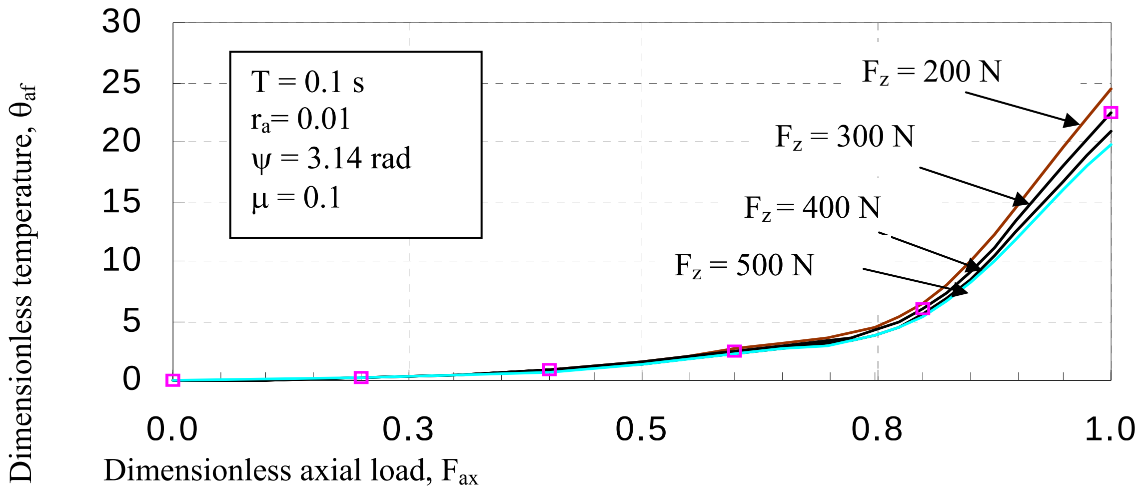

Figure 5: *Dimensionless temperature vs. axial load*

For example, the theoretical temperature in the centre of sphere – plate fretting contact (steel – steel materials, normal load F_z = 500 N, friction coefficient μ = 0.9, frequency 100 Hz, rayon of sphere r = 12.5 mm) for first fretting cicle is 14.05 ^{o}C. In time, the temperature has a oscilating evolution with increasind tendency. Thus, the temperature after 1000 cicles will be 38.65 ^{o}C.

4. CONCLUSIONS

The heat flux in the fretting contact is dependently to slip area and to plastically displacement.

The general conduction heat equation can be solved for annular heating source which is specifically for fretting phenomena. It is necessary to delimitate a critical angle in the annular contact for to integrate the conduction heat equation.

The maximum temperature appears in the centre of the fretting contact for all normal loads and frequencies. The temperature decreases to rim of fretting contact and the maximum, for every radius, is placed to opposite axial load.

The fretting temperature has an oscillating evolution in time, but the average temperature increases.

The main fretting parameters for temperature field are frequency, friction coefficient and normal load.

The maximum fretting temperature can be used to explain the specifically fretting wear.

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