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Thermal constriction phenomenon in fretting: Theory and implications ☆

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ABSTRACT

Contact temperature in fretting has a significant effect on the process. Since direct temperature measurement is impossible, analytical models are required to estimate the friction-induced temperature rise for the optimization of the system performance. The objective of this work is to present models for the micro and macro thermal constriction phenomena in fretting. The effect of the process parameters is examined. The analysis showed that the contact temperature rise can be quite significant when the contact pressure-to-hardness ratio is high and when the material thermal conductivity is low. The paper is concluded with recommendations for future work.

1. Introduction

Due to the nature of engineering surfaces, the real contact area is a very small fraction of the apparent area of contact, giving rise to "thermal constriction (or spreading) phenomenon". This phenomenon results in a steep temperature gradient in the subsurface layer, and possibly a significant rise in the contact temperature [1–4]. The friction-induced temperature rise in the fretting zone has far reaching effect on the oxidation process, the material microstructure, as well as its physical and mechanical properties. The effect of temperature on fretting has been investigated by many investigators [5–9]. The existence of transition temperature(s), at which the wear rate changes significantly, was observed in these studies. Therefore, proper laboratory simulation of fretting wear/fatigue tests requires that the contact temperature due to friction heating and external sources in the specimens and the original components to be identical [10].

The disturbed temperature field around the contact asperity is contained within a very shallow subsurface layer of the order of 50–100 μm, and changes rapidly within one-quarter of the oscillation cycle, which is typically of the order of 10 ms [2,11]. This demonstrates that with the physical dimensions and the response time of temperature sensing elements, the desired spatial and temporal resolutions cannot be achieved for direct measurement of the contact temperature. Presently, the contact temperature can only be estimated using analytical models and computer simulation tools. Such predictions are essential at the design and operation stages for the optimization of the fretting tribo-system parameters and its performance. To predict the response behavior of a real fretting tribo-system (of a complicated geometry, and realistic thermal boundary conditions), the division of frictional heat, and the thermal characteristic of the whole system should be considered. This can only be achieved using numerical methods, e.g., finite element and finite difference, similar to the work done to solve the heat transfer process in sliding tribo-systems [12–15]. In the analyses presented in [12,13], the thermal constriction resistance for constant, uniform heat flow in static contact was used. Ling and Pu [12] noted, however, that more detailed analysis of the thermal constriction resistance requires additional work. The only missing link in following this approach is the lack of qualitative understanding and quantitative modeling of the thermal constriction phenomenon.

This paper presents an overview of an analytical approach to formulate the thermal constriction phenomenon in fretting, in terms of the micro- and macroscopic features of the surface topography, the applied external load, the amplitude and frequency of oscillation, and the material properties. Since the temperature rise is directly proportional to the heat flow rate, the partitioning of the frictional heat between contacting solids has to be defined a priori. Satisfying the requirement for the continuity of the average contact temperature and the conservation of energy, a model for the heat partition coefficient is also presented. The debatable question on whether or not the contact temperature in fretting is high is addressed, considering a wide range of materials and applied loads. The paper is concluded with

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Nomenclature

a	amplitude of oscillation, μm
A_a	apparent contact area, m^2
A_c	contact area, m^2
A_{cn}	contour contact area, m^2
A_{hfc}	cross-sectional area of the HFC, m^2
A_{mic}	micro-contact area, m^2
A_r	real contact area, m^2
AR	aspect ratio of the rectangular micro-contact area, $AR=H_x/H_y$
c_p	material specific heat, J kg^{-1} K^{-1}
C_{th}	thermal capacitance, J K^{-1}
C'	the distributed electrical capacitance per unit length, F m^{-1}
d	distance, m
e_x, e_y	the eccentric position of the contact asperity with respect to the center of the HFC, m
e^*	dimensionless eccentricity parameter, defined by Eq. (44), m
$\mathbf{E}(\cdots)$	expected value
f	frequency of oscillation, s^{-1}
$f(h)$	Gaussian distribution of asperity height (h)
$F(t_s)$	probability density function of the distance t_s between micro-contacts above the asperity height (h)
Fo	Fourier modulus, $Fo=\alpha/f\delta^2$; $Fo_{mic}=\alpha/f\delta^2_{mic}$ and $Fo_{mac}=\alpha/f\delta^2_{mac}$
H	hardness, N m^{-2}
H_x, H_y	length and height of the rectangular heat flow channel, m
k	material thermal conductivity, W m^{-1} K^{-1}
L	half the length of the side of an asperity of a square cross-section, μm
L_{mac}	half the length of the side of the contour area, μm
$\lvert m \rvert$	mean absolute slope of the surface asperities, radian
M	number of micro-contacts within the contour area A_{cn}
n_{hfc}	linear density of heat flow channels within the contour area, $n_{hfc}=\sqrt{M}/2L_{mac}$
N_{nr}	number of discrete heat sources in the near region
p_a	applied pressure, N m^{-2}
p_m	flow pressure of the softer material, N m^{-2}
q	heat flux, W m^{-2}
q_f	instantaneous heat flux over the micro-contact area, W m^{-2}
$\bar{q}_f$	average heat flux over the micro-contact area during the fretting cycle, W m^{-2}
q_e	effective uniform heat flux, $q_e=\varepsilon^2 q_f$, W m^{-2}
q_{fr}	uniform heat flux over the far region, $q_e=\varepsilon^2 q_f$, W m^{-2}
q_{ihs}	image heat source, $q_{ihs}=q_f$, W m^{-2}
q_o	amplitude of the sinusoidal heat source, W m^{-2}
q_{shs}	source heat source, $q_{shs}=q_f$, W m^{-2}
q_{sin}	sinusoidal uniform heat flux, W m^{-2}
Q	total heat flow rate, W
Q_f	total frictional heat flow rate over the contour contact area, W
r	radius of circular sector element, m
R'	the distributed electrical resistance per unit length, Ω m^{-1}
$\mathbf{R}_c$	thermal constriction resistance, K W^{-1}
$\mathbf{R}_{th}$	resistive component of the thermal impedance $\mathbf{Z}_c$, K W^{-1}
$\mathcal{R}$	radius of the equivalent circular heat source, m
$\Re$	radius of the randomly distributed micro-contact areas, m
$\bar{\Re}$	average radius of the randomly distributed micro-contact areas, m
S	spacing between two neighboring micro-contacts, m
t	time, s
t_s	distance between micro-contact contacts, m
u	separation between the median plane of the equivalent rough surface and the smooth semi-infinite body, m
v	instantaneous relative velocity between contacting solids, m s^{-1}
V	volume of the lumped body, m^3
x, y, z	Cartesian coordinate system
$\bar{x}$,$\bar{y}$,$\bar{z}$	dimensionless position coordinates, $\bar{x}=x/L$, $\bar{y}=y/L$, $\bar{z}=z/L$
$\mathbf{X}_{th}$	capacitive reactance component of the thermal impedance $\mathbf{Z}_c$, K W^{-1}
$\mathbf{Z}_c$	thermal constriction impedance, K W^{-1}
$\mathbf{Z}_{mac}$	macroscopic thermal constriction impedance, K W^{-1}
$\mathbf{Z}_{mic}$	microscopic thermal constriction impedance, K W^{-1}
$\mathbf{Z}_{mic,t}$	total microscopic thermal constriction impedance of all HFC's, K W^{-1}
$\mathbf{Z}_{interface}$	overall thermal constriction impedance of the interface, K W^{-1}

Greek symbols

α	material thermal diffusivity, m^2 s^{-1}
$\Delta\beta$	included angle of a circular sector element, radian
γ	ratio of the contour area relative to the average micro-contact area
δ	characteristic length of the heat source under consideration (Eq. (29), m
ε^2	constriction ratio, $\varepsilon^2=A_r/A_a$
η	parameter defined in Eq. (28)
θ	temperature rise, K
θ_c	contact temperature, K
$\theta_{c,max}$	maximum contact temperature of the micro-contact area, K
θ_d	temperature deviation in the thermally disturbed zone, K
θ_i	interface temperature under perfect contact conditions, K
θ_m	mean temperature of the cross-section of the HFC at the contact plane, $z=0$, K
$\dot{\theta}$	rate of change of temperature, K s^{-1}
$\bar{\theta}$	average temperature rise, K
$\Delta\bar{\theta}_c$	average contact temperature of the micro-contact area, K
$\Delta\theta_c$	'pseudo' temperature drop at the contact interface, K
$\Delta\bar{\theta}_m$	temperature drop due to the material resistance in the thermally disturbed zone, K
Θ	dimensionless temperature parameter, $\Theta=(\theta k/q_f L)$
μ	coefficient of friction
ξ	heat partitioning coefficient
ρ	mass density, kg m^{-3}
Φ	standard deviation of surface asperity heights, m
ς	parameter defined in Eqs. (40) and (41)
τ	period of reciprocation, s
N	phase difference between the heat flow and the temperature at any point, radian
$\Phi(\bar{\Re})$	probability density function of the size of the micro-contact areas
P	constriction parameter for concentric contact
P^*	constriction parameter for eccentric contact
ω	circular frequency of reciprocation, $\omega=2\pi f$, s^{-1}