Tribology: Principles and Design Applications

Tribology

Principles and Design Applications

R. D. Arnell
P. B. Davies
J. Halling
T. L. Whomes

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MACMILLAN

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Preface

In 1975 we and four of our former colleagues wrote the textbook *Principles of Tribology*. That book was very successful both in the United Kingdom and overseas and it is still being sold today. However, 13 years after the first publication of the book, the publishers suggested that we should consider revising the text, to include the more important developments which had taken place in the meantime.

Although we have remained active in tribological research, it was only when we started work on this revision that we realised that the developments which have taken place have been so extensive that they could not be accommodated simply by revision of our existing text. As a result, although we have reused some of our original material, the present book has resulted from a complete reappraisal of our ideas on the necessary content of a modern introductory textbook on tribology. As the title of the book implies, it has been our intention to write a book which will provide a thorough grounding in the principles of our subject for undergraduates and new research workers and will also act as a basic reference book for practising designers.

In the areas of friction and wear, although there has been a great deal of high-quality research on the underlying physical and mechanical processes, there are no current, or indeed foreseeable, models which will allow quantitative predictions of friction coefficients or wear rates from basic physical, chemical and mechanical properties. Such predictions will continue to be based on experimental measurements. Therefore, in these areas, we have attempted to set out as clearly as possible the underlying processes and thus to assist the reader in making sensible initial choices of materials.

In the areas of fluid film lubrication, as well as covering the fundamental mechanisms, we present simple design procedures for hydrodynamic bearings and incorporate the more important aspects of the growing amount of information on elastohydrodynamic lubrication, with examples of its use in design.

We have also included in the book introductions to more practical considerations such as lubricant selection, lubricant-supply systems, condition monitoring and failure analysis.

We should like to record our thanks to Mrs Marise Ellidge for her help in preparing the typescript and to Miss Jenny Shaw, formerly Engineering Editor of Macmillan Education, for her great tact and patience.

May, 1990

R. D. A.

P. B. D.

J. H.

T. L. W.

Notation

<i>Symbol</i>	<i>Definition</i>
A	Real area of contact
A_F	Area of filter
a	Semixaxis of contact ellipse in transverse direction, or radius of contact circle (Chapters 1, 7)
a	Width of axial supply groove (Chapter 6)
B	Width of bearing
b	Length of journal bearing (Chapter 6)
b	Semixaxis of contact ellipse in direction of motion (Chapter 7)
C	Dynamic load capacity of rolling bearing (Chapter 8)
C_0	Static capacity of rolling bearing
C	k_r/k
C_p	Specific heat
C_d	Diametral clearance
c	Radial clearance
D	Diameter of gear wheel
d	Diameter of journal bearing
d_m	Mean diameter of rolling bearing
E	Elastic modulus
E'	Elastic modulus of contact $= 2 \left/ \left(\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right) \right.$
E^*	Elastic contact modulus $= 1 \left/ \left(\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right) \right.$
e	Shaft eccentricity
F	Shear or friction force
F_a	Axial force
F_R	Rolling friction

F_{rad}	Radial force
F_S	Sliding friction
F_x, F_y, F_z	Force in coordinate directions
$\bar{F}$	$F/(\eta U_0 BL/h_1)$
f	Fraction of scratched volume to become wear debris
$\hat{G}$	Materials parameter ($= E'\alpha$)
g	Acceleration due to gravity
g_e	$= \frac{\hat{W}}{\hat{U}^{1/2}} \left\{ \begin{array}{ll} \text{rectangular} & = \frac{\hat{W}^{8/3}}{\hat{U}^2} \\ \text{contact} & = \left(\frac{\hat{W}}{\hat{U}} \right)^2 \hat{H} \end{array} \right\} \left\{ \begin{array}{l} \text{elliptical} \\ \text{contact} \end{array} \right.$
g_h	$= \frac{\hat{W}}{\hat{U}} \hat{H}$
g_v	$= \frac{\hat{W}^{3/2}}{\hat{U}^{1/2}} \hat{G} \left\{ \begin{array}{ll} \text{rectangular} & = \frac{\hat{W}^{8/3}}{\hat{U}^2} \\ \text{contact} & = \left(\frac{\hat{W}}{\hat{U}} \right)^2 \hat{H} \end{array} \right\} \left\{ \begin{array}{l} \text{elliptical} \\ \text{contact} \end{array} \right.$
H	Hardness (Chapters 2, 3)
H	Power to rotate shaft (Chapter 6)
$\bar{H}$	Dimensionless power coefficient
$\hat{H}$	Dimensionless film thickness ($= h/R$)
h	Dimensionless surface separation (Chapter 1)
h	Film thickness (Chapters 6, 7, 8)
h_c	Central film thickness
h_m	Film thickness at maximum pressure
h_{max}	Maximum film thickness in a journal bearing
h_{min}	Minimum film thickness in a journal bearing
h_0	Minimum film thickness
h_p	Film thickness at pitch line
h_s	Starved film thickness
h_1	Outlet film thickness of slider
h_2	Inlet film thickness of slider
h_∞	Film thickness with fully flooded inlet
I	Inlet shear heating parameter $= \left(\frac{\eta_0 \delta U^2}{K} \right)$
J	Inlet factor ($= bx_i/(2Rh_0)^{2/3}$)
j	Coordinate in X direction
K	Wear coefficient (Chapter 3)
K	Bearing inclination (Chapter 5)
K	Thermal capacity constant (Chapter 6)
K	Thermal conductivity (Chapter 7)
K_F	Filter characteristic
K_G	Grease lubrication constant
k	Yield shear stress (Chapters 1, 2, 3)
k	Specific wear rate (Chapter 4)
k	Proportion of heat convected by oil (Chapter 6)

x NOTATION

k_e	Ellipticity parameter ($= a/b$)
k_0	Constant specific wear rate
k_r	Contaminant shear stress
L	Length of sliding bearing (Chapter 5)
L	Life of bearing in revolutions (Chapters 3, 8)
l	Length of axial supply groove (Chapter 6)
l	Centre distance of gears (Chapter 7)
M	Mass supported by journal bearing (Chapter 6)
M	Moment of frictional force (Chapter 8)
m	Dimensionless distance to inlet boundary ($= x/b$)
m_i	Critical inlet boundary distance
N	Speed (rev/s)
N_F	Number of cycles to failure
N_l	Number of ordinates of spacing l in sample length
n	Exponent in stress-strain equation (Chapter 1)
n	Number of contacts (Chapter 3)
n	Speed (rev/min) (Chapter 9)
P	Load per unit length (Chapter 1)
P	Power, rate of heat generation (Chapters 5, 8)
P	Dynamic equivalent load on rolling bearing (Chapter 8)
P_0	Static load on rolling bearing
p	Pressure
p_0	Yield pressure
p_f	Pressure of fluid in supply groove
p_h	Maximum Hertzian pressure
p_{mean}	Mean contact pressure
p_{max}	Maximum pressure
$\bar{p}$	Normalised pressure ($= p/H$)
Q	Tangential force in rolling contact (Chapter 2)
Q	Wear volume (Chapter 3)
Q	Volume rate of flow (Chapters 5, 6, 9)
$\bar{Q}$	$Q/(Bh_1 U_0)$
$\bar{Q}$	Dimensionless flow rate
Q_p	Pressure-induced flow
Q_v	Velocity-induced flow
Q_d	Depth wear rate
q	Tangential traction in rolling contact
R	Equivalent radius of curvature (Chapter 7)
R	Relubrication factor (Chapter 9)
R_A	Mean roughness of a surface
R_e	Reynolds number
$R(l)$	Autocorrelation function
R_x	Radius of curvature in direction of rolling
R_y	Radius of curvature in transverse direction

$\bar{R}$	Ratio between plastic and elastic area
R_1	Radius of journal bearing
R_2	Radius of shaft
$r(l)$	Normalised autocorrelation function
s	Dimensionless asperity height (Chapter 1)
s	Friction force/unit area (Chapter 2)
s	Slid distance (Chapter 3)
T	Temperature
T_e	Effective temperature of oil
T_f	Temperature of oil at feed groove
T_1	First transition load
T_2	Second transition load
$\bar{T}$	Dimensionless temperature coefficient
t	Thickness of surface film
U	Rolling speed ($= (U_1 + U_2)/2$)
$\hat{U}$	Dimensionless speed parameter ($= \eta U / E' R$)
U_0	Velocity of moving surface or shaft surface
U_c	Velocity of surface
u	Speed
V	Scratch volume
V_p	Velocity at pitch line
V_e	Entraining velocity at pitch line
V_r	Viscosity ratio
V_t	Viscosity ratio at operating temperature
W	Load
$\hat{W}$	Dimensionless load parameter
$\bar{W}$	$W / (\eta U_0 B (L/h)^2)$ (Chapter 5)
$\bar{W}$	Dimensionless load coefficient
W_0	Load/unit length
x	Coordinate in direction of rolling
x_i	Distance from inlet to edge of Hertzian contact
x_m	Coordinate for maximum pressure
Y	Load factor
y	Transverse coordinate
z	Coordinate normal to plane of contact
α	Parameter defining accuracy of Hertz equations (Chapter 1)
α	Constant (Chapter 2)
α	Pressure viscosity coefficient (Chapter 7)
β	Radius of asperity tip (Chapter 1)
β	Mechanical constant defining load capacity (Chapter 3)
γ	Surface energy (Chapter 2)
γ	R_y / R_x (Chapter 7)
ΔT	Temperature rise
δ	Normal approach of surfaces (Chapter 1)

δ_e	Normal approach at limit of elastic deformation
δ	Temperature–viscosity coefficient
ε	Hysteresis loss coefficient (Chapter 2)
ε	Eccentricity ratio
η	Number of asperities per unit area (Chapter 1)
η	Dynamic viscosity (Chapters 5, 6, 7, 8, 9)
η_e	Effective dynamic viscosity
η_f	Dynamic viscosity of oil in supply groove
η_0	Viscosity at ambient temperature and pressure
η_s	Viscosity at surface temperature, ambient pressure
η_x	Viscosity at surface temperature, actual pressure
θ	Semiangle of conical asperity (Chapter 2)
θ	Polar coordinate (Chapter 6)
Λ	Parameter defining amount of asperity contact (Chapter 2)
λ	Parameter governing normal approach (Chapter 1)
λ	Coefficient of rolling resistance (Chapter 2)
λ	Specific film thickness ratio ($= h/R$) (Chapters 7, 8, 9)
μ	Coefficient of friction
ν	Poisson's ratio (Chapters 1, 7)
ν	Kinematic viscosity (Chapters 6, 7, 8, 9)
ξ	$apcV/2\alpha$
ρ	Density
σ	Standard deviation
σ_r	Composite roughness
σ_Y	Uniaxial yield stress
τ	Shear stress
τ_s	Interfacial shear strength
ψ	Plasticity index $\left(= \frac{E}{H} \left(\frac{\sigma}{\beta} \right)^{1/2} \right)$ (Chapter 2)
ψ	Attitude angle (Chapter 6)
ϕ	$(1 + 2\gamma)^{-1}$ (Chapter 7)
ϕ	Normal pressure angle of gear teeth
$\phi(z)$	Surface height distribution function

Subscripts

1, 2 Refer to the two surfaces of the contact