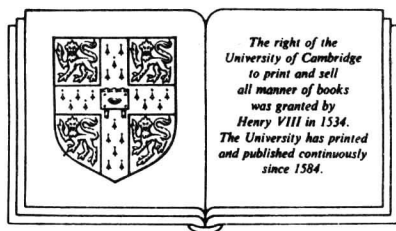# Physical analysis
for tribology

Physical analysis for tribology

Terence F. J. Quinn

Professor of Engineering
School of Engineering and Applied Science
United States International University
(European Campus)
Bushey, Hertfordshire

The right of the
University of Cambridge
to print and sell
all manner of books
was granted by
Henry VIII in 1534.
The University has printed
and published continuously
since 1584.

CAMBRIDGE UNIVERSITY PRESS

Cambridge

New York   *Port Chester*

Melbourne   *Sydney*

Preface

This book has been written with the aim of demonstrating the power of using modern techniques of physical analysis for studying the complex interactions that often occur between the contacting surfaces of tribo-systems, that is, systems involving relative motion between the various elements.

It is an *interdisciplinary* book, which should be of interest to tribologists whose major discipline is physics, chemistry, metallurgy or any branch of engineering involved with moving parts. Obviously, mechanical and production engineers will have more interest in tribology than (say) civil engineers or electrical engineers, but even with these disciplines, tribological problems can occur for example traction between asphalt and rubber and the wear of carbon brushes.

The book aims to be understandable by readers at all levels of technical competence with an interest in tribology. It should be of special interest to those final year undergraduate students intending to make a career in the research and development laboratories associated with the oil companies, the electricity generating industry, the aerospace companies, the steel-making and steel-forming enterprises, the automotive and diesel engine manufacturers, the railways, or any other industrial concern heavily dependent upon good tribological knowledge and practice.

Even those undergraduates destined for the production side of these industries, should find the introductory chapter on tribology useful background reading, especially if they are involved with design. Certain aspects of the chapters on the analysis of lubricant films, surface temperatures pitting failures and ceramic tribo-systems should also be of interest to these prospective industrial engineers.

The introductory chapters on the various physical methods of analysis have been written so that the chapters on applications can be understood by non-specialists *without reference* to any other sources of information. The master's degree student, or first year doctoral degree student, should find these chapters of use in their studies, even if their interest in tribology is only peripheral.

Obviously, the applications chapters are aimed at committed tribologists and those engineers and other technologists involved with the successful functioning of tribo-systems. Even if the particular tribo-systems chosen for this book do not match with the systems actually of interest to these people, the methods of application and the interpretation of the analytical results will be relevant.

The chapters dealing with the basic aspects of the physical analytical techniques have been deliberately placed separately from the applications, rather than discuss each technique together with its applications. It was considered a more suitable way to deal with all of the thirteen physical analytical techniques covered by this book and their application to the study of tribo-systems, especially as some techniques are of universal applicability. In this way, some of the more important topics of tribology are discussed in a more comprehensive and unified manner. The choice of topics ensures that most aspects of tribological endeavour are covered in this book. There is some bias towards the research

interests of the author. For instance, the chapter on the analysis of oxidational wear in tribo-systems contains several references to my work over the past 20 years or so. Such bias is inevitable in a book on a subject which has interested me since I first began research in 1953 at the research laboratories of Associated Electrical Industries at Aldermaston. There has been, however, an attempt to include as much reference as possible to the contributions of other investigators using physical analaysis in their approach to tribology.

Some of the more specialized surface analytical techniques such as time-of-flight secondary ion mass spectrometry (TOF-SIMS), static secondary ion mass spectrometry (SIMS), liquid metal ion source, secondary ion mass spectrometry (LMIS-SIMS), scanning tunnelling microscopy (STM) and Fourier-transform infra-red (FTIR) spectroscopy, have not been included, chiefly on the grounds that they have not been applied to tribological problems.

It is possible that some of the *nuclear techniques*, such as Rutherford back-scattering (RBS), nuclear reaction analysis (NRA) and proton-induced X-ray analysis (PIXE) will *eventually* be used more frequently than heretofore in the study of tribosystems. Certainly, radio-active tracers were applied with some success in the early days of nuclear energy. The lack of availability of particle accelerators and/or the problems of providing protection from ionizing radiations, has tended to limit the use of these techniques in tribological investigations. To include *all possible* physical techniques for analysing the products of surface interactions between tribo-elements would be *prohibitive* (and not very relevant to the practising tribologist). Hence the compromise solution embodied by this book.

It is hoped that this compromise will not prevent all readers of this book from gaining *some* new knowledge, regardless of their main interest. If, as a result of reading this book, those readers with strong tribologist interests can appreciate the power of using physical analysis in their investigations, and can talk *knowingly* with the experts carrying out that analysis, then I will feel I have accomplished my original aims in writing the book. If, on the other hand, the analytical experts also begin to appreciate the fundamental tribology of the tribosystems they are called upon to analyse as a result of reading this book, then this will be a definite bonus as far as the furtherance of tribological knowledge is concerned.

Nomenclature

$A_1 =$ Area of densitometer aperture (in Equation 2.38)

$A_2 =$ Area covered by opaque particles (in Equation 2.38)

$(A_b) =$ Absorption coefficient (light).

$A =$ General Arrhenius constant.

$A_{real} =$ Real area of contact ($= W/p_m$).

$(A_e)_s =$ Elastic area of single constant.

$(A_p)_m =$ Real area of multiple contact.

$(A'_p)_m =$ Interpenetration area (normal to sliding direction).

$(A_e)_m =$ Multiple area of elastic contact.

$(A_n) =$ Nominal (apparent) area of contact.

$(A_p) =$ Arrhenius constant for parabolic oxidation of tribo-elements during sliding.

$AA =$ Arithmetical average deviation from the centre line of a surface profile.

$(A)_\parallel =$ Real area of contact between *parallel* members of graphite/graphite sliding interfaces.

$(A)_{PE} =$ Area of sample from which photoelectrons are detected.

$(A)_T =$ Real area of contact between *tilted* members of graphite/graphite interfaces.

$(A)_R =$ Real area of contact between *randomly* oriented members of graphite/graphite interfaces.

$\delta A_r =$ Contribution to the total contact area from an asperity in the rth level (Archard's simple model)

$(A)_w =$ Atomic weight.

$AES =$ Auger Electron Spectroscopy.

$AGR =$ Advanced Gas Cooled Reactor.

$a =$ Radius of contact (generally).

$(a_e), (a_p) =$ Radii of elastic, plastic contact.

$(a_i) =$ Inverse sensitivity factor for element (i) (AES).

$(a_L) =$ Amplitude of light wave.

$(a_w) =$ Scale factor of Weibull Equation (2.35).

$(a_{uc}) =$ Side of unit cell in the X-direction [100] of a crystal.

$(a^*_{uc}) =$ Side of unit cell in the X*-direction, (d_{100}) in the reciprocal lattice.

$(a_i^H) =$ Handbook value for (I_s^H/I_i^H) (Auger analysis).

$(a_i^0) =$ Relative inverse sensitivity factor between standard element(s) and pure element (i) under the same conditions [equals (I_s^H/I_i^H)].

$(\alpha_{uc}) =$ Angle between $\mathbf{b}_{uc}$ and $\mathbf{c}_{uc}$ in the unit cell.

$(\alpha_{uc}^*) =$ Angle between $\mathbf{b}_{uc}^*$ and $\mathbf{c}_{uc}^*$ in the reciprocal unit cell.

$\alpha' =$ Modified Auger parameter [Equation (4.29)].

$(\alpha_P) =$ Pressure/viscosity coefficient.

$(\alpha_{Pe}) =$ Collection of terms related to the Peclet Number [see Equation (6.4)].

$(\alpha_1) =$ Part of function growth Equation (6.28).

$(\alpha_{SA}) =$ Semi-aperture angle.

$B =$ Constant of *inverse* logarithmic and *direct* logarithmic 'oxide growth with time' laws.

$(B_{DW}) =$ Debye–Waller temperature factor $(= B_0 + B_T)$.

$BE =$ Binding Energy.

$B_{10} =$ Life which 90% of bearings will reach *without* failure.

$b =$ Diameter of point in reciprocal lattice.

$(\mathbf{b}_{uc}) =$ Side of unit cell in the Y-direction [010] of a crystal.

$(\mathbf{b}_{uc}^*) =$ Side of unit cell in the Y^*-direction, $\mathbf{d}_{010}$, in the reciprocal lattice of a crystal.

$(b_W) =$ Slope of Weibull plot.

$\beta =$ One of the constants of Equation (1.6).

$(\beta_{uc}) =$ Angle between $\mathbf{a}_{uc}$ and $\mathbf{c}_{uc}$ in the unit cell.

$(\beta_{uc}^*) =$ Angle between a_{uc}^* and $\mathbf{c}_{uc}^*$ in the reciprocal lattice unit cell.

$C =$ Contrast of an electron micrograph.

$(C_A) =$ True concentration of constituent A.

$(C_B) =$ Contrast of background adjacent to a feature in an electron micrograph.

$(C_f) =$ Contrast of a feature in an electron micrograph.

$(C_C) =$ Chromatic aberration constant of an electron microscope lens systems.

$(C_{dyn}) =$ Basic dynamic capacity of a bearing (ie load corresponding to the B_{10} life).

$CLA =$ Centre Line Average.

$CPT =$ Crack Propagation Time.

$(C_S) =$ Spherical aberration constant of an electron microscope lens system.

$(C_x) =$ Atomic fraction of the x-component.

$(C_w) =$ Constant of Equation (6.33) related to ξ, k_p and t_o.

$c =$ Velocity of light.

$(c_o) =$ Specific heat of the oxide formed on the surface of tribo-elements.

$(c_{uc}) =$ Side of unit cell in the Z-direction [001] of a crystal.

$(c_{uc}^*) =$ Side of unit cell in the Z^*-direction, $\mathbf{d}_{001}$, in the reciprocal lattice of a crystal.

$(c_x) =$ Constant of Equation (4.12).

$(c_z) =$ Distance between the slits of Young's Double-Slit Interferometer.

$D =$ Ratio of combined surface roughness to the minimum thickness of a lubricant film.

$(D_{min}) =$ Least distance of distinct vision (optical systems).

$(D_{ss}) =$ 'Slits-to-Screen' Distance in Young's double slits.

$(D_o) =$ Optical density of a 'Ferrogram'.

$(D_p) =$ Density of photographic blackening.

$(D_1), (D_2), (D_{F_3}), (D_{F_4}) =$ Different definitions of the D-ratio [Equations 7.5(a)–(d)].

$(D_s) =$ 'Specimen-to-film distance' in the flat plate X-ray diffraction method.

$d =$ Distance of sliding between two model asperities $(= 2a)$.

$(d_a) =$ Thickness of air film (in Newton's Rings and Multiple Beam Interferometers).

$(d_g) =$ Thickness of plane-parallel film (glass).

$(d_t) =$ Thickness (generally).

$(d_i) =$ Interplanar spacing of each atomic layer in a wear particle (according to Holm, 1946).

$(d_{min}) =$ Minimum resolvable distance in the object.

$(d_p) =$ Thickness of crystalline specimen.

$(d_p)_c =$ Critical thickness of crystalline specimen when *both* kinematic and dynamical theories of electron diffraction are relevant.

$(d_s) =$ Diameter of spherical crystal.

$(\mathbf{d}_{hkl}) =$ Interplanar spacing vector of the (hkl) planes in a crystal lattice.

$(\mathbf{d}_{hkl}^*) =$ Reciprocal lattice vector related to $\mathbf{d}_{hkl}$ by Equation (3.7).

$\Delta =$ Phase difference.

$\Delta r_i =$ Radius of disc of confusion (optics).

$\Delta \sigma =$ 'Relaxation' angle for Bragg reflection.

$(\delta_{expt}) =$ Experimentally determined division of heat at the interface $(= H_1 / UF)$.

$(\delta_{theory}) =$ Theoretical division of heat at the sliding interface.

$(E_1), (E_2) =$ Young's Modulus of Elasticity for a *hard hemi-spherical asperity* and a *soft flat*.

$E(\theta) =$ *Differential* cross-section for elastic scattering of electrons.

$E'' =$ Reduced elastic modulus.

$E_c =$ Critical energy for K X-ray line excitation.

$E_i =$ Energy of inner shell of an atom.

$E_p =$ Energy of primary X-ray beam.

$(E_n), (E_m) =$ Energy of nth and mth, orbit of electron in an atom.

$EPMA =$ Electron Probe Microanalysis.

$e =$ Electronic charge.

$\varepsilon =$ Crystallite size.

$(\varepsilon_p) =$ Crystal(lite) size parallel to the incident beam of radiation.

$(\varepsilon_0) =$ The permittivity of vacuo.

$F =$ Force of friction.

$(F_{\text{kin}}) =$ Kinetic force of friction.

$(F_{\text{stat}}) =$ Static force of friction.

$(F_e)_m =$ Frictional force between multiple elastic contacts.

$(F_p)_m =$ Frictional force between multiple plastic contacts.

$(F_\parallel) =$ Force required to shear *parallel* members of twinned crystallites.

$(F_T) =$ Force required to shear *tilted* members of twinned crystallites.

$(F_P) =$ Force required for *ploughing* of asperities.

$(F_e)_{hkl} =$ Structure factor for electrons.

$F(t) =$ Probability of failure of a percentage of the population in a life-time (t_B) of a bearing.

$F(\lambda_R) =$ Fraction of total elastic area of contact across which asperity contacts occur.

$(F_x)_{hkl} =$ Amplitude of resultant of all the X-ray waves scattered by the n-atoms in the unit cell into the angle $(2\theta_{hkl})$ [i.e. Structure factor for X-rays].

$(F_R) =$ $4(R_R)/(1 - R_R)^2$, [see Equation (2.21)].

$f =$ X-ray flux (XPS).

$f(\chi) =$ Absorption function [see Equations (4.21) and (4.22)].

$f_X(f_e) =$ Atomic scattering factor for X-rays (electrons).

$(f_X)_T =$ Atomic scattering factor for X-rays at temperature (T).

$(f_o) =$ Mass fraction of oxide that is composed of oxygen.

$(f_{\text{eye}}) =$ Focal length of eyepiece lens.

$(f_{\text{obj}}) =$ Focal length of objective lens.

$\Phi =$ One of the constants of Equation (1.6).

$\Phi_i =$ Phase difference between X-ray wave scattered by an atom at fractional coordinates, $x_i\, y_i\, z_i$, in the unit cell, compared with the wave scattered by an atom at the origin.

$\phi =$ Phase of light wave.

$\phi_e =$ *Exponential* distribution of asperity heights.

$\phi_R =$ Angle of specimen rotation (figure 5.17).

$\phi_G =$ *Gaussian* distribution of asperity heights.

$\phi_{hkl} =$ Scattering angle (equals to $2\theta_{hkl}$).

$\phi_p =$ Angle between incident electron beam and specimen surface (AES).

$\phi_s =$ Sliding direction (Table 9.1).

$\phi_{sp} =$ Spectrometer work function (XPS and AES).

$\gamma_{uc} =$ Angle between $\mathbf{a}_{uc}$ and $\mathbf{b}_{uc}$ in the unit cell.

$\gamma_{uc}^* =$ Angle between a_{uc}^* and $\mathbf{b}_{uc}^*$ in the reciprocal lattice unit cell.

$\gamma_F =$ Fluorescent correction [Equation (4.23)].

$H =$ Constant of Equation [4.22(a)] equals $[1.2(A)_w/Z^2]$.

$H_1 =$ Rate of heat flow along the pin (at the interspace between the pin and the disc).

$H_2 =$ Heat flow rate entering section of pin where thermocouple measuring T_A was conducting heat away (see Figure 6.1).

HEED $=$ High Energy Electron Diffraction (see also THEED and RHEED).

$h =$ Planck's constant ($= 6.626 \times 10^{-34}$ J–s).

$(h^*) = (h_{lub})/(h_{min})_0$.

$(h_c) =$ Convective heat transfer coefficient.

$(h_{lub}) =$ Lubricant film thickness.

$(h_{min}) =$ *Minimum* lubricant film thickness.

$(h_{min})_0 =$ *Central* lubricant film thickness.

$(h_Z) =$ Increment of asperity heights in Z-direction for Archard's (1953) simple model.

$h, k, l =$ Miller indices describing the (hkl) planes in a crystal (never separated from each other).

$\eta_0 =$ Dynamic viscosity coefficient (at normal atmospheric pressure, P_0).

η or $\eta(P) =$ Dynamic viscosity coefficient as a function of pressure (i.e. $\eta(P) = \eta_0 \exp(\alpha_p)(P - P_0)$).

$I =$ Incident intensity (generally).

$I_R =$ Reflected intensity (generally).

$I_T =$ Transmitted intensity (generally).

$I_a =$ Intensity of X-rays scattered by an atom.

$I_e =$ Intensity of X-rays scattered by an electron.

$I_{hkl} =$ Intensity of X-rays scattered into a cone of semi-angle $(2\theta_{hkl})$ from original direction.

$(I_{hkl})_{ED} =$ Intensity of electrons diffracted from original direction.

$I_A =$ Auger electron current from element A.

$I_i =$ *Measured* Auger current from element i in a multi-element specimen.

$I_0 =$ Electron intensity *incident* upon a transmission electron microscope specimen (or HEED specimen).

$I_c =$ Electron intensity *emerging* from a transmission electron microscope specimen.

$(I_c)_0 =$ Electron intensity transmitted through an electron microscope specimen when *no* scattered electrons are assumed to return to the original beam direction.

$(I_c)_f =$ Intensity of electron beam in the region of a feature of the electron micrograph.

$(I_c)_B =$ Intensity of electron beam in the region of the background adjacent to the feature.

$I(x) =$ Intensity as a function of distance (x) into specimen.

$I_F =$ Intensity of X-rays produced by characteristic line fluorescence.

$I_1, I_2 =$ Intermediate and final images in a simple optical microscope.

$I_K =$ Total number of electrons scattered through *small* angles on passing through an electron microscope specimen.

$I_n =$ Relative Integrated Intensity from the *n*th component of a multi-component specimen (X-ray diffraction).

$I_{pe} =$ Peak intensity (electron diffraction patterns).

$I_{we} =$ Integrated intensity (electron diffraction patterns.)

$I_{px} =$ Intensity of X-rays due to primary excitation by electrons (electron probe microanalysis).

$(I_{hkl})_w =$ Relative integrated intensity of X-rays scattered into semi-angle $(2\theta_{hkl})$.

$(I'_{hkl})_{ED} =$ Intensity of electrons diffracted into a complete diffraction ring.

$(I_x) =$ Combined intensity of interfering light waves.

$J =$ Mean ionization potential.

$K =$ K-factor that is the probability of producing a wear particle per asperity encounter.

$K_e =$ Equivalent thermal conductivity, which allows for the effect of anoxide film upon the transfer of heat.

$K_S =$ Thermal conductivity of steel.

$K_i =$ Constant of Equation (4.35) relating to I_A.

$KE =$ Kinetic Energy.

$K_s =$ Fraction of electrons *singly* scattered into *all* angles/unit thickness (TEM).

$K_R =$ Constant of Rayleigh's Criterion [Equation (2.4)].

$K_r =$ Constant of Equation (7.15).

$(K_S)_p =$ Thermal conductivity of steel (pin).

$(K_S)_d =$ Thermal conductivity of steel (disc).

$K_o =$ Thermal conductivity of oxide.

$K_{xe} =$ Constant of the definition of the reciprocal lattice vector (equals λ or 10λ for XRD and unity for electron diffraction).

$k =$ General oxidation rate constant or the constant introduced in Equation (4.33) to preserve its dimensional stability.

$k_D =$ Constant of the Gaussian distribution of asperity heights.

$k_c =$ Constant of *cubic* growth (of oxide) law.

$k_d =$ Constant of *direct logarithmic* growth (of oxide) law.

$k_i =$ Constant of *inverse logarithmic* growth (of oxide) law.

$k_l =$ Constant of *linear* growth (of oxide) law.

$k_p =$ Constant of *parabolic* growth (of oxide) law.

$L =$ Specimen to photographic film/plate distance in the electron diffraction camera.

$L_a =$ Crystallite size in the *X*- or *Y*-direction of graphite.

$L_c =$ Crystallite size in the *Z*-direction of graphite.

$L_{co} =$ Roughness width cut-off.

LEED $=$ Low-Energy Electron Diffraction.

$L_F =$ Latent Heat of fusion/unit volume.

$LTP =$ Life to pitting failure.

$L_1 =$ Length of pin between thermocouples reading T_A and T_B (see Figure 6.1).

$\lambda =$ Wavelength (generally).

$\lambda_b =$ Wavelength of *blue* light.

$\lambda_e =$ Mean free path of *elastically* scattered electrons.

$\lambda_i =$ Mean free path of *inelastically* scattered electrons.

$\lambda_p =$ Wavelength of X-rays modified by interaction with matter.

$\lambda_R =$ Lambda ratio (equals $1/D$).

$\lambda_r =$ Wavelength of *red* light.

$\lambda_T =$ Mean free path for scattering of electrons by both inelastic and elastic interactions.

$M =$ Magnification.

$m^* = \ln(r^*)$.

$m =$ Multiplicity factor (or quantum number).

$m_e =$ Mass of the electron.

$\mu =$ Refractive index (optical wavelengths).

$\mu_{kin} =$ Kinetic coefficient of friction.

$\mu_l =$ Linear absorption coefficient for X-rays.

$\mu_m =$ Mass absorption coefficient for X-rays.

$\mu_\parallel =$ Contribution to the kinetic coefficient of friction from crystallites oriented *parallel* to sliding surface.

$\mu_R =$ Contribution to the Kinetic coefficient of friction from the crystallites oriented *randomly* with respect to sliding surface.

$N =$ Number of circular contacts (of radius a) between two surfaces in relative motion.

$N(E) =$ Number of electrons with energy (E).

$N_A =$ Number of atoms per unit volume.

$N_i =$ Number of atoms per unit area on site i of the surface (AES).

$N_R =$ Number of revolutions (cycles) to first pit (in a contact fatigue experiment).

$N_T =$ Total number of asperities in contact between two surfaces (contact mechanics insofaras it relates to stationary surfaces).

$NA =$ Numerical Aperture [equals $\mu \sin(\alpha_{SA})$].

$n_{CL} =$ Total number of elemental areas within the interval L_{CO} (surface roughness analysis).

$n =$ Order of interference (optical interferogram), *or* quantum number (Bohr theory).

$n_C =$ Number of contacts (N) per unit area of surface.

$n_A =$ Fraction of emitted Auger electrons actually collected by analyser (AES).

$n(\sigma)\,d\sigma =$ Number of [001] poles lying between σ and $(\sigma + d\sigma)$ with respect to the electron beam.

$v =$ Kinematic viscosity or frequency (generally).

$v_{nm} =$ Frequency of (optical) radiation given off (or absorbed) when electron goes from energy level (E_n) to energy level (E_m) (or vice versa).

$\bar{v}, \bar{v}_{nm} =$ Wave number (reciprocal of frequency).

$v_{max} =$ Maximum frequency.

$v_1, v_2 =$ Poisson's ratios for surfaces 1 and 2.

OPD $=$ Optical path difference between two parts of the wavefront impingeing upon the dispersing element.

$P_q =$ A P-fold rotation axis associated with a translation of (a/P) times the repeat distance along that axis.

$P_R =$ *Percentage ratio* of randomly-oriented to preferentially-oriented graphitic crystallites.

$P_A =$ Peak-to-Peak Height (AES) [see Equation (4.35)].

$P =$ Pressure (generally).

$P_P =$ Force required to plough (or deform) asperities.

PSO $=$ Point surface origin (Pitting through contact fatigue).

$P_T =$ Transparency of AES analyser.

$P(Z, Z + dZ) =$ Amplitude probability.

$p =$ Probability of mis-match between adjacent (001) planes in graphitic crystallites.

$(p_s) =$ Fraction of electrons singly scattered *through small angles* per unit specimen thickness.

$(p_{max}) =$ Maximum Hertzian pressure.

$(p_m) =$ Hardness (or mean pressure, if less than yield strength).

$(p_m)_{local} =$ Local hardness.

$(p_m)_\perp =$ Hardness measured in a direction *perpendicular* to the basal planes of graphite.

$(p_m)_{\parallel} =$ Hardness measured in a direction *parallel* to the basal planes of graphite.

$(p_m)_0 =$ Room temperature hardness.

$p_1 =$ Linear momentum.

$p_\phi =$ Angular momentum.

$Q =$ General activation energy for oxidation.

$Q_p =$ Activation energy for *parabolic oxidation* of tribo-elements during sliding.

$q =$ Reduced pressure $= [1/(\alpha_P)]\{1 - \exp[-(\alpha_P)P]\}$.

$q^* = q(h_{min})_0^2/[12(\eta_0)(\bar{\mu})(a)]$.

$q_i =$ Screening factor for element A on site i (AES).

$R =$ Radius of hemispherical asperity (also used for electrical *resistance*).

$R_S =$ Radius of reference sphere (crystallography), or, parameter related to the radius of curvature of asperities on a *real* surface.

$\bar{R} =$ Universal gas constant ($= 8.314\,\text{kJ}/(\text{kmol–K})$).

$R_B =$ Rydberg constant.

$R_{BS} =$ Back-scattering coefficient of electrons in the electron probe microanalyser.

$R_{ES} =$ Radius of the Ewald sphere.

$R_{eff} =$ Effective radius (of the cylindrical camera used in the glancing-angle, edge-irradiated X-ray diffraction film technique).

$R_f =$ Fraction of crystallites *randomly-oriented* with respect to surface of graphitic contact film

$R_L =$ Radius of curvature (of an optical lens).

$\text{RMS} =$ Root-mean-square surface roughness.

$R_P =$ Levelling depth.

$R_a =$ Average roughness height (see also AA, CLA).

$R_R =$ Fraction of light intensity reflected at an interface between optical media.

$R_t =$ Radius of pin (in cylindrical pin on disc wear machine).

$R_{RC} =$ Radius of cylindrical single crystal camera.

$R_T =$ 'Peak-to-valley' surface roughness.

$R_r =$ Reduced radius [given by Equation (5.44)].

$R_1', R_2' =$ Radii of the two contacting bodies involved in (R_r).

$\text{RHEED} =$ Reflection High Energy Electron Diffraction.

$R_{ED} =$ Distance of an electron diffraction maximum from centre spot of the electron diffraction pattern.

$r' =$ Radius of disc of confusion (see also Δr_i).

$r_i =$ Back-scattering factor for element A on site i of the surface (AES).

$r_n =$ Radius of the nth orbit of an atom.

$r =$ Radius of *sector* of spherical ball drawn parallel to flat against which ball is elastically loaded.

$r^{\star} = r/a.$

$\rho =$ Density (generally).

$\rho_A(Z) =$ Amplitude density function.

$(\rho_{hkl}) =$ Angle between normals to (hkl) and (001) planes.

$\rho_0 =$ Density of oxide.

$\rho_z =$ Radius of the [100] zone of the electron diffraction pattern from a single crystal of cubic material.

$(\rho\lambda_e) =$ Transparency thickness (electron scattering).

$S =$ Adhesive component of F_{kin} [see Equation 1.16].

$S_A(E_p, E_i) =$ Electron impact ionization cross-section of element A (AES).

$S_S =$ Atomic sensitivity factor.

$S_{\|} =$ Shear strength of junctions between opposing surfaces when crystallites have their basal planes oriented *parallel* to the interface.

$S_R =$ Shear strength of junctions between opposing surfaces when crystallites have their basal planes oriented *randomly* to the interface.

$SEM =$ Scanning Electron Microscopy.

$SP =$ Stopping Power of a specimen (in the Electron Probe Microanalyser).

$s =$ Mean tangential shear stress (in a solid).

$s_f =$ Shear rate (for a liquid).

$\Sigma =$ Exposure of a photographic film or plate.

$\sigma =$ Orientation of [001] poles with respect to electron beam (or standard deviation of asperity heights).

$\sigma_C =$ Modified Lenard coefficient [see Equation (4.22(b))].

$\sigma_e =$ Elastic electron scattering cross-section.

$\sigma_i =$ Inelastic electron scattering cross-section.

$\sigma_{PE} =$ Photoelectric cross-section [see Equation (4.25)].

$T =$ Temperature (generally).

$T_2 =$ Transition load beyond which severe metallic wear changes to mild-oxidational wear (Welsh, 1965).

$T_3 =$ Transition load beyond which mild-oxidational wear changes to severe-oxidational wear (Welsh, 1965).

$T^* = [(\chi_s)(p_m)_0 / K_S]$ [see Equation (6.20)].

$T(x) =$ Temperature at distance (x) from heat source (H_1).

$(T_A) =$ Thermocouple reading where pin emerges from the insulated portion of the calorimeter (see Figure 6.1).

$(T_B) =$ Thermocouple reading at a distance (L_1) from the thermocouple reading (T_A) (see Figure 6.1).

$(T_B)_m =$ Measured temperature as given by a thermocouple embedded just below the wearing surface of the pin.

$(T_{AE}) =$ Transparency of the analyzer (AES).

$(T_c) =$ Temperature of the real areas of contact during sliding (sometimes called the 'flash temperature').

$(T_D) =$ Detector efficiency for electrons emitted from the sample of the X-ray photoelectron spectrometer.

$(T_E) =$ Temperature of air flowing past the exposed portion of the pin (in Figure 6.1).

$(T_e^*) = [(\chi_s)(p_m)_0 / K_e]$ [see Equation (6.26)].

$(T_m) =$ Melting point.

$TEM =$ Transmission Electron Microscopy.

$THEED =$ Transmission High Energy Electron Diffraction.

$T_o =$ Temperature of oxidation at the real areas of contact during sliding.

$T_{OS} =$ Thermocouple reading of the *outside surface* of the insulator surrounding the pin (see Figure 6.1).

$T_S =$ General surface temperature.

$T_{SA}, T_{SB} =$ General surface temperatures of bodies A and B in sliding contact.

$(T_S)_d =$ General Surface Temperature of disc.

$(T_S)_p =$ General Surface Temperature of pin.

$T_T =$ Fraction of the incident light intensity that is *transmitted* at an interface between optical media.

$t =$ time (generally).

$(t/t_0) =$ Average time fraction during which *no* contact occurs (Section 7.5.2).

$t_B =$ Individual bearing life.

$t_{bl} =$ Bearing length ratio.

$t_c =$ Characteristic life.

$t_d =$ Fictitious *excess* temperature of disc, assuming all heat generated at the interface goes into the disc (of a pin-on-disc wear machine).

$t_o =$ Time to build up a critical oxide film thickness during oxidational wear.

$t_p =$ Fictitious *excess* temperature of pin, assuming all heat goes into the pin.

$\tau_e =$ *Elastic* shear stress between each surface asperity junction.

$\tau_f =$ Shear stress in liquid.

$U =$ Speed of a moving surface.

$\tilde{U} =$ Normalized speed [see Equation (1.34(a))].

$\bar{U} = (U_1 + U_2)/2$, the mean speed of the speeds (U_1 and U_2) of the bearing surfaces.

$(U_O) = (E_P)/(E_C)$ (Electron probe microanalysis).

$u_O =$ Distance of *object* from objective lens (working distance).

$V =$ Volume (generally) or valence levels (in AES).

$(V_A) =$ Accelerating voltage.

$[(\Delta V_A)/(V_A)] =$ Stability of accelerating voltage.

$(V_C) =$ Critical electron accelerating voltage required for the excitation of a given series of X-ray spectra.

$(V_f) =$ Visibility of a feature in an electron.

$(V_n) =$ Volume percentage of (nth) component in a multi-component specimen.

$v =$ Speed of an elementary particle moving in a field-free environment.

$v_O =$ Distance of *image* from *objective* lens.

$v_{ac} =$ Volume of the unit cell.

$W =$ Load (generally).

$\tilde{W} =$ Normalized pressure [see Equation (1.34(b))].

$W_A =$ Half-width of an Auger peak (i.e. the separation between the positive and negative peaks in the $(dN(E)/dE)$ spectrum.

$(W_e)_s =$ Normal load causing *elastic* deformation of a *single* contact.

$(W_p)_s =$ Normal load causing *plastic (as well* as *elastic)* deformation (at a single contact).

$(W_p)_m =$ Normal load-carrying *multiple, plastic,* contact.

$w =$ Wear rate (volume removed per unit sliding distance).

$\tilde{w} =$ normalized wear rate [see Equation (1.34(c))].

$w_\alpha, w_\beta, w_\gamma =$ First, second and third terms in the general expression for oxidational wear [see Equations (1.40), (1.41) and (1.42)].

$w_m =$ Mass removed per unit rolling distance.

$w_X =$ X-ray fluorescent yield (in AES).

$w_c =$ *True* width of diffraction line (due to limited crystallite size).

$(w_c)_s =$ Width of (sharp) lines of standard material (E > 1000Å).

$(w_c)_m =$ *Measured* width of diffraction line.

$X_d =$ Thermal diffusivity of disc material.

$X_i =$ Atomic percentage concentration of element i (AES).

$X_o =$ Thermal diffusivity of oxide $(= K_o/(\rho_o c_o))$.

XPS = X-ray Photoelectron Spectroscopy.

XRD = X-ray Diffraction.

$x_i, y_i, z_i =$ Fractional coordinates of ith atom in the unit cell.

$\xi =$ Critical oxide film thickness.

$\xi_d, \xi_p =$ Thickness of critical oxide film formed on disc and pin surfaces respectively.

$\xi_N =$ Number of atomic layers in a wear particle (according to Holm, 1946).

$\theta_A =$ Arc angle (see Figure 5.17).

$\theta =$ Angle between c-axis and the sliding interface (or sometimes used as an abbreviated form for θ_{hkl}).

$\theta_E =$ Angular efficiency function (XPS).

$(\theta_{hkl}) =$ Bragg angle (sometimes written without subscripts).

$\theta_m =$ 'Hot-spot' temperature (excess over the general surface temperature, T_S).

$(\theta_p) =$ Incident angle of primary beam (AES).

$\psi =$ Take-off angle (EPMA).

$(\psi_p) =$ Reduced flow pressure.

$Y =$ Elastic limit.

$(y_E) =$ Efficiency of producing photoelectrons.

$Z =$ Atomic number.

$(Z_n) =$ Number of atoms removed per atomic encounter.

$(Z_h) =$ Collection of terms relating to heat flow in a pin-and-disc tribo-system [see Equation (6.9)].

$\omega_0 =$ Angular velocity of specimen at 0.