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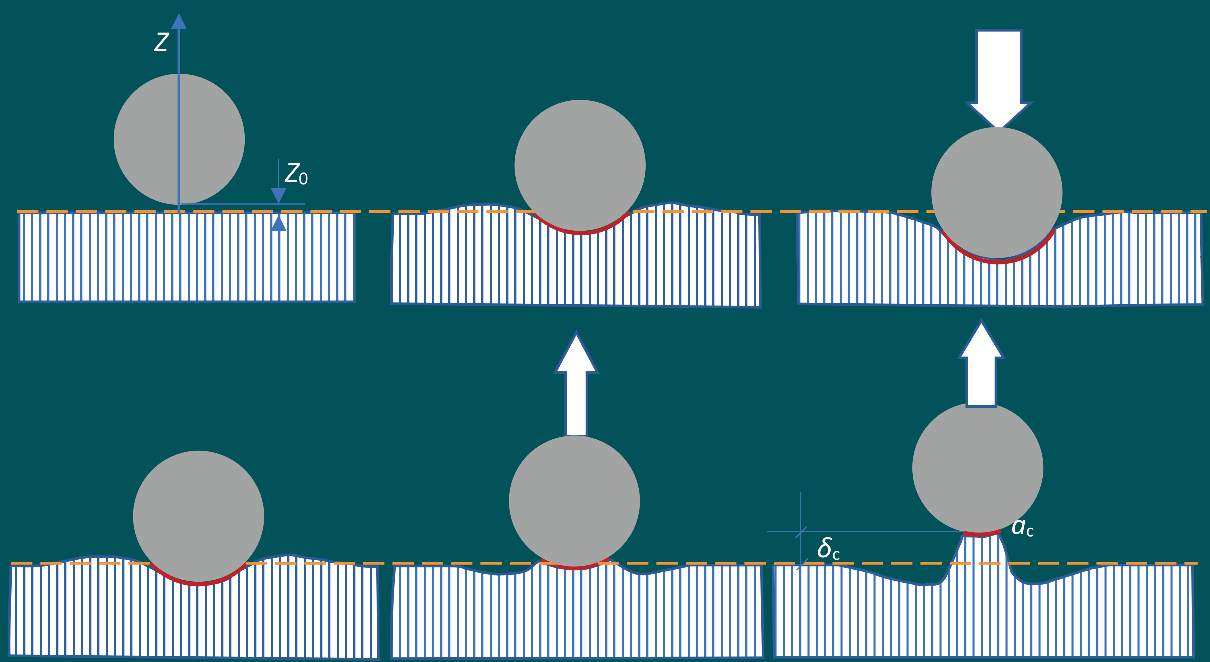
ADVANCED CHARACTERIZATION OF ENGINEERING MATERIALS USING INDENTATION TECHNIQUES



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List of Important Symbols

a	–	contact radius or geometric dimension
a_c	–	contact radius considering adhesion forces
a_{pz}	–	radius of the plastic zone
$\bar{a}$	–	contact radius between the sphere and substrate considering adhesion forces
A	–	contact area between the bodies or the plastically deformed impression area, or the cross-sectional area of the scratch path in the scratch test
A_a	–	total expected contact area or actual contact area
A_p	–	impression area projected onto the material surface
A_s	–	lateral surface area of the indenter corresponding to its maximum displacement
$\bar{A}$	–	contact area between the sphere and substrate considering adhesion forces
b	–	Burgers vector magnitude
c	–	crack length in glass or geometric dimension
C	–	constraint factor
C_e, C_p	–	constants depending on the material and indenter shape
d	–	diameter of the spherical cap of the impression
D	–	diameter of the spherical indenter
$erfc(z)$	–	complementary error function
E	–	stiffness, longitudinal elastic modulus
E', E^*, E_r	–	reduced longitudinal elastic modulus
f	–	coefficient defining the ratio of the radius of the plastic zone to the contact radius
$F_n(h)$	–	statistical function fitting the Gaussian distribution of irregularities
$F_n(\lambda)$	–	statistical function fitting roughness distribution to Gaussian distribution
G	–	shear modulus
G^*	–	complex shear modulus
G'	–	real component of the complex shear modulus
G''	–	imaginary component of the complex shear modulus
h	–	normalized distance between planes or indenter displacement, or the height of the pile-up ridge
h_0	–	distance at which stresses occur due to the Lennard-Jones potential, or maximum indenter displacement
h_a	–	depth at which the indenter has lost contact with the material
h_c	–	contact depth corresponding to the contact radius
h_i	–	initial indenter penetration at load Pi
h_i'	–	initial indenter penetration obtained by extrapolation
h_{max}	–	maximum indenter displacement
h_r	–	residual depth of the impression at its axis after unloading
h_x	–	additional indenter displacement depth
h'	–	root mean square deviation from the mean line of the rough surface
$h(c)$	–	distance between contacting bodies
$h(c)^D$	–	distance between contacting bodies considering Dugdale stresses
$h(c)^H$	–	distance between contacting bodies according to Hertz
H	–	hardness
H_0	–	macroscopic hardness

H_{fr} – hardness due to lattice friction
H_{ISE} – hardness with scale effect
H_{ss} – hardness due to solid solution strengthening
k – constant in Meyer's equation or calibration coefficient, or spring constant
$K_v(z)$ – modified Bessel function of the second kind
l – geometric dimension
L_0 – indenter load causing its displacement h_c in glass without residual stresses
L_c – critical load in the scratch test causing coating delamination
L_t – indenter load causing its displacement h_c in glass with residual stresses
m – coefficient equal to a/c or a constant depending on the material and indenter shape
M – Taylor coefficient
n – expected number of contacts between the rough surface and flat surface, or constant in Meyer's equation, or calibration coefficient, or number of radial cracks
N – number of irregularities on the surface
p – pressure exerted by a spherical indenter
p_0 – pressure in the symmetry axis of the system
p_{av} – average pressure
p_m – mean pressure exerted by the indenter
$p(r)$ – pressure distribution profile
$p(r)^H$ – pressure distribution profile according to Hertz
$p(r)^D$ – pressure distribution profile due to Dugdale stresses
P – indenter load or indenter load causing cracks of length c in glass without residual stresses
P_c – force needed to overcome adhesion forces or critical load at which the transition between elastic and plastic deformation occurs
P_i – minimum indenter load in the initial loading phase
P_t – load greater than the critical load P_c
P^* – load causing cracks of length c in glass with residual stresses
$\bar{P}$ – area of the sphere considering adhesion forces
R – radius of the spherical indenter or radius of curvature of the apex of an irregularity, or radius of curvature of the apex of a sharp indenter
R^2 – Pearson correlation coefficient
R_e – material yield strength
S – contact stiffness
t – time or coating thickness
$u(r)$ – deflection profile
Up – plastic deformation energy of the material in the indentation test
Us – elastic deformation energy of the material in the indentation test
Ut – total deformation energy of the material in the indentation test
V – volume of the material
w_{el} – elastic deformation energy per unit volume
W – work done on the loss of adhesion between the coating and substrate
W_{el} – total elastic deformation energy
x – strain hardening coefficient
z – height of surface roughness
z_0 – distance between the indenter and substrate where adhesion forces act
α – coefficient accounting for adhesion forces, or half-apex angle of a sharp indenter, or parameter describing the effect of roughness on the indentation test results, or coefficient dependent on dislocation structure
α' – half-apex angle of the impression after unloading
β – average radius of peaks of contacting rough surfaces or angle between the indenter and material surface
γ – surface energy per unit contact area
δ – displacement of the spherical indenter
δ_c – critical penetration depth at the failure of the adhesive bond
$\bar{\delta}$ – displacement of the sphere into the substrate considering adhesion forces
$\Delta\gamma$ – work required to overcome adhesion forces
ε – strain or constant dependent on the indenter shape in the Oliver-Pharr method

$\bar{\varepsilon}$ – creep rate
η – surface density of roughness irregularities or viscosity
η^* – complex viscosity
η' – real component of complex viscosity
η'' – imaginary component of complex viscosity
θ – angle between the indenter and material surface
λ – coefficient accounting for adhesion forces, or Stribeck oil film parameter, or damping coefficient
μ – Tabor's parameter
μ_c – coefficient of friction between the indenter and substrate in the scratch test
ν – Poisson's ratio
ρ_{GDN} – density of geometrically necessary dislocations
ρ_{SSD} – dislocation density in the material
σ – standard deviation of surface roughness distribution
σ_0 – maximum stress resulting from the Lennard-Jones potential
σ_F – flow stress
σ_R – residual stress
σ_s – maximum height of surface roughness
σ_{th} – theoretical stress resulting from the Lennard-Jones potential
υ – average dislocation velocity
φ – phase shift between force and displacement
$\Phi(z)dz$ – probability that the height of irregularities falls within a given range $<z, z+dz>$
$\Phi^*(s)$ – normalized distribution of irregularities following the Gaussian distribution
χ – constant dependent on the indenter shape
Ψ – index describing elastoplastic deformations in the contact of irregularities
ω – frequency

1. Introduction

Over the centuries, the development of human civilization has been closely associated with the search for increasingly better materials that could win battles, enhance the quality of life, or enable the exploration of previously unknown regions. However, it is only since the beginning of the last century that we have observed rapid advancements in this area, driven by the production of new materials and the refinement of manufacturing techniques for existing ones. This rapid progress in new materials has also necessitated the development of research methods that allow for increasingly in-depth studies of the properties of newly developed, manufactured, and processed materials. A hundred years ago, tensile testing or hardness measurement sufficed to characterize the mechanical properties of materials. These methods are still in use today; however, the ever-increasing demands placed on new materials by designers have driven the need for novel research methods that enable more precise and detailed determination of their mechanical properties. Current requirements also extend to determining mechanical properties not only on a macro scale but also—due to the development of nanomaterials and techniques related to the deposition of thin layers and coatings—on a micro- and nanometric scale. It may seem that these issues pertain only to precision electronic systems, but even engineers designing much larger structures, such as bridges, want to know the properties of cement mortar in the zone adjacent to the aggregate, which spans an area several tens of micrometers wide, as the mechanical properties of this zone determine the mechanical properties of the entire concrete structure. Knowledge of the properties of materials used in various types of engineering constructions is essential for the proper selection of these materials by designers and technologists. One of the modern techniques for determining the mechanical properties of various groups of engineering materials is the indentation method, which involves pressing a diamond indenter into the material being tested. The method for determining the mechanical properties of materials based on the indentation test allows for the determination of many useful mechanical properties of materials belonging to various groups of engineering materials. It can be used to determine material properties on a macro-, micro-, and nanoscopic scale. For example, it allows for the determination of material hardness and stiffness (Young's modulus), and in the case of brittle materials, such as ceramics or hard metals and alloys, it enables the determination of the critical stress intensity factor. Using this method, it is possible to determine not only the values of residual stresses of the first, second, and third types in metals and alloys but also their nature (sign). The indentation test also enables the study of creep rates in various materials and the determination of dislocation density in metallic materials and their mobility. These material properties can be investigated under both static and dynamic loading conditions. The theoretical foundations for the indentation test using a spherical indenter were first formulated by Heinrich Hertz at the end of the nineteenth century [1, 2], and in subsequent research, they were further developed for a conical indenter by the Scottish mathematician Ian Naismith Sneddon [3, 4].

This edition represents the second version of the original Polish edition, revised and expanded to include additional updates and improvements.