Glossary

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COMMUNICATION is often the key issue in practical failure analysis. Communication is required among specific parties who are trying to solve a problem. It is recognized that the exact definition of a particular term may be less important than conveying the concept that solves the problem. However, it is typical in failure analysis and problem solving to consult the literature (including Handbooks such as this one) or other people to find information on similar problems. Without clear communication and consistent terminology, one cannot know if the problems are really similar.

In failure analysis work, it is often not possible to pin down a particular damage sequence or root cause with complete certainty. However, if the work is performed in a professional manner, there is a good probability of identifying some helpful solutions to at least reduce the likelihood of recurrence. This glossary is intended to help promote clear thinking and useful failure analysis. The process of defining terms is useful to the parties involved in solving a failure analysis problem, in that it increases their own comprehension of the physical facts and also facilitates communication with the other parties who need to understand the results of the investigation.

Strict use of proper terminology is critical to clear communication. Several organizations have compiled glossaries of terms used in failure analysis, including ASTM, SAE, and ASM International. In some cases (e.g., ASTM), accepted definitions of terms is by consensus approval of a committee. In other instances (e.g., ASM), there is no formal approval procedure nor is there a committee responsible for terminology. As a result, there may be more than one common use of a specific term, and there may be more than one definition of a term.

The definitions used in the following glossary are not always consistent with those for the same terms found in the *ASM Materials Engineering Dictionary* (J.R. Davis, editor, ASM International, 1992) or in glossaries in other *ASM Handbook* volumes. The use of a term (e.g., corrosion fatigue) may change with time as understanding evolves. The definitions presented here are those used in this Volume and reflect common and modern understanding of these terms as used in the literature and in reports by practicing failure analysts. However, as in all communication, if the way in which a particular term is being used is not clear, the speaker or author should be asked for clarification.

Several terms used in discussions of failure analysis can be confusing or interpreted variously by different persons. Cases in point include mode, stress cracking, ductile, brittle, and cleavage. An example of the evolution of definitions, as previously noted, is the term quasi-cleavage, which is truly a form of cleavage and a microscale fracture surface appearance of a quenched and tempered steel. The fracture surface is typically dominated by cleavage, but there are typically small patches of microvoid coalescence (MVC) present or thin ribbons of MVC contained in the fracture surface. As the patches of MVC increase, the fracture surface is more accurately described as (microscale) mixed cleavage and MVC. In a matrix dominated by cleavage, there is nothing “quasi” about the cleavage, because the term *quasi* implies something different than cleavage.

Sometimes a modifying adjective may considerably improve the clarity of the sentence in which it is used. For example, *ductile* can refer to both a process/mechanism at the microscale or an appearance at the macroscale. The term *mode* is used in multiple ways: It is defined in ASTM E 1823 in terms of surface displacement of the crack tip created by various loading conditions. It is defined within *ASME Failure Methods and Effects Analysis* terminology, and there are some eight additional definitions in *Webster's Unabridged Dictionary.* There are still more uses of the term, as in *fracture mode, failure mode,* and so on. These latter two terms are not in the *ASM Materials Engineering Dictionary,* nor are they in an ASTM glossary. Consequently, their use has no underlying, commonly accepted definition and should be avoided if possible.

Other examples of terms that may be misinterpreted include *static fatigue* and *stress cracking.* The compilers also discourage the use of terms that have been removed from glossaries created by consensus approval. An example is the term *endurance limit.* The endurance limit presumably indicates a threshold stress for infinite

life in cyclic loading. It appears in *S-N* data for materials that strain age and is therefore associated with a dislocation-interstitial pinning mechanism. If some event occurs to cause depinning (say, an increased stress), a new saturation stress is obtained; that is, the endurance limit is changed. The term endurance limit is no longer contained in a standard glossary of terms used in fracture and fatigue (ASTM E 1823).

There are a group of terms used to describe deviations from ideality and that are in some instances the technical root cause for failure. They include *imperfection, discontinuity,* defect and *root cause.* In some instances these terms are used interchangeably by some writers, and in other cases clear distinctions are made. In some instances, specific terms have been defined by legal jurisdictions. The failure analyst should consider the legal implication of his terminology. As noted, the courts have defined the meanings of certain words, and these meanings may not correspond to what the analyst intends. Furthermore, various courts may not be consistent. For example, some metallurgists have examined a fracture surface and identified a defect at the fracture origin. By this they mean nothing more than a discontinuity and perhaps a minute discontinuity. However, within a legal context, the identification of a defect suggests a defective component, legal liability for the manufacturer, and a possible need for a recall or other corrective action.

The definition of defect herein is based on deviation from a specification or a component being unfit for its intended purpose. An actual or perceived failure does not automatically mean there is a defect. Even if there is a defect, that condition may or may not relate to the failure. It is believed this framework provides a rational method for deciding if there is, in fact, a defect. However, it does not eliminate all controversy as specifications may or may not be clear, appropriate, and up-to-date. There may also be disagreement regarding the intended purpose of a component. A discussion on this matter from a legal perspective is in two references: (a) Asperger, J.J., "Legal Definition of a Product Failure: What the Law Requires of the Designer and the Manufacturer," *Failure Prevention Through Education, Getting to the Root Cause, Conference Proceedings,* ASM International, May 2000, and (b) "Product Liability and Design" in this Volume of the *ASM Handbook.*

475 °C embrittlement
: Embrittlement of ferritic and semiferritic steels containing more than 13% Cr that occurs when they are held or slowly cooled through the 400 to 500 °C (750 to 930 °F) temperature range. Embrittlement is presumed to be due to the grain-boundary precipitation of a chromium-rich phase together with the creation of a precipitate-free zone (PFZ) adjacent to the grain boundary. Because the precipitation creates a PFZ, fracture is likely to be intergranular.

500 to 700 °C embrittlement
: Embrittlement that occurs when high-alloy steels (e.g., hot work steels and high-speed steels) are cooled to form martensite and are subsequently tempered or slowly cooled through the 500 to 700 °C (930 to 1290 °F) temperature range. Tempering results in a fine dispersion of carbides. A small increase in hardness is associated with the embrittlement.

A

abrasion
: The process of grinding or wearing away through the use of abrasives; a roughening or scratching of a surface due to abrasive wear.

abrasive wear
: The removal of material from a surface when hard particles slide or roll across the surface under pressure. The particles may be loose or may be part of another surface in contact with the surface being abraded. Compare with adhesive wear.

adhesive wear
: The removal or displacement of material from a surface by the welding together and subsequent shearing of minute areas of two surfaces that slide across each other under pressure. Compare with abrasive wear.

adiabatic
: Occurring without loss or gain of heat in the system, which may result in a local temperature increase or decrease. Adiabatic conditions differ from isothermal conditions (under which the temperature remains constant).

adiabatic shear bands

Shear bands created under adiabatic conditions; that is, bands created under conditions of local heating created by high strain-rate deformation.

alligatoring

The longitudinal splitting of flat slabs in a plane parallel to the rolled surface.

alligator skin

See orange peel.

ambient

Something usually used in relation to temperature, as “ambient temperature” surrounding a part or assembly. Often taken to mean “comfortable indoor temperature.”

annealing or growth twin

A twin formed in a crystal or grain during recrystallization or, rarely, during solidification.

anode

The electrode of an electrolytic cell at which oxidation occurs. Contrast with cathode.

arrest lines (marks)

Lines or thin regions that appear on fracture surfaces. There are two types of arrest lines: those created in monotonic loading and those from cyclic loading; the latter give information on the crack front position at a given point in time. Arrest lines in monotonic loading are created when the stored elastic strain energy cannot drive a crack completely across the remaining ligament. At the microscale, monotonic arrest lines are regions of microvoid coalescence, while the remainder of the fracture surface shows cleavage or quasi-cleavage cracking. Arrest lines in cyclic loading are created when the component remains in the unloaded condition for a time sufficiently long to cause crevice corrosion at the crack tip or for a sudden change in loading spectra. See also beach marks and rib mark.

asperity

In tribology, a protuberance in the small-scale topographical irregularities of a solid surface.

axial

Longitudinal, or parallel to the axis or centerline of a part. Usually refers to axial compression or axial tension or orientation of a metallographic or mechanical test coupon.

axial strain

The linear strain in a plane parallel to the longitudinal axis. Strain may be axial (tensile or compressive) or shear. For constant-volume materials, axial strain in a direction is equal in magnitude to the areal strain on a plane whose normal is in the direction of axial strain. Axial strain is the integral of a change in length divided by a length:

$$e = \int \frac{dL}{L}$$

If the length is considered to be a constant (typically the initial, i.e., gage length, L_0):

$$e = \frac{1}{L_o} \int_{L_o}^{L_f} dL = \left(\frac{L_f - L_o}{L_o} \right)$$

However, if the instantaneous length is considered:

$$e = \int_{L_o}^{L_f} \frac{dL}{L} = \ln\left(\frac{L_f}{L_o} \right)$$

See also shear strain.

B

banded structure

A segregated structure consisting of alternating, nearly parallel bands of different composition and possibly microstructure (as in steels with pearlite banding). Banding is typically aligned in the direction of primary flow in hot working but is often caused by conditions present when the material is cast.

beach marks

Macroscopic (visible) progression marks on a fracture surface that indicate successive positions of the advancing crack front. The classic appearance is of irregular elliptical or semielliptical rings radiating outward from one or more origins. After some growth, the curvature may be lost or reversed as affected by component geometry. Curvature is an indication of the stress field and is also affected by biaxial loading conditions and the shape of the remaining uncracked ligament. Beach marks (also known as clamshell marks, tide marks, or arrest marks) are typically found on service fractures where the part is loaded randomly, intermittently, or with periodic variations in mean stress, alternating stress, or environmental conditions. Not to be confused with striation (a microscale feature) and monotonic crack arrest lines (which are macroscale and form by a different mechanism). Beach marks formed during intermittent loading are formed by crevice corrosion. In steels, this causes the progression mark to have a dark or black appearance.

bifurcation

The separation of materials into two parts. See also crack bifurcation.

blue brittleness

Brittleness exhibited by some steels after being heated to a temperature within the range of approximately 205 to 370 °C (400 to 700 °F), particularly if the steel is worked at the elevated temperature. Killed steels are virtually free of this kind of brittleness.

breaking stress

See rupture stress.

Brinell hardness number, HB

A number related to the applied load and to the surface area of the permanent impression made by a ball indenter, computed from:

$$HB = \frac{2P}{p\,D\left(D - \sqrt{D^2 - d^2}\right)}$$

where P is applied load, kgf; D is diameter of ball, mm; and d is mean diameter of the impression, mm.

Brinell hardness test

A test for determining the hardness of a material by forcing a hard steel or carbide ball of specified diameter into the surface of the material under a specified load for a specified time. The result is expressed as the Brinell hardness number.

Brinelling

Damage to a solid bearing surface characterized by one or more plastically formed indentations brought about by overload. This term is often applied in the case of rolling-element bearings. See also false Brinelling.

brittle

Permitting little or no plastic (permanent) deformation prior to fracture. The term is used at both the macroscale and microscale. Contrast with ductile.

brittle crack propagation

A sudden propagation of a crack with the absorption of no energy except that stored elastically in the body. Microscopic examination may reveal some plastic deformation that is not noticeable to the unaided eye. Contrast with ductile crack propagation.

brittle erosion behavior

Erosion behavior having characteristic properties (e.g., little or no plastic flow, the formation of cracks) that can be associated with brittle fracture of the exposed surface. The maximum volume removal occurs at an angle near 90°, in contrast to approximately 25° for ductile erosion behavior.

brittle fracture

Separation of a solid accompanied by little or no macroscopic and/or microscopic plastic deformation. Typically, brittle fracture occurs by rapid crack propagation, with less expenditure of energy than for ductile fracture. The term is used at the macroscale to describe appearance and at the microscale to describe both appearance and mechanism.

brittleness

The tendency of a material to fracture without first undergoing plastic deformation. Contrast with ductility.

buckle

(1) An indented valley in the surface of a sand casting due to expansion of the molding sand. (2) A local waviness in metal bar or sheet, usually transverse to the direction of rolling, caused by inconsistencies in the temperature or thickness of the material being rolled.

buckling

A compression and torsion phenomenon that occurs when, after some critical level of load, a bulge, bend, bow, kink, or other wavy condition is produced in a beam, column, plate, bar, or sheet product. The level of stress that causes buckling in a given component is dependent mainly on geometry and elastic modulus, but in some shapes, yield strength also has a strong influence on the resistence to buckling.

bulk modulus

See bulk modulus of elasticity.

bulk modulus of elasticity, *K*

The measure of resistance to change in volume; the ratio of hydrostatic stress (σ_m) to the corresponding unit change in volume (ΔV). This elastic constant can be expressed by:

$$K = \frac{s_m}{\Delta V / V} = \frac{-p}{\Delta V / V} = \frac{1}{b}$$

where K is the bulk modulus of elasticity, σ_m is hydrostatic or mean normal stress, p is hydrostatic pressure, and β is compressibility. Also known as bulk modulus, hydrostatic modulus, and volumetric modulus of elasticity.

burning

(1) Permanently damaging a metal or alloy by heating to cause either incipient melting or intergranular oxidation. See also overheating and grain-boundary liquation. (2) In grinding, getting the work hot enough to cause discoloration or to change the microstructure by tempering or hardening.

C

carbon flotation

Free graphite that has separated from the molten iron in a cast iron. This imperfection tends to occur at the upper surfaces of the cope of castings.

casting shrinkage

Voids formed in cast products when insufficient molten metal is fed into the solidifying casting to make up for the volume loss due to cooling. See also liquid shrinkage, shrinkage cavity, solidification shrinkage, and solid shrinkage.

catastrophic wear

Rapidly occurring or accelerating surface damage, deterioration, or change of shape caused by wear to such a degree that the service life of a part is appreciably shortened or its function is destroyed.

cathode

The electrode of an electrolytic cell at which reduction is the principal reaction. (Electrons flow toward the cathode in the external circuit.) Contrast with anode.

caustic cracking

A form of stress-corrosion cracking most frequently encountered in carbon steels or iron-chromium-nickel alloys that are exposed to concentrated hydroxide solutions at temperatures of 200 to 250 °C (400 to 480 °F). See also caustic embrittlement.

caustic embrittlement

A form of hydrogen embrittlement sometimes caused by caustic cleaning of steel parts, especially those that have been hardened to relatively high strength levels. See also hydrogen embrittlement.

cavitation

(1) The formation and rapid collapse, within a liquid, of cavities or bubbles that contain vapor or gas or both. Cavitation caused by severe turbulent flow often leads to cavitation damage of adjacent materials, which may include loss of material or changes in surface properties. (2) The description of microscale void formation, primarily in the grain boundaries during high-temperature deformation.

cavitation erosion

See cavitation.

centerline shrinkage

Porosity due to incomplete fill after partial solidification of a casting (ingots or continuous-cast slabs or billets) or that occurs along the central plane or axis of a cast metal section. See also shrinkage porosity.

chafing fatigue

Fatigue initiated in a surface damaged by rubbing against another body. See also fretting.

Charpy (impact) test

Pendulum impact test (e.g., per ASTM E 23) in which a V-notched, keyhole-notched, or U-notched, rectangular specimen, supported at both ends, is struck in the center of its length, behind the notch, by a striker mounted at the lower end of a bar that can swing as a pendulum. The energy that is absorbed in fracture is calculated from the height to which the striker would have risen had there been no specimen and the height to which it actually rises after fracture of the specimen. Contrast with Izod test. Other measured specimen responses can include lateral contraction and percent shear fracture.

chevron pattern

A macroscale pattern of nested “V”-shaped ridges. The apex of the V's point back to the region of fracture initiation. The “V” pattern is created when the crack propagates faster in the interior of the material than at the surface. Half-V-shaped ridges are created when crack propagation is faster at the surface than in the interior. The latter marks are often described as radial marks. The term chevron pattern is sometimes used interchangeably with the term herringbone pattern. However, there are differences in appearance. First, a chevron pattern is a macroscale pattern, while a herringbone pattern is a microscale pattern. Secondly, a herringbone pattern, although it is a series of nested V's, is created by the different mechanism of a central spine created by cleavage on a {100} plane and continued intermittent lateral crack expansion of the crack on {1,1,2} twinning planes (i.e., see tongue).

chill

A white cast iron or cast aluminum structure that is produced by rapid solidification. Usually intentionally produced to provide desirable wear characteristics.

chord modulus

The slope of the chord drawn between any two specific points on a stress-strain curve. See also modulus of elasticity. A term commonly used in the polymer field to specify how a single value for the modulus of elasticity is determined from a nonlinear load elongation graph from a tensile test.

clamshell marks

See beach marks.

cleavage

(1) Fracture of a crystal by crack propagation across a crystallographic plane of low index. (2) The tendency to cleave or split along definite crystallographic planes. (3) Sometimes used to describe brittle fracture at the macro- or microscale in amorphous materials (such as glasses).

cleavage crack

In crystalline material, a transgranular fracture that extends along a cleavage plane, resulting in bright reflecting facets. Contrast with microvoid coalescence (MVC). Sometimes used to describe the macroscale brittle fracture of amorphous materials (such as glasses and glassy polymers).

cleavage plane

(1) In metals, a characteristic crystallographic plane or set of planes in a crystal on which a cleavage crack occurs easily. (2) In noncrystalline material, the plane on which brittle fracture occurs.

cold shot

(1) A portion of the surface of an ingot or casting showing premature solidification; caused by splashing of molten metal onto a cold mold wall during pouring. (2) A small globule of metal embedded in, but not entirely fused with, a casting.

cold shut

(1) In castings, a discontinuity on or immediately beneath the surface of a casting, caused by the meeting of two streams of liquid metal that failed to merge. A cold shut may have the appearance of a crack or seam with smooth, rounded edges. (2) In wrought products, a fissure or lap on a surface that has been closed without fusion during working, or a folding back of metal onto its own surface during flow in the die cavity.

columnar structure

A coarse structure of parallel, high-aspect-ratio grains formed by directional growth that is most often observed in castings. Similar structures are sometimes seen in steels subjected to extensive surface decarburization.

composite material

A heterogeneous, solid structural material consisting of two or more distinct components that are mechanically or metallurgically bonded together, such as a wire, filament, or particles of a high-melting-point substance embedded in a metal or nonmetal matrix.

compression

Pertaining to forces on a body or part of a body that tend to crush, or compress, the body. There is contraction in the direction of the force and expansion perpendicular to the force.

compressive strength

The maximum compressive stress a material is capable of developing. With a brittle material that fails in compression by fracturing, the compressive strength has a definite value. In the case of ductile, malleable, or semiviscous materials (which do not fail in compression by a shattering fracture), the value obtained for compressive stength is an arbitrary value dependent on the degree of distortion that is regarded as effective failure of the material.

compressive stress

A stress that causes a body to deform (shorten) in the direction of the applied load. Contrast with tensile stress.

contact fatigue

Cracking and subsequent pitting of a surface subjected to alternating Hertzian (contact stresses), such as those produced under rolling contact or combined rolling and sliding. The phenomenon of contact fatigue is encountered most often in rolling-element bearings or in gears, where the surface stresses are high due to the concentrated loads and are repeated many times during normal operation. Fracture is at the subsurface location of the maximum Hertzian shear stress.

contact (Hertzian) stress

The pressure at a contact between two solid bodies calculated according to Hertz's equations for elastic deformation. The theoretical area of contact between two nonconforming surfaces is frequently quite small. The interaction between these surfaces is often described as either point or line contact. Common examples of point contact are mating helical gears, cams and crowned followers, ball bearings and their races, and train wheels and rails. If the mating parts can be considered semiinfinite and if material behavior is linearly elastic, then the local stress state can be described by Hertzian theory, as long as the contacting surfaces can be modeled as quadratic functions of those spatial coordinates defining the surfaces. Even in the absence of friction, the resulting three-dimensional stress state is quite complex, and although the local stress state is compressive, that is, the principal stresses beneath the load are negative, large subsurface shear stresses, which can serve as crack initiation sites, exist beneath the load.

corrosion

The chemical or electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material and its properties. See also corrosion fatigue, crevice corrosion, denickelification, dezincification, erosion-corrosion, exfoliation, filiform corrosion, fretting corrosion, galvanic corrosion, general corrosion, graphitic corrosion, impingement attack, interdendritic corrosion, intergranular corrosion, internal oxidation, oxidation, parting, pitting, poultice corrosion, rust, selective leaching, stray-current corrosion, stress-corrosion cracking, and sulfide stress cracking.

corrosion fatigue

Cracking produced by the combined action of repeated or fluctuating stress and a corrosive environment.

corrosive wear

Wear in which chemical or electrochemical reaction with the environment is significant.

Coulomb-Mohr fracture criterion

A theory of fracture based on experimental values for both tensile and compressive strength in which fracture on a plane is hypothesized to occur when a critical combination of normal and shear stress occur on the plane (maximum pressure reduced shear stress). The critical combination of stresses is assumed to be a linear relationship:

$$|\tau| + \mu\sigma = \tau_i(\text{uniaxial load})$$

where τ and σ are shear and normal stress, respectively, and μ and τ_i are material constants.

crack

(1) A pair of surfaces and the associated discontinuity created by separation under stress of atoms previously bonded. This does not include internal free surfaces created by corrosion processes or solidification imperfections. (2) The process by which a solid object becomes fragmented due to separation of atomic bonds under stress. Cracking is often accompanied by or preceded by deformation.

crack bifurcation

The spliting of a crack into two paths, or the intersection of a crack with a preexisting crack.

crack extension

An incremental increase in crack size. See also crack length (a) or depth, effective crack size, and physical crack size.

crack extension force

The elastic energy per unit of new separation area that is made available at the front of an ideal crack in an elastic solid during a virtual increment of forward crack extension. Also described as the strain energy release rate.

crack length (*a*) or depth

In fracture-mechanics-based analyses, the physical crack size used to determine the crack growth rate and the stress-intensity factor. For a compact-type specimen, crack length is measured from the line connecting the bearing points of load application. For a center-crack tension specimen, crack length is measured from the perpendicular bisector of the central crack.

crack mouth opening displacement (CMOD)

See crack tip opening displacement (CTOD).

crack opening displacement (COD)

See crack tip opening displacement (CTOD)

crack plane orientation and growth direction

A three-letter identification system used to identify the longitudinal (L), transverse (T), and short transverse (S) direction of the applied stress normal to the plane on which the crack propagates and the direction of crack growth. Used for both prismatic and cylindrical sections. For example, a L-T orientation indicates a stress in the longitudinal (or rolling) direction, and crack propagation is in the wide transverse direction. See ASTM E 399 for a complete description.

crack size (*a*)

A lineal measure of a principal planar dimension of a crack. This measure is commonly used in the calculation of quantities descriptive of the stress and displacement fields. In practice, the value of crack size is obtained from procedures for measurement of physical crack size, original crack size, or effective crack size, as appropriate to the situation under consideration. See also crack length (a) or depth.

crack tip opening displacement (CTOD)

The crack displacement resulting from the total deformation (elastic plus plastic) at variously defined locations near the original crack tip.

crack-tip plane strain

A stress-strain field near a crack tip that approaches plane strain to the degree required by an empirical criterion.

creep

Time-dependent strain occurring under stress. The creep strain occurring at a diminishing rate is called primary or transient creep (stage I); that occurring at a minimum and almost constant rate, secondary or steady-rate creep (stage II); and that occurring at an accelerating rate, tertiary creep (stage III).

creep rate

The slope of the creep-time curve at a given time. See also minimum creep rate.

creep-rupture strength

The stress that causes fracture in a creep test at a given time in a specified constant environment. Also known as stress-rupture strength.

creep strain

The time-dependent total strain (including the initial instantaneous elastic strain) produced by applied stress during a creep test.

creep strength

The stress that causes a given creep strain in a creep test at a given time in a specified constant environment.

creep stress

The constant load divided by the original cross-sectional area of the specimen.

crevice corrosion

Localized corrosion of a metal surface at, or immediately adjacent to, an area that is shielded from full exposure to the environment because of close proximity between the metal and the surface of another material.

cross direction

See transverse direction.

crush

(1) An indentation in a casting surface due to displacement of sand into the mold cavity when the mold is closed. (2) Permanent localized compressive deformation. (3) The spalling of (usually thin) surface-treated cases on gears due to overload; also known as case crushing.

cumulative damage

In fatigue loading, a measure of damage, as expressed as a fraction of life to failure, as it accumulates with the number of cycles. When the stress level is changed, the life is changed. Therefore, damage accumulates according to the stress level and number of cycles spent at a given stress. The most common (but not only) model for linear cumulative damage is the Palmgren-Miner cumulative damage model. In the following equation, n_i is the number of load cycles spent at a stress for which the life is N_i. Failure is assumed to occur when the damage summation becomes unity:

$$D = \sum \frac{n_i}{N_i}$$

cup fracture (cup-and-cone fracture)

A mixed-mode fracture, often seen in cylindrical-shaped components or tension test specimens of a ductile material, where the core of the necked region undergoes fracture by microvoid coalescence, creating the cup bottom. As the crack grows from this central region, the degree of constraint is reduced, and fracture continues in the remaining outer ring under conditions of plane stress, creating the slanted cup walls. Closely related fracture appearance also is seen in small width-to-thickness-ratio prismatic tensile specimens. One of the mating fracture surfaces looks similar to a miniature cup, having a central depressed flat-face region surrounded by a shear lip. The other fracture surface looks similar to a miniature truncated cone.

cupping

The condition sometimes occurring in heavily cold-worked rods and wires in which the outside fibers are still intact and the central zone has failed in a series of cup-and-cone fractures.

cut

A raised, rough surface on a casting due to erosion by the metal stream of part of the sand mold or core.

cyclic loading

(1) Repetitive loading, as with regularly recurring stresses on a part, that sometimes leads to fatigue fracture. (2) Loads that change value by following a regular or irregular repeating sequence of change.

D

dealloying

The selective corrosion of one or more components of a solid-solution alloy. Also called parting or selective leaching. See also decarburization, denickelification, dezincification, and graphitic corrosion.

decarburization

Loss of carbon from a free surface (component surface or surface of a crack intersecting the surface) of a carbon-containing alloy due to reaction with one or more chemical substances in a medium that contacts the surface.

decohesion

The process of creating a pair of free surfaces where a grain boundary or second-phase boundary existed previously.

defect

(1) An imperfection (deviation from perfection) that can be shown to cause failure by a quantitative analysis and that would not have occurred in the absence of the imperfection. (2) (Legal) Manufacturing defect: (a) a failure to conform to stated specifications; (b) nonsatisfaction of user requirements; (c) deviation from the norm; (d) when a product leaves the assembly line in substandard condition, differs from the manufacturer's intended result, or differs from other ostensibly identical units of the same product line. (3) (Legal) Design defect: (a) less safe than expected by the ordinary consumer; (b) excessive preventable danger. (4) (Legal) Marketing defect: failure to warn or inadequate warning of hazard and risk involved with use of a product. Note: Legal definitions may vary from jurisdiction to jurisdiction. Those legal definitions cited here are from the article “Product Liability and Design” in this Volume and also in *Materials Selection and Design,* Volume 20, *ASM Handbook,* page 147. An example is a deviation from specification. It can be the cause of a failure that makes the part unsuitable for its intended purpose. However, just because a part fails does not imply that it contained a defect, and not all defects are a cause for failure. (2) Laws of various jurisdictions may also define what constitutes a defect of defective product.

deformation

A change in the shape of a body due to stress, thermal change, change in moisture, or other causes.

deformation bands

Bands produced within individual grains during cold working that differ in orientation from the matrix.

deformation twin

See mechanical twin (deformation twin) and Neumann bands.

dendrite

A crystal with a treelike branching pattern. Dendrites are most evident in cast metals slowly cooled through the solidification range.

denickelification

Corrosion in which nickel is selectively leached from nickel-containing alloys. Most commonly observed in copper-nickel alloys after extended service in fresh water. See also selective leaching.

depletion

Selective removal of one component of an alloy, usually from the surface or preferentially from grain-boundary regions. See also selective leaching.

deposit attack or corrosion

See poultice corrosion.

deviatoric stress

The nonhydrostatic component of the state of stress on a body. It is the deviatoric component that causes shape change (plastic deformation).

dezincification

Corrosion in which zinc is selectively leached from zinc-containing alloys. Most commonly found in copper-zinc alloys containing less than 85% Cu after extended service in water containing dissolved oxygen. See also selective leaching.

diamond pyramid hardness test

See Vickers hardness test.

diffuse necking

The nonuniform strain distribution along the length of a member loaded in tension that develops at the maximum load. The term “diffuse” is used because the neck develops slowly, with little change in load, but an increase in axial strain near the load maximum. Contrast to local necking.

dimpled rupture fracture

Ductile fracture that occurs through the formation and coalescence of microvoids (dimples) along the fracture path. The fracture surface of such a ductile fracture appears dimpled when observed at high magnification and usually is most clearly resolved when viewed in a scanning electron microscope.

distortion

Any deviation from an original size, shape, or contour that occurs because of the application of stress or the release of residual stress and may be associated with exposure to high or low temperature.

ductile

Capable of being plastically deformed before fracturing.

ductile-brittle transition temperature (DBTT)

Temperature at which a marked change occurs in the fracture resistance of body-centered cubic and hexagonal close-packed metals from ductile behavior to brittle behavior. The transition occurs in those metals in which the yield strength increases sharply with decreasing temperature and which are capable of fracturing by cleavage or an intergranular mode with very little accompanying plastic deformation. The transition temperature also depends on strain rate.

ductile crack propagation

Slow crack propagation that is accompanied by noticeable plastic deformation and requires energy to be supplied from outside the body. Contrast with brittle crack propagation.

ductile erosion behavior

Erosion behavior having characteristic properties (such as considerable plastic deformation) that can be associated with ductile fracture of the exposed solid surface. A characteristic ripple pattern forms on the exposed surface at low values of angle of attack. Contrast with brittle erosion behavior.

ductile fracture

Macroscale and microscale term. Used at the macroscale to indicate visible plastic deformation associated with fracture (often implies high energy absorption). Used at the microscale to describe plastic deformation associated with fracture, typically by microvoid coalescence. Contrast with brittle fracture.

ductility

The ability of a material to deform plastically before fracturing. Measured by elongation or reduction of area in a tension test, by height of the cup formed, in a cupping test, or by the radius or angle of bend in a bend test. Contrast with brittleness; see also plastic deformation.

dynamic

Moving, or having high velocity. Frequently used with high strain-rate ($\geq 0.1\ s^{-1}$) testing of metal specimens.

E

effective crack size, a_e

The physical crack size augmented for the effects of crack-tip plastic deformation. Sometimes the effective crack size is calculated from a measured value of a physical crack size plus a calculated value of a plastic-zone adjustment. A preferred method for calculation of effective crack size compares compliance from the secant of a load-deflection trace with the elastic compliance from a calibration for the type of specimen.

effective stress

A calculated parameter used in a mathematical expression that predicts the onset of an event (typically yield and fatigue failure) when a critical value of the effective stress is obtained. The most common effective stress is the von Mises stress.

elastic constants

The factors of proportionality that relate elastic displacement of a material to applied forces. See also bulk modulus of elasticity, modulus of elasticity, Poisson's ratio, and shear modulus.

elastic deformation

Shape change and volume change due to an applied stress that is low enough so that the material returns to its original shape and volume when the stress is removed.

elasticity

The property of a material by virtue of which deformation caused by stress disappears on removal of the stress. A perfectly elastic body completely recovers its original shape and dimensions after release of stress.

elastic limit

The maximum stress a material is capable of sustaining without any permanent shape change remaining on complete release of the stress. See also proportional limit.

elastic strain

The mathematical value that quantifies elastic deformation.

elongation

A term used in mechanical testing to describe the amount of extension of a test piece when stressed. Expressed in units of length or as strain (percent change in length). Quantitative value describing the length increase of the gage length of a tensile-test bar due to the deformation up to and including the fracture process. Note that elongation (expressed as length or strain) is not an inherent material property but depends on the dimension of the specimen tested as well as whether it is measured under load, such as with a laser extensometer, or after fracture, generally after manually remating the fracture surfaces in a fixture.

embrittlement

The severe loss of ductility and/or toughness of a material.

end grain

Grain flow lines that intersect with the exposed surface of the ends of bar stock, tubing, or the parting lines of forgings. A long, narrow test specimen sectioned so that the grain is parallel to the longitudinal axis of the specimen has no exposed end grain, except at the extreme ends. In contrast, a corresponding specimen cut in the transverse direction has end-grain exposure at all points along its length. End grain is especially pronounced in the short-transverse direction on die forgings designed with a flash line.

end-grain attack

Preferential corrosive attack of grains exposed by cutting through the cross section or at the parting lines of forgings.

endurance limit

Obsolete term used to describe a characteristic in components subject to fatigue cracking. The use of this term is now discouraged, because it does not reflect the current understanding of how fatigue cracks initiate and grow. It referred to the maximum stress below which a material can presumably endure an infinite number of stress cycles. If the stress is not completely reversed, the value of the mean stress, the minimum stress, or the stress ratio also should be stated. Compare with fatigue limit.

erosion

Destruction of materials by the abrasive action of moving fluids, usually accelerated by the presence of solid particles carried with the fluid. See also erosion-corrosion.

erosion-corrosion

A conjoint action involving corrosion and erosion in the presence of a moving corrosive fluid, leading to the accelerated loss of material.

etch pits

(1) Localized corrosion attack at the microscopic scale. Typically seen on a polished and etched metallographic specimen. Etch pits typically have recognizable, simple geometric shape (square, rectangle, triangle) and therefore reveal, in a qualitative way, the orientation of a grain. (2) A conjoint action involving corrosion and erosion in the presence of a moving corrosive fluid, leading to the accelerated loss of material.

exfoliation

Corrosion that proceeds from the sites of initiation along planes parallel to the surface, generally along grain boundaries, forming bulky corrosion products that create generally undesired free internal surfaces and give rise to a layered appearance.

F

failure

(1) A general term used to imply that a part in service (a) has become completely inoperable, (b) is still operable but is incapable of satisfactorily performing its intended function, or (c) has deteriorated seriously, to the point that it has become unreliable or unsafe for continued use. (2) Also commonly applied to manufacturing processes that produce components that do not meet specifications.

false Brinelling

Damage to a solid bearing surface characterized by indentations not caused by plastic deformation resulting from overload but thought to be due to other causes such as fretting corrosion. See also Brinelling.

fatigue

The phenomenon leading to fracture or cracking under repeated or fluctuating stresses having a maximum value less than the ultimate tensile strength (and for ductile materials, usually less than the yield strength) of the material. See also fatigue failure, high-cycle fatigue, low-cycle fatigue, yield strength, and ultimate strength.

fatigue crack growth rate, *da*/*dN*

The rate of crack extension caused by constant-amplitude fatigue loading, expressed in terms of crack extension per cycle of load application. Note that this is not a single-value parameter. See also Paris law.

fatigue failure

Failure that occurs when a specimen undergoing cyclic loading, due to applied loads or temperature variations, completely fractures into two parts or has been significantly reduced in stiffness by cracking. Fatigue failure generally occurs at loads that, when applied statically, would produce little perceptible effect.

fatigue life

The number of stress cycles that can be sustained prior to failure under a stated test condition.

fatigue limit

(1) The maximum stress that presumably leads to fatigue fracture in a specified number of stress cycles. If the stress is not completely reversed, the value of the mean stress, the minimum stress, or the stress ratio also should be stated. Compare with endurance limit. Preference is to quote the medial value of the stress, based on statistical analysis of the experimental data. (2) The limiting value of median fatigue strength as the number of cycles becomes very large (SAE definition). *Note:* certain materials and environments preclude the attainment of fatigue limits. Values tabulated as fatigue limits in literature are frequently (but not always) values for 50% survival at N cycles with zero mean stress.

fatigue notch factor, k_f

The ratio of the fatigue strength of an unnotched specimen to the fatigue strength of a notched specimen of the same material and condition; both strengths are determined at the same number of stress cycles.

fatigue notch sensitivity, q

An estimate of the true effect of a notch (as contrasted to a theoretical effect based on the elastic stress concentration factor) or hole of a given size and shape on the fatigue properties of a material; measured by $q = (k_f - 1)/(k_t - 1)$, where k_f is the fatigue notch factor and k_t is the stress concentration factor. A material is said to be fully notch sensitive if q approaches a value of 1.0; it is not notch sensitive if the ratio approaches 0.

fatigue ratio

The fatigue limit under completely reversed flexural stress divided by the tensile strength for the same alloy and condition.

fatigue strength

The maximum stress that can be sustained for a specified number of stress cycles without failure, the stress being completely reversed within each cycle, unless otherwise stated.

fatigue striation

(1) A microscale fatigue fracture feature sometimes observed that indicates the position of the crack front after each succeeding cycle of stress. The distance between striations indicates the advance of the crack front during one stress cycle, and a line normal to the striation indicates the direction of local crack propagation. Not to be confused with beach marks, which are much larger (macroscopic) and form differently. Also not to be confused with other similarly appearing microscale features, such as a stretch zone at the tip of a preexisting cracklike imperfection, a Wallner line, and so on. (2) In glasses, a fracture-surface marking consisting of the separation of the advancing crack front into separate fracture planes. Also known as coarse hackle, step fracture, or lance. Striations may also be called shark's teeth or whiskers.

fatigue wear

Wear of a solid surface caused by fracture arising from material fatigue.

fiber

The characteristic of wrought metal that indicates directional properties. It can be revealed by etching of a longitudinal section or is manifested by the fibrous or woody appearance of a fracture. It is caused either by (a) extension of the constituents of the metal, both metallic and nonmetallic, in the direction of

working during rolling, extrusion, or other solid-state processes or (b) by crystallographic alignment of the matrix phase itself.

fiber-reinforced composite

A material consisting of two or more discrete physical phases in which a fibrous phase is dispersed in a continuous matrix phase. The fibrous phase may be macro-, micro-, or submicroscopic, but it must retain its physical identity so that it could conceivably be removed from the matrix intact.

fiber stress

Local stress at a small area (a point or line) on a section where the stress is not uniform, as in a beam under a bending load.

fibrous fracture

(1) A gray and matte fracture that results in ductile materials that have undergone the crack-formation mechanism of microvoid coalescence. (2) The appearance of the fracture surface of a highly anisotropic material, such as hard-drawn wire or a material containing a banded structure.

fibrous structure

(1) In forgings, a structure revealed as laminations, not necessarily detrimental, on an etched section or as a ropy appearance on a fracture. (2) In wrought iron, a structure consisting of slag fibers embedded in ferrite. (3) In rolled steel plate stock, a uniform, lamination-free, fine-grained structure on a fractured surface.

filiform corrosion

Corrosion that occurs under some coatings in the form of randomly distributed threadlike filaments.

fisheye

A generally round, internal discontinuity found on fracture surfaces of steel that is due to the presence of a hydrogen-related intergranular crack that may have initiated the rest of the fracture. In welds, often associated with the presence of moisture during the welding operation. See also flake.

fishmouth fracture

The macroscale appearance of a longitudinal fracture in an internally pressurized pipe, tube, or pressure vessel.

flake

A short, discontinuous internal crack in ferrous metals attributed to stresses produced by localized transformation and hydrogen-solubility effects during cooling after hot working. In fracture surfaces, flakes appear as bright, silvery areas with a coarse texture. In deep acid-etched transverse sections, they appear as discontinuities that are usually in the midway to center location of the section. Also known as hairline cracks and shatter cracks.

flow

Movement (slipping or sliding) of essentially parallel planes within an element of a material in parallel directions; occurs under the action of shear stress. Continuous action in this manner, at constant volume and without disintegration of the material, is termed yield, creep, or plastic deformation.

flow lines

(1) Light and dark bands showing the direction of metal flow during hot or cold working; revealed by macroetching. (2) The generally uneven (and therefore variously light reflective) ridged or wavy pattern on a macro- or micro-metallographic surface caused by working of metal with chemical segregation.

fluting

(1) A type of pitting in which cavities occur in a regular pattern, forming grooves or flutes. Fluting is caused by fretting or by electric arcing. (2) Long tear ridges apparently created by planar slip between cleavage cracks; a characteristic microscale feature that sometimes appears on fracture surfaces, especially in titanium alloys.

fold

A macroscale imperfection in metal, usually on or near the surface, caused by folding metal back onto its own surface during its flow into a die cavity or during working.

fractography

Examination of fracture surfaces and adjacent areas with the intent to determine conditions that caused fracture. Examination at the macroscale (up to 25 diameters) typically provides information regarding loading conditions (monotonic versus cyclic, axial, bending, torsion), the crack initiation site, and crack propagation direction, as well as the need to consider the contribution of environmental substances to

the ease of cracking. Microscale examination typically provides information regarding fracture mechanisms, interaction with the microstructure, and details of any environmental involvement. (2) Also refers to a descriptive explanation of a fracture process, with specific reference to a description of, or photographs of, the fracture surface. Macrofractography involves low magnification (approximately <25 diam); microfractography, high magnification (approximately >25 diam).

fracture

The process by which a component separates into multiple fragments. See also crack.

fracture mechanics

The quantitative analytical prediction of the ability of a material to resist fracture based on the relationship among the applied stress state, a preexisting flaw, and the fracture toughness of a material. The ability to resist fracture may be expressed as a critical value of the stress-intensity factor (K), the strain energy release rate, the J-integral, or the crack tip opening displacement (CTOD) . See also linear elastic fracture mechanics.

fracture stress

True, normal stress at the minimum cross section at the beginning of fracture (ASTM E 1823).

fracture surface

(1) The irregular surface produced when a piece of metal is broken. (2) A break in the mechanical continuity of a body. (3) Cracks, crazing, delamination, or a combination thereof resulting from physical damage to a pultrusion (ASTM E 1823).

fracture test

Test in which a specimen is broken and its fracture surface is examined with the unaided eye or with a low-power microscope to determine such factors as composition, grain size, case depth, or presence of discontinuities.

fracture toughness

A generic term for measures of resistance to extension of a crack. The term is sometimes restricted to results of fracture mechanics tests, which are directly applicable in fracture control. However, the term is also commonly used to include results from simple tests of notched or precracked specimens not based on fracture mechanics analysis. Results from tests of the latter type are often useful for fracture control, based on either service experience or empirical correlations with fracture mechanics tests. See also crack extension force, crack tip opening displacement (CTOD) J-integral, and stress-intensity factor

fretting

Wear that occurs between tight-fitting surfaces subjected to oscillation at very small amplitude. This type of wear can be a combination of oxidative wear and abrasive wear. See also fretting corrosion.

fretting corrosion

The deterioration at the interface between contacting surfaces as the result of corrosion and slight oscillatory slip between the two surfaces.

fretting fatigue

Fatigue fracture that initiates at a surface area where fretting has occurred.

G

galling

A condition whereby excessive friction between high spots results in localized welding, with subsequent transfer of material and a further roughening of the rubbing surfaces of one or both of two mating parts.

galvanic corrosion

Accelerated corrosion of a metal because of an electrical contact with a more noble metal or nonmetallic conductor in a corrosive electrolyte.

gas hole

A hole in a casting or weld formed by gas escaping from molten metal as it solidifies. Gas holes may occur individually, in clusters, or be distributed throughout the solidified metal.

gas porosity

Fine holes or pores within a metal that are caused by entrapped gas or by evolution of dissolved gas during solidification.

general corrosion

A form of corrosion that is distributed more or less uniformly over a surface.

glide

See slip.

grain

An individual crystal in a polycrystalline metal or alloy, including twinned regions or subgrains if present.

grain boundary

An interface separating two grains at which the orientation of the lattice changes from that of one grain to that of the other. When the orientation change is very small, the boundary is sometimes referred to as a sub-boundary structure or a low-angle boundary.

grain-boundary corrosion

Same as intergranular corrosion; see also corrosion and interdendritic corrosion.

grain-boundary denudation

A nonequilibrium condition in which there is a solute composition gradient of a solute from the grain boundary to the grain interior. The condition is often created when a phase rich in the solute forms in the grain boundary. See also precipitate-free zone (PFZ).

grain-boundary liquation

An advanced stage of overheating in which material in the region of the grain boundaries melts. Sometimes also described as burning, but burning may not always be associated with melting. See also burning.

grain flow

Light and dark bands visible on metallographic sections indicating the direction of primary flow of worked components after macro- or micro-examination of an etched microstructure. The variable etching is caused by the nonremoval of microscale segregation. Grain flow produced by proper die design can improve mechanical properties of forgings in the orientation in which they are most useful to the component strength in service.

granular fracture

A type of irregular surface produced when metal is broken that is characterized by a rough, grainlike appearance, rather than a smooth or fibrous one. It can be subclassified as transgranular or intergranular. This type of fracture is frequently called crystalline fracture; however, the inference that the metal broke because it “crystallized” is not justified, because all metals are crystalline in the solid state. See also fibrous fracture and silky fracture.

graphitic corrosion

Deterioration of cast iron in which the metallic constituents are selectively leached or converted to corrosion products, leaving the graphite intact; it occurs in relatively mild aqueous solutions and in buried pipe and fittings. The term “graphitization” is commonly used to identify this form of corrosion but is not recommended because of its use in metallurgy for the decomposition of carbide to graphite.

growth twin

See annealing or growth twin.

H

hackle (glassy materials, ceramics)

A line on a crack surface, running parallel to the local direction of cracking, separating parallel but noncoplanar portions of the crack surface. See also mist hackle, shear hackle, twist hackle, and wake hackle.

hackle marks (ceramics, glassy materials)

Fine ridges on the fracture surface of a glass, parallel to the direction of propagation of the fracture.

hairline crack

A fine or closed crack.

hardness

A measure of the resistance of a material to surface indentation or abrasion; may be thought of as a function of the stress required to produce some specified type of surface deformation. There is no absolute scale for hardness; therefore, to express hardness quantitatively, each type of test has its own

scale of arbitrarily defined hardness. Indentation hardness can be measured by Brinell, Knoop, Rockwell, Vickers, and Webster hardness tests. Scratch tests include file hardness scales and Moh's hardness scale for minerals. Dynamic hardness testers, such as the Scleroscope or Equotip, give values that are more dependent on the elastic response of the material than the traditional indentation hardness methods. Microindentation methods (Knoop and Vickers) are particularly useful to the failure analyst, because they can show local property variations that are masked by larger indenters.

Hartmann lines

See Lüders lines.

heat-affected zone

That portion of the base metal that was not melted during brazing, cutting, or welding, but whose microstructure and mechanical properties were altered by the heat.

herringbone pattern

See comments with chevron pattern.

Hertzian stress

See contact (Hertzian) stress.

high-cycle fatigue

Fatigue that occurs at relatively large numbers of cycles. The arbitrary, but commonly accepted, dividing line between high-cycle fatigue and low-cycle fatigue is considered to be approximately 10^4 to 10^5 cycles. In practice, this distinction is made by determining whether the dominant component of the strain imposed during cyclic loading is elastic (high cycle) or plastic (low cycle), which in turn depends on the properties of the metal and on the magnitude of the nominal stress. High-cycle fatigue is controlled primarily by crack initiation behavior of the material, as opposed to crack growth behavior. Contrast with low-cycle fatigue.

Hill yield criterion

A criterion used to describe the onset of plastic deformation for anisotropic materials. In its most general form, it assumes the presence of three different axial yield stresses and three different shear yield stresses. The criterion is formulated mathematically so as to reduce to the von Mises yield criterion if the material is isotropic. Mathematically:

$$F(s_{yy} - s_{zz})^2 + G(s_{zz} - s_{xx})^2 + H(s_{xx} - s_{yy})^2 + 2Ls_{yz}^2 + 2Ms_{zx}^2 + 2Ns_{xy}^2 = 2f(s_{ij})$$

where F, G, H, L, M, and N are constants, and $f(\sigma_{ij})$ is the yield surface. In practice, many anisotropic cubic materials show reasonable isotropy in the plane of the sheet but different behavior normal to this plane. In such a case, the Hill criterion in principal stress form reduces to:

$$s_{xx}^2 + s_{yy}^2 - \frac{R}{R+1} s_{xx} s_{yy} = 2X^2$$

where X is the yield strength in the rolling direction, R = constant = $H/G = H/F$.

Hooke's law

A generalization, applicable to all solid materials, that states that stress is directly proportional to strain. This law is valid only up to the proportional limit, or the end of the straight-line portion of the stress-strain diagram. See also modulus of elasticity.

hot crack

See solidification shrinkage crack.

hot tear

A crack or fracture formed before completion of solidification because of hindered contraction. A hot tear is frequently open to the surface of the casting or weld and thus exposed to the atmosphere. This may result in oxidation, decarburization, or other metal-atmosphere reactions at the tear surface.

hydrogen blistering

The formation of blisters on or below a metal surface from excessive internal hydrogen pressure. Hydrogen may be formed during cleaning, plating, corrosion, and so on.

hydrogen damage

A general term for the embrittlement, cracking, blistering, and hydride formation that can occur when hydrogen is present in some metals.

hydrogen embrittlement

A condition of low ductility or cracking in metals resulting from the absorption of hydrogen. See also hydrogen-induced delayed cracking.

hydrogen-induced delayed cracking

A term sometimes used to identify a form of hydrogen embrittlement in which a metal appears to fracture spontaneously under a steady stress less than the yield stress. There is usually a delay between the application of stress (or exposure of the stressed metal to hydrogen) and the onset of cracking. Also referred to as static fatigue, although the use of this term is discouraged.

hydrostatic modulus

See bulk modulus of elasticity.

hydrostatic stress

The general three-dimensional state of stress acting on a body consists of three independent shear stresses and three independent normal stresses. The hydrostatic stress is defined as the mean value of the normal stresses. Constant volume materials cannot permanently deform when the loading conditions create a stress state that is purely hydrostatic. Thus, the presence of a hydrostatic stress is important for understanding of brittle fracture.

I

impact energy

The amount of energy required to fracture a material at high strain-rate conditions, usually measured by means of an Izod test or Charpy (impact) test. The type of specimen and test conditions affect the values and therefore should be specified.

impact load

An especially severe shock load such as that caused by instantaneous arrest of a falling mass, by shock meeting of two parts (in a mechanical hammer, for example), or by explosive impact, in which there can be an exceptionally rapid buildup of stress.

impact strength

See impact energy.

imperfection

A deviation from ideality. An imperfection may or may not be a defect, may or may not be addressed by a specification, and may or may not be related to a failure. All defects are imperfections. Imperfections may be geometric, metallurgical, and cosmetic.

impingement attack

Corrosion associated with turbulent flow of liquid. May be accelerated by entrained gas bubbles. See also erosion-corrosion.

incipient melting

Heating of material into a two-phase liquid-solid region on the phase diagram so that some liquid is formed.

inclusion

A particle of foreign material in a metallic matrix. The particle is usually a compound (such as an oxide, sulfide, or silicate) but may be of any substance that is foreign to (and essentially insoluble in) the matrix at low fractions of the melting point. Inclusions are usually considered undesirable, although in some cases—such as in free-machining metals—manganese sulfides, phosphorus, lead, selenium, or tellurium may be deliberately introduced to improve machinability. Inclusions, in some cases, result from the removal of undesirable impurities from solid solution (e.g., sulfur, nitrogen). Ladle additions may also be made to reduce the grain size, again resulting in inclusions in the matrix.

intercrystalline

See intergranular.

interdendritic corrosion

Corrosive attack that progresses preferentially along interdendritic paths. This type of attack results from local differences in composition commonly encountered in alloy castings and in some wrought precipitation hardending alloys. See also corrosion.

interface

The boundary between two contacting parts or regions of parts.

intergranular
Between crystals or grains, that is, in or immediately adjacent to the grain boundary. Also known as intercrystalline. Contrast with transgranular.

intergranular corrosion
Corrosion that occurs preferentially at or immediately adjacent to grain boundaries (usually with slight or negligible attack in the grain interior). See also interdendritic corrosion.

intergranular cracking
Cracking or fracturing that occurs in or immediately adjacent to the grain boundary in a polycrystalline aggregate. Contrast with transgranular cracking or fracture.

intergranular fracture
Macroscale brittle fracture of a metal in which the fracture is between the grains, or crystals, that form the metal. The microscale fracturing mechanism may be ductile or brittle. Contrast with transgranular cracking or fracture.

intergranular stress-corrosion cracking
Stress-corrosion cracking in which the cracking occurs in, or immediately adjacent to, the grain boundaries.

internal oxidation
(1) Isolated corrosion beneath the metal surface. This occurs as the result of preferential oxidation of certain alloy constituents by inward diffusion of oxygen, nitrogen, sulfur, and so on. Also known as subsurface corrosion. (2) Preferential in situ oxidation of certain components of phases within the bulk of a solid alloy accomplished by diffusion of oxygen into the body. This is commonly used to prepare electrical contact materials.

intracrystalline
See transgranular.

Izod test
A type of impact test in which a V-notched specimen, mounted vertically and loaded in cantilever bending, is subjected to a sudden blow delivered by the weight at the end of a pendulum arm. The energy required to break off the free end is a measure of the impact strength or toughness of the material. Contrast with Charpy (impact) test.

J

***J*-integral**
A mathematical expression for a line or surface integral that encloses the crack front from one crack surface to the other, used to characterize the local stress field around a crack front. Associated with plastic flow during crack extension, in contrast to the stress-intensity factor (K), which applies for linear elastic behavior (ASTM E 1823).

***J*-*R* curve**
See *R*-curve.

K

Knoop hardness number, HK
A number related to the applied load and to the projected area of the permanent impression made by a rhombic-based pyramidal diamond indenter having included edge angles of 172°, 30 min and 130°, 0 min computed from the equation:

$$HK = \frac{P}{0.07028d^2}$$

where P is applied load, kgf; and d is long diagonal of the impression, mm. In reporting Knoop hardness numbers, the test load is stated.

Knoop hardness test
An indentation hardness test using calibrated machines to force a rhombic-based pyramidal diamond indenter having specified edge angles, under specified conditions, into the surface of the material under test and to measure the long diagonal after removal of the load.

L

lamination
A type of discontinuity, with separation or weakness generally aligned parallel to the worked surface of a metal.

lap (forging lap)
A surface imperfection in worked metal caused by folding over a fin overfill or similar surface condition, then impressing this into the surface by subsequent working without welding it.

leaching
See selective leaching.

linear elastic fracture mechanics
A method of fracture analysis that can determine the stress (or load) required to induce fracture instability in a structure containing a cracklike flaw of known size and shape when the relationship between local stress and strain is assumed to be linear. See also stress-intensity factor.

liquid metal embrittlement
See liquid metal induced embrittlement.

liquid metal induced embrittlement
The decrease in ductility and toughness of a metal caused by contact with another metal in liquid form. Results in intergranular fracture. Formerly known as liquid metal embrittlement.

liquid shrinkage
The reduction in volume of liquid metal as it cools to the liquidus.

local necking
The development of a nonuniform strain gradient in tensile sheet specimens with a large width-to-thickness ratio. The strain gradient results in the formation of a narrow trough across the face (width) of the specimen. For uniaxial loading, the strain gradient is usually inclined at an angle to the load (typically approximately 55° for isotropic materials). The local neck develops under plane-strain loading conditions, while diffuse necking develops under conditions of axisymmetric deformation, which is initially plane stress.

longitudinal direction
That direction parallel to the direction of maximum elongation in a worked material. See also normal direction and transverse direction. Two labeling conventions are common for designating the orientations of rolled sheet and plate material:

L, T, S designations	RD, ND, TD designations
L, longitudinal	RD, rolling direction
T, long transverse	ND, normal direction
S, short transverse	TD, transverse direction

low-cycle fatigue
Fatigue that occurs at relatively small numbers of cycles ($<10^4$ cycles). Low-cycle fatigue is accompanied by more plastic strain at the crack tip than in high-cycle fatigue. Compare with high-cycle fatigue.

Lüders lines
Elongated surface markings or depressions, often visible to the unaided eye on smooth surfaces, that form along the length of a tension specimen at an angle of approximately 45° to the loading axis. Caused by localized plastic deformation, they result from discontinuous (inhomogeneous) yielding. Also known as Lüders bands, Hartmann lines, Piobert lines, or stretcher strains.

M

macroscopic
Visible at magnifications at or below 25 diameters.

macroshrinkage
Isolated, clustered, or interconnected voids in a casting that are detectable macroscopically. Such voids are usually associated with abrupt changes in section size and are caused by feeding that is insufficient to compensate for solidification shrinkage.

macrostructure

The structure of metals as revealed by macroscopic examination of a specimen. The examination may be carried out using an as-polished or a polished and etched specimen.

magnification

The ratio of the length of a line in the image plane (for example, ground glass or a photographic plate) to the length of the same line in the object. Magnifications are usually expressed in linear terms and in units called diameters.

malleability

The characteristic of metals that permits plastic deformation without fracture. See also ductility.

matrix

The continuous or principal phase in which another constituent is dispersed.

maximum strength

See ultimate strength.

mechanical (cold) crack

A crack or fracture in a casting resulting from rough handling or from thermal shock, such as may occur at shakeout or during heat treatment.

mechanical properties

The properties of a material that reveal its elastic and inelastic (plastic) behavior when force is applied, thereby indicating its suitability for mechanical (load-bearing) applications. Examples are elongation, fatigue limit, hardness, fracture toughness, tensile strength, and yield strength. Compare with physical properties. Some definitions exclude elastic constants (including the modulus of elasticity) from a list of mechanical properties because the value of these constants is controlled by interatomic bonding forces and is therefore a physical property. Others would include the elastic constants and use a definition of mechanical properties that includes the requirement of the imposition of a force or a deformation to the material. In any event, most mechanical properties are highly (micro) structure sensitive, except for the elastic constants, which in macroscale polycrystalline materials usually do not vary significantly with microstructure.

mechanical twin (deformation twin)

A twin formed in a crystal by simple shear and/or simple shear plus shuffle movements under external loading.

median crack

Damage produced in glass by the static or translational contact of a hard, sharp object on the glass surface. The crack propagates into the glass perpendicular to the original surface.

microcrack

A crack of microscopic proportions. Also known as microfissure.

microporosity

Microscale porosity in castings, often the result of interdendritic shrinkage.

microscopic

Visible only at magnifications above some arbitrary level, often taken as 25 or 50 diameters. Contrast to macroscopic.

microshrinkage

A casting imperfection consisting of interdendritic voids. Microshrinkage results from contraction during solidification, where the opportunity to supply filler material is inadequate to compensate for shrinkage in the liquid-to-solid transformation. Alloys with wide ranges in solidification temperature are particularly susceptible.

microstructure

The structure of metals and alloys as revealed after polishing and etching at magnifications greater than some low magnification (25 or 50 diameters).

microvoid coalescence (MVC)

Ductile micromechanism of fracture that occurs due to the nucleation of microscale voids, followed by their growth and eventual coalescence; initiation is caused by particle cracking or interfacial failure between an inclusion or precipitate particle and the surrounding matrix.

minimum creep rate

The creep rate during steady-state (linear) creep behavior (stage II). See also creep rate.

mirror region (ceramics, glassy materials)

The comparatively smooth region that symmetrically surrounds a fracture origin. The mirror region ends in a microscopically irregular manner at the beginning of the mist region.

misrun

A casting not fully formed because of solidification of metal before the mold is filled.

mist hackle (ceramics, glassy materials)

Markings on the surface of a crack acceleratain close to the effective terminal velocity, observable first as a mist on the surface and, with increasing velocity, revealing a fibrous texture elongated in the direction of cracking and coarsening up to the stage at which the crack bifurcates. Velocity bifurcation or velocity forking is the splitting of a single crack into two mature diverging cracks at or near the effective terminal velocity of approximately half the transverse speed of sound in the material. See also bifurcation.

mode

(1) One of the three classes of crack (surface) displacements adjacent to the crack tip. These displacement modes are associated with stress and strain fields around the crack tip and are designated I (opening mode), II (in-plane shear), and III (out-of-plane shear, torsion). See also crack-tip strain and crack tip opening displacement. (2) In reliability-centered maintenance, the total collection of a set of events that are likely to cause a failed state.

modulus of elasticity, *E*.

(1) The measure of rigidity or stiffness of a metal; the ratio of stress, below the proportional limit, to the corresponding strain. In terms of the stress-strain diagram, the modulus of elasticity is the slope of the stress-strain curve in the range of linear proportionality of stress to strain. Also known as Young's modulus. (2) For materials that do not conform to Hooke's law throughout the elastic range, the slope of either the tangent to the stress-strain curve at the origin or at low stress, the secant drawn from the origin to any specified point on the stress-strain curve, or the chord connecting any two specific points on the stress-strain curve is usually taken to be the modulus of elasticity. In these cases, the modulus is referred to as the tangent modulus, secant modulus, or chord modulus, respectively.

modulus of rigidity

See shear modulus.

modulus of rupture

Nominal stress at fracture in a bend test or torsion test. In bending, the modulus of rupture is the bending moment at fracture divided by the section modulus. In torsion, modulus of rupture is the torque at fracture divided by the polar section modulus. See also modulus of rupture in bending and modulus of rupture in torsion.

modulus of rupture in bending, S_b

The value of maximum tensile or compressive stress (whichever causes failure) in the extreme fiber on a beam loaded to failure in bending, computed from:

$$S_b = \frac{M_C}{I}$$

where M is maximum bending moment, computed from the maximum load and the original moment arm; c is initial distance from the neutral axis to the extreme fiber where failure occurs; and I is initial moment of inertia of the cross section about the neutral axis. See also modulus of rupture.

modulus of rupture in torsion, S_s

The value of maximum shear stress in the extreme fiber of a member of circular cross section loaded to failure in torsion, computed from:

$$S_S = \frac{Tr}{J}$$

where T is maximum twisting moment, r is original outer radius, and J is polar moment of inertia of the original cross section. See also modulus of rupture.

mud cracks

A microscale fractographic artifact created when a liquid dries on the fracture surface. Often associated with (a) incomplete removal of a cleaning agent from a fracture surface prior to examination in the scanning electron microscope or (b) dried solutions created from stress-corrosion cracking conditions.

N

necking
(1) Reduction of the cross-sectional area of metal in a localized area by stretching. See also diffuse necking and local necking. (2) Reduction in the diameter of a portion of the length of a cylindrical shell or tube.

Neumann bands
Deformation twinning in ferrite. See mechanical twin (deformation twin).

neutron embrittlement
Embrittlement resulting from bombardment with neutrons, usually encountered in metals that have been exposed to a neutron flux in the core of a reactor. In steels, neutron embrittlement is evidenced by a rise in the ductile-to-brittle transition temperature. See also radiation damage.

nil ductility transition temperature (NDT or NDTT)
The maximum temperature at which a standard drop-weight specimen breaks.

nominal strength
See ultimate strength.

normal direction
That direction perpendicular to the plane of working in a worked material. See also longitudinal direction.

notch
See stress concentration.

notch acuity
The severity of the stress concentration produced by a given notch in a particular structure. If the depth of the notch is very small compared with the width (or diameter) of the narrowest cross section, acuity may be expressed as the ratio of the notch depth to the notch root radius. Otherwise, acuity is defined as the ratio of one-half the width (or diameter) of the narrowest cross section to the notch root radius.

notch brittleness
Susceptibility of a material to brittle fracture at points of stress concentration. For example, in a notch tension test, the material is said to be notch brittle if the notch strength is less than the tensile strength of an unnotched specimen. Otherwise, it is said to be notch ductile.

notch depth
The distance from the surface of a test specimen to the bottom of the notch. In a cylindrical test specimen, the percentage of the original cross-sectional area removed by machining an annular groove.

notch rupture strength
The ratio of applied load to original area of the minimum cross section in a stress-rupture test of a notched specimen.

notch sensitivity
A measure of the reduction in strength of a metal caused by the presence of stress concentration. Values can be obtained for static, impact, or fatigue tests.

notch strength
The maximum load on a notched tension-test specimen divided by the minimum cross-sectional area (the area at the root of the notch). Also called notch tensile strength.

notch tensile strength
See notch strength.

O

orange peel
A rough surface visible on a plastically deformed component. The rough surface is due to a large grain size, and individual grains may be visible on the surface of the component.

orientation
See crack plane orientation and growth direction, longitudinal direction, normal direction, and transverse direction.

overheating

Heating a metal or alloy to such a high temperature that its properties are impaired. When the original properties cannot be restored by further heat treating, by mechanical working, or by a combination of working and heat treating, the overheating is known as burning.

oxidation

(1) A reaction in which there is an increase in valence resulting from a loss of electrons. Contrast with reduction. (2) A corrosion reaction in which the corroded metal forms an oxide; usually applied to reaction with a gas containing elemental oxygen, such as air.

oxidative wear

A type of wear resulting from the sliding action between two metallic components that generates oxide films on the metal surfaces. These oxide films prevent the formation of a metallic bond between the sliding surfaces, resulting in fine wear debris and low wear rates.

P

Paris law

The mathematical description of fatigue crack growth rate in the linear region of a plot of (log) crack growth rate (da/dN) versus (log) change in stress-intensity factor (K):

$$\frac{da}{dN} = C(\Delta K)^m$$

parting

The selective corrosion of one or more components of a solid-solution alloy. See also dealloying.

pebbles

See orange peel.

pencil glide

Glide on multiple slip planes in a common direction in all of the planes.

percussion cone

Damage produced by contact stresses generated by mechanical contact of a hard, blunt object with a glass surface. Typically, it has the appearance of a semicircular or circular crack on the damaged surface, propagating into the glass, flaring out with increasing depth into a cone-shaped crack; also called impact bruise, butterfly bruise, bump check, and Hertzian crack.

persistent slip lines

Small steps contained within a grain and visible at the microscale on free surfaces or in metallographic cross sections of parts that have been subject to a number of cyclic loads slightly below the number needed to initiate a crack. The precursor to a fatigue crack.

physical crack size, a_p

The distance from a reference plane to the observed crack front. This distance may represent an average of several measurements along the crack front. The reference plane depends on the specimen form, and it is normally taken to be either the boundary or a plane containing either the load line or the centerline of a specimen or plate.

physical properties

Properties of a metal or alloy that are relatively insensitive to microstructure and can be measured without the application of force; for example, density, electrical conductivity, coefficient of thermal expansion, magnetic permeability, and lattice parameter. Does not include chemical reactivity. Compare with mechanical properties. The modulus of elasticity can be considered a physical property, because it is structure-insensitive at the engineering scale of measurement. The modulus of elasticity is controlled by interatomic binding forces, and it can be determined from physical testing (e.g., by the speed of sound and density of a material).

pinhole

A small, rounded hole just below the surface of a casting, sometimes visible only after machining. Such holes, often localized, have bright interior surfaces.

Piobert lines

See Lüders lines.

pitting

(1) Corrosion of a metal surface, confined to a point or small area, that takes the form of cavities. (2) In tribology, a type of wear characterized by the presence of surface cavities formed by processes such as fatigue, local adhesion, or cavitation. See also etch pits.

plane-strain deformation

Deformation due to a two-dimensional strain state; all components of the strain tensor lie in a common plane. Stress-strain constitutive equations then predict a three-dimensional state of stress. Contrast to plane-stress loading in which all of the stress vectors lie in a common plane. The constitutive equations then predict a three-dimensional state of strain. The term is used in linear elastic fracture mechanics to indicate a lower value of fracture toughness than plane-stress fracture toughness and a fracture that is macroscale brittle.

plane-strain fracture toughness, K_{Ic}

Fracture toughness measured for opening mode (mode I) loading conditions in which plane-strain conditions exist. Determination of plane-strain fracture toughness is defined according to ASTM E 399. It is a minimum value of toughness and often identified as K_{Ic}.

plane-strain loading

(1) A condition of plastic flow in which there is no normal strain in some direction. (2) In analytical mechanics, a statement that there is no displacement in some direction, for example, in the *z* direction, and that displacements in other directions do not depend on *z*. Contrast with plane-stress loading.

plane stress

A loading condition for which all of the internal stress vectors lie in a common (two-dimensional) plane. Stress-strain constitutive equations then predict a three-dimensional state of strain. The term is used in fracture mechanics to indicate a higher value of fracture toughness than plane-strain fracture toughness. The fracture is macroscale ductile and on a plane of maximum shear stress.

plane-stress fracture toughness, K_c

Critical value of stress intensity for unstable crack growth.

plane-stress loading

A loading condition in which all force vectors lie in a common plane. The two-dimensional stress state leads to three-dimensional strain. Contrast with plane-strain loading.

plastic deformation

The permanent (inelastic) distortion of metals under applied stresses that strain the material beyond its elastic limit.

plowing

In tribology, the formation of grooves by plastic deformation of the softer of two surfaces in relative motion.

Poisson's ratio

The absolute value of the ratio of the transverse strain to the corresponding axial strain, in a body subjected to uniaxial stress.

polycrystalline

Comprising an aggregate of more than one crystal and usually a large number of crystals.

pore

(1) A small void in the body of a metal. (2) A minute cavity in a powder metallurgy compact, sometimes intentional. (3) A minute perforation in an electroplated coating.

porosity

Fine holes or pores within a metal.

poultice corrosion

A term used in the automotive industry to describe the corrosion of vehicle body parts due to the collection of road salts and debris on ledges and in pockets that are kept moist by weather and washing. Also called deposit attack or deposit corrosion.

precipitate-free zone (PFZ)

A region adjacent to the grain boundary in which there is no (or little) precipitate, while there is a precipitate present in the grain interior (usually fine) and precipitates in the grain boundary. Often associated with poor corrosion resistance and/or poor fracture toughness. The presence of a PFZ often results in fracture in the region.

preferred orientation

A condition of a polycrystalline aggregate in which the crystal axes are not randomly distributed with respect to the component geometry, but rather exhibit a tendency for alignment of a specific direction(s) of the crystal parallel to a coordinate axis of the bulk material. Some textures are axisymmetric (fiber textures), in which a single direction in a grain is aligned with the principal working direction. In other cases, two directions of the grain are aligned with directions of the bulk body after working (rolling or deformation textures) and textures in rolled sheet after annealing (annealing textures). See also fiber and texture.

primary creep

The first, or initial, stage of creep, or time-dependent deformation.

principal stress

The maximum or minimum value of the normal stress at a point in a plane considered with respect to all possible orientations of the considered plane. On such principal planes, the shear stress is zero. There are three principal stresses on three mutually perpendicular planes. The state of stress at a point may be: (1) uniaxial, a state of stress in which two of the three principal stresses are zero; (2) biaxial, a state of stress in which only one of the three principal stresses is zero; or (3) triaxial, a state of stress in which none of the principal stresses is necessarily zero. Multiaxial stress refers to either biaxial or triaxial stress.

proportional limit

The maximum stress at which strain remains directly proportional to stress; the upper end of the straight-line portion of the stress-strain or load-elongation curve. See also elastic limit. Materials, in general, show some nonlinear elastic behavior, so the elastic limit is (slightly) greater than the proportional limit.

pure ductile tearing

Microscale ductile crack propagation by microvoid coalescence on the plane of maximum normal stress.

Q

quasi-cleavage fracture

Term that was used to refer to a fracture mode that combines the characteristics of cleavage fracture and dimpled rupture fracture or tear ridges. The term is used to describe a microscale fracture appearance in steels that tends to result from (a) sudden or impact loading, (b) low temperature, (c) high levels of constraint (ambient temperature) or (d) in heavily cold worked parts (ambient temperature). The preferred term is “cleavage with ductile tear ridges.”

quench-age embrittlement

Embrittlement of low-carbon steels resulting from precipitation of solute carbon at existing dislocations and from precipitation hardening of the steel caused by differences in carbon solubility in ferrite at different temperatures. Quench-age embrittlement usually is caused by rapid cooling of the steel from temperatures slightly below Ac_1 (the temperature at which pearlite begins to form) and can be minimized by quenching from lower temperatures.

quench crack

A crack formed as a result of stresses created by thermal gradients and volumetric changes due to phase transformations (e.g., austenite to martensite transformation).

R

radial marks

Macroscale ridges or thin ledges appearing as lines on a fracture surface. Radial marks are created under conditions of rapid crack growth. The lines often radiate from the fracture origin and are visible to the unaided eye or at low magnification. Radial marks can result from the intersection and connection of brittle cleavage fractures propagating at different levels. Alternatively, relatively tall, sharp-edged ridges may be created by small-scale ductile shear on intersecting planes. The appearance of radial lines varies considerably with the ductility of the material prior to and during fracture. In some microstructures (e.g., pearlitic steels), the lines may be poorly defined as diffuse ridges parallel to the direction of crack growth and may not be visible near the initiation site, but only after some growth of the crack front. See also chevron pattern.

radiation damage

A general term for the alteration of properties of a material arising from exposure to ionizing radiation (penetrating radiation), such as x-rays, gamma rays, neutrons, heavy-particle radiation, or fission fragments in nuclear fuel material. See also neutron embrittlement.

ratchet marks

The macroscale fractographic feature created by crack propagation on two closely spaced parallel planes (multiple origins) and connected by a thin ligament. After some growth, the cracks typically coalesce into a single crack, with the disappearance of the connecting ligament. Ratchet marks are most pronounced in cyclic loading and are an important indicator of the location of crack initiation. The connecting ligament is parallel to the direction of crack propagation. Ratchet marks are usually visible to the unaided eye but sometimes require low-power magnification.

rattail

A shallow, indented, and irregular line on a casting surface due to sand expansion.

***R*-curve**

A plot of crack-extension resistance as a function of stable crack extension, which is the difference between either the physical crack size or the effective crack size and the original crack size. *R*-curves normally depend on specimen thickness and, for some materials, on temperature and strain rate. Also known as *J*-*R* curve.

reduction

(1) In forging, rolling, and drawing, either the ratio of the original to final cross-sectional area or the percentage decrease in cross-sectional area. (2) A reaction in which there is a decrease in valence resulting from a gain in electrons. Contrast with oxidation.

reduction of area

A measure of strain. The difference between the original cross-sectional area of a tension specimen and the smallest area at or after fracture, as specified for the material being tested normalized by the original cross-sectional area. Also known as reduction in area.

residual stress

Stress present in a body that is free of external forces or thermal gradients. Residual stresses are created by strain gradients and therefore occur from either mechanical or thermal processing. Such stresses are generally a result of fabrication processes, including heat treating and forming, and can be detrimental or helpful to the service requirements of the component or assembly (e.g., by shot peening). Residual stresses may be intentionally designed into the component or assembly or may be an unknown by-product. These stresses must be added to the applied stresses in a strict three-dimensional mathematical form, if they are to be used for any sort of useful quantitative predictions of strength or life assessment.

rib mark

A curved line on a crack surface, usually convex in the general direction toward which the crack is running. The term is useful in referring to a mark of this shape until its specific nature is learned.

ripple mark

See Wallner line.

river pattern

A microscale characteristic pattern of cleavage crack propagation on closely spaced parallel planes connected by a thin ligament. Cracking on the connecting ligament may be ductile or brittle. Crack coalescence occurs as crack propagation occurs on the multiple planes, so that the microscale direction of crack propagation can be identified (i.e., “down river”).

rock candy fracture

A macro-scale and microscale fracture appearance that exhibits separated-grain facets. Most often used to describe the macroscale appearance of an intergranular fracture in a large-grained metal, although the term is also used to describe the microscale appearance of facets observed from an intergranular fracture path with equiaxed grains.

Rockwell hardness number, HR

A number derived from the net increase in the depth of impression as the load on an indenter is increased from a fixed minor load to a major load and then returned to the minor load. Rockwell hardness numbers are always quoted with a scale symbol representing the penetrator, load, and dial used.

Rockwell hardness test

An indentation hardness test using a calibrated machine that uses the depth of indentation, under load, as a measure of hardness. Either a 120° diamond cone with a slightly rounded point or a 1.6 or 3.2 mm ($\frac{1}{16}$ or $\frac{1}{8}$ in.) diameter steel ball is used as the indenter. Larger balls, up to at least 12.5 mm ($\frac{1}{2}$ in.), are also used for plastics and so on.

Rockwell superficial hardness test

Same as Rockwell hardness test, except that smaller minor and major loads are used and a more precisely cut diamond is used for the N scale test.

rubbing (polishing)

A macro- or microscale fractographic feature resulting from relative movement of two crack faces. Common in fatigue loading. Compare to scuffing.

rupture stress

The stress at failure. Also known as breaking stress or fracture stress. Unless otherwise specified, rupture stress is calculated on the basis of original area for axial loading.

rust

A corrosion product consisting primarily of hydrated iron oxide. A term properly applied only to ferrous alloys.

S

sand hole

A pit in the surface of a sand casting resulting from a deposit of loose sand on the surface of the mold.

scab

A raised and rough area on the surface of a casting due to sand being dislodged from the surface of the mold.

Scleroscope hardness number, HSc or HSd

A number related to the height of rebound of a diamond-tipped hammer dropped on the material being tested. It is measured on a scale determined by dividing into 100 units the average rebound of the hammer from a quenched (to maximum hardness) and untempered AISI W5 tool steel test block.

Scleroscope hardness test

A dynamic indentation hardness test using a calibrated instrument that drops a diamond-tipped hammer from a fixed height onto the surface of the material being tested. The height of rebound of the hammer is a measure of the hardness of the material.

scoring

In tribology, a severe form of wear characterized by the formation of extensive grooves and scratches in the direction of sliding.

scratching

In tribology, the mechanical removal and/or displacement of material from a surface by the action of abrasive particles or protuberances sliding across the surfaces. See also plowing.

scuffing

A form of adhesive wear that produces superficial scratches or a high polish on the rubbing surfaces. It is observed most often on inadequately lubricated parts.

seam

(1) An unfused fold or lap that appears as a crack (typically oxidized) on a metal surface. (2) A macroscale, longitudinal, nonmetallic inclusion at or near the surface of a wrought material.

season cracking

Cracking resulting from the combined effects of corrosion and internal stress. A term usually applied to stress-corrosion cracking of brass in the presence of chemical substances to which it is susceptible.

secant modulus

The slope of the secant drawn from the origin to any specified point on a stress-strain curve. See also modulus of elasticity

secondary crack

A crack that is present in a component that has a larger, more obvious crack. The secondary crack may be parallel to the main crack, or it may have another orientation.

secondary creep
The second state of creep deformation. See also creep.

segregation
Nonuniform distribution of alloying elements, impurities, or phases. Used to describe both macro- and microscale distributions.

selective leaching
Corrosion in which one element is preferentially removed from an alloy, leaving a residue (often porous) of the elements that are more resistant to the particular environment. See also decarburization, denickelification, dezincification, and graphitic corrosion.

sensitization
In austenitic stainless steels, the precipitation of chromium carbides, usually at grain boundaries, on exposure to temperatures of approximately 675 to 900 °C (1250 to 1650 °F), leaving the near-grain-boundary area depleted of chromium and therefore susceptible to preferential attack by a corroding (oxidizing) medium.

shark's teeth
A striation consisting of a daggerlike step fracture starting at the scored edge and extending to or nearly to the compression edge.

shatter crack
See flake.

shear bands
Bands of intense localized plastic shear strain that may vary from microscale to macroscale dimensions. Macro- and/or microscale bands occur when deformation is concentrated inhomogeneously in sheets that extend across regional groups of grains. Only one slip system is usually active in each regional group of grains, different systems being present in adjoining groups. The bands develop initially crystallographically at the micron scale and then become noncrystallographic as they grow to form on planes of maximum shear stress. See also adiabatic shear bands.

shear fracture
A ductile (macro- and microscale) fracture in which a crystal (or a polycrystalline mass) has separated by sliding or tearing under the action of shear stresses. See also shear stress.

shear hackle
A hackle generated by interaction of a shear component with the principal tension under which the crack is running.

shear ledges
See radial marks.

shear lip
A macroscale slanting plane on a fracture surface or “ears” on the fracture surface. Often used in the description of mixed-mode fractures in which a central portion of the fracture surface is normal to the applied load, but the fracture surface then changes to a slant as it approaches the free surface perpendicular to the direction of crack propagation.

shear modulus, *G*.
The ratio of shear stress to the corresponding shear strain for shear stresses for elastic deformation. Values of shear modulus are usually determined by torsion testing. Also known as modulus of rigidity.

shear strain
The displacement of a point on a plane relative to a perpendicular point on a parallel plane divided by the distance between the two planes. Alternatively, the tangent of the angular change, due to force, between two lines originally perpendicular to each other through a point in a body. Compare to axial strain.

shear strength
The maximum shear stress that a material is capable of sustaining. Shear strength is calculated from the maximum load during a shear or torsion test and is based on the original dimensions of the cross section of the specimen.

shear stress
A load intensity (stress) that exists on a plane due to a force acting parallel to the plane. Also known as tangential stress.

shock load

The sudden application of an external force that results in a very rapid buildup of stress—for example, piston loading in internal combustion engines and explosive loading.

shrinkage

See casting shrinkage.

shrinkage cavity

A macroscale void left in cast metals as a result of solidification shrinkage. Shrinkage cavities occur in the last metal to solidify after casting. Compare with shrinkage porosity.

shrinkage porosity

(1) Microscale interdendritic porosity in a casting caused by inadequate feeding during solidification. (2) Macroscale cavities in the last area to solidify, for example, along the centerline of an ingot.

silky fracture

A metal fracture in which the broken metal surface has a fine texture, usually dull in appearance. Characteristic of tough and strong metals. Contrast with brittle fracture, cleavage, rock candy fracture, and granular fracture.

slant fracture

A type of fracture appearance, typical of plane-stress loading conditions, in which the plane of metal separation is inclined at an angle (usually approximately 45°) to the axis of the applied stress. May occupy a portion or all of the total fracture surface. See also shear lip.

slip

Plastic deformation by the irreversible shear displacement (translation) of one part of a crystal relative to another in a definite crystallographic direction and on a specific crystallographic plane. Sometimes called glide. See also flow.

***S*-*N* curve**

A plot of stress (S) against the number of cycles to failure (N) to describe fatigue behavior. The stress can be the maximum stress (S_{max}) or the alternating stress amplitude (S_a). The stress values are nominal stress; that is, there is no adjustment for stress concentration unless specifically noted. The diagram indicates the *S*-*N* relationship for a specified value of the mean stress (S_m) or the stress ratio (A or R) and often a specified probability of survival. Values on the abcissa (N) are almost always plotted logarithmically. Values on the ordinate (S) may or may not be plotted logarithmically. Also known as *S*-*N* diagram.

solidification shrinkage

The reduction in volume of metal from beginning to end of solidification.

solidification shrinkage crack

A crack that forms, usually at elevated temperature, because of the internal (shrinkage) stresses that develop during solidification of a metal casting. Also known as hot crack.

solid shrinkage

The reduction in volume of metal from the solidus to room temperature.

spalling

The cracking and flaking of particles out of a surface.

static fatigue

Fracture that occurs as a function of time but is not “fatigue” in the sense that loading is static rather than cyclic. Refers to sustained-load cracking, for example, see hydrogen-induced delayed cracking. Also used with ceramics. Use of this term is discouraged in favor of more accurate descriptions of the specific cracking mechanism.

static loading

Stationary or very slow loading. Frequently used in connection with routine tension testing of metal specimens. Contrast with dynamic.

steady-rate creep

See creep.

strain

The unit of change in the size or shape of a body due to force. Strain may be defined as normalized length or areal change (change in length divided by a length, change in area divided by an area). It is then known as “nominal” or “engineering” strain. Strain may also be defined as the integral of the

length (or area) change divided by the instantaneous length (or area). The resulting integral then gives the "true strain" as ln (final length/initial length), ln (initial height/final height), or ln (initial area/final area).

strain-age embrittlement

A loss in ductility accompanied by an increase in hardness and strength that occurs when low-carbon steel (especially rimmed or capped steel) is aged following plastic deformation. It occurs principally in low- and medium-carbon steels that have not been aluminum deoxidized. Embrittlement occurs for cold-worked materials that are subsequently heated to temperatures between room temperature and 300 °C (570 °F). The degree of embrittlement is a function of aging time and temperature, occurring in a matter of minutes at approximately 200 °C (400 °F) but requiring a few hours to a year at room temperature. The degradation that results is presumed to be due to nitrogen contents that exceed 0.009%. There is likely a secondary embrittling effect due to carbon. Strain-age embrittlement results in transgranular fracture. Its presence may be detected by a return of the yield point or a displacement of an indexed transition temperature to higher temperatures in an impact pendulum test.

strain energy release rate

See crack extension force.

strain hardening

The increase in flow stress (and hardness) caused by plastic deformation at temperatures below the recrystallization range. Sometimes also described as work hardening. Contrast with strain softening.

strain hardening/strain-hardening exponent

The increase in flow stress caused by prior plastic deformation. Mathematically often written as (so-called "Holloman behavior"):

$$\sigma = K\varepsilon^n$$

where n is the strain-hardening exponent, and K is the strength coefficient.

strain-rate hardening

The increase in flow stress with an increase in strain rate. Mathematically, assumed to be of the form:

$$\sigma = a\dot{\varepsilon}^m$$

where m is the strain-rate sensitivity exponent. Values of m depend on several metallurgical variables as well as the temperature. An increase in temperature increases m until dynamic softening (recovery and or recrystallization) initiates.

strain softening

The decrease in flow stress with strain, as during dynamic recrystallization.

stray-current corrosion

Corrosion caused by electric current from a source external to the intended electrical circuit, for example, extraneous current in the earth.

stress

The intensity of an internally distributed force or components of forces that resist a change in the volume or shape of a material that is or has been subjected to external forces. Stress may be expressed in force per unit area as "nominal," "engineering," or "far stress" and is calculated on the basis of the original dimensions of the cross section of the specimen. "True" stress is calculated on the basis of the instantaneous rather than nominal area. Stress can be either axial (tension or compression) or shear. Usually expressed in pounds per square inch (psi) or megapascals (MPa).

stress amplitude

One-half the algebraic difference between the maximum and minimum stress in one cycle of a repetitively varying stress.

stress concentration

The elevation in local stress caused by a change in contour or a discontinuity. Typical stress-concentration areas are sharp-cornered grooves or notches, threads, fillets, holes, and so on. Also known as stress raiser.

stress-concentration factor, K_t

A multiplying factor for increased local stress created by the presence of a structural (geometric) discontinuity such as a notch or hole; K_t is the ratio of the actual local stress acting in a direction

compared to the nominal stress acting in the same direction. Also known as theoretical stress-concentration factor.

stress-corrosion cracking, SCC

A cracking process that requires the simultaneous action of a corrodent and sustained stress acting on a susceptible material. This excludes corrosion-reduced sections that fail by fast fracture. It also excludes intergranular or transgranular corrosion, which can disintegrate an alloy without applied or residual stress. See also corrosion.

stress crack

Incorrect term when used in metals, because all true cracks are due to stresses. Used in polymers to refer to cracks that are not expected based on known values of applied stresses and may be facilitated by the presence of chemical substances to which the material in question is sensitive.

stress cycle

The smallest segment of the stress-time function that is repeated periodically.

stress-intensity factor, *K*

The magnitude of the mathematically ideal crack tip stress field for a particular mode in a homogeneous linear elastic body:

$$K = s\sqrt{p\,a}\,[\,f(a/W)]$$

where σ is the nominal stress, a is the crack length, and $f(a/W)$ is a geometric correction factor. Subscripts are used to indicate (a) type of loading, (b) dynamic versus static loading, and (c) critical values of K for fracture:

K_c	Plane-stress fracture toughness. The value of stress intensity at which crack propagation becomes rapid in sections thinner than those in which plane-strain conditions prevail.
K_I	Stress-intensity factor for a loading condition that displaces the crack faces in a direction normal to the crack plane (also known as the opening mode of deformation).
K_{II}	Stress-intensity factor for in-plane shear.
K_{III}	Stress-intensity factor for out-of-plane shear.
K_{Ic}	Plane-strain fracture toughness. The minimum value of K_c for any given material and condition, which is attained when rapid crack propagation in the opening mode is governed by plane-strain conditions.
K_{Id}	Dynamic fracture toughness. The fracture toughness determined under dynamic loading conditions; it is used as an approximation of K_{Ic} for very tough materials.
K_{ISCC}	Threshold stress-intensity factor for stress-corrosion cracking when loading conditions meet plane-strain requirements.
K_Q	Provisional value for plane-strain fracture toughness (see ASTM E 399)
K_{th}	Threshold stress intensity for stress-corrosion cracking. A value of stress intensity characteristic of a specific combination of material, material condition, and corrosive environment above which stress-corrosion crack propagation occurs and below which the material is immune from stress-corrosion cracking.

stress-intensity factor range, Δ*K*

The range of the stress-intensity factor (K_{max} - K_{min}) during a fatigue cycle. K_{min} corresponds to the load minimum for $R > 0$ and is taken as 0 when $R \leq 0$.

stress raiser

See stress concentration.

stress ratio, *A* or *R*

The algebraic ratio of two specified stress values in a stress cycle. Two commonly used stress ratios are (a) the ratio of the alternating stress amplitude to the mean stress, $A = S_a/S_m$, and (b) the ratio of the minimum stress to the maximum stress, $R = S_{min}/S_{max}$.

stress-relief embrittlement

Loss of toughness in heat-affected zone and/or weld metal as a result of stress relieving a welded structure. Stress-relief cracking leads to intergranular cracking of weld. Also known as postweld heat treat cracking and reheat cracking.

stress-rupture strength

See creep-rupture strength.

stress-strain diagram

A graph in which corresponding values of stress and strain are plotted against each other. Values of stress are usually plotted vertically (ordinate or *y*-axis) and values of strain horizontally (abscissa or *x*-axis). Such plots can be misleading, because it is also common to plot the dependent variable on the *y*-axis and the independent variable on the *x*-axis. With this convention, if load is controlled in the test rather than extension (or strain), the dependent variable (load or stress) would be plotted on the *y*-axis. Also known as deformation curve and stress-strain curve.

stretch zone

A region of crack extension from a preexisting cracklike imperfection caused by crack tip blunting and subsequent ductile tearing.

striated

Used to describe a wavelike or rippled pattern on a fracture surface. May be caused by microstructural features (such as a lamellar eutectoid structure) or cyclic loading (fatigue striations). See also striation.

striation

(1) A fatigue fracture feature often observed at the microscale that indicates the position of the crack front after an increment of crack growth. Each striation is caused by a load cycle, but a load cycle may not produce evidence of crack extension. The distance between striations indicates the advance of the crack front across that crystal during one stress cycle, and a line normal to the striation indicates the direction of local crack propagation. Not to be confused with beach marks, which are much larger (macroscopic) and form differently. Also not to be confused with other similarly appearing microscale features such as a stretch zone at the tip of a preexisting cracklike imperfection, a Wallner line, and so on. Also known as whiskers; see also shark's teeth. (2) In glasses, a fracture-surface marking consisting of the separation of the advancing crack front into separate fracture planes. Also known as coarse hackle, step fracture, or lance. Striations may also be called shark's teeth or whiskers. See also striated.

stringer

In wrought materials, an elongated configuration of microconstituents or foreign material aligned in the direction of working. The term is commonly associated with elongated oxide or sulfide inclusions or strings of spheroidal oxides in steel.

sub-boundary structure (subgrain structure)

A network of low-angle boundaries, usually with misorientations less than 1° within the main grains of a microstructure.

subgrain

A portion of a crystal or grain, with an orientation slightly different from the orientation of neighboring portions of the same crystal.

subsurface corrosion

See internal oxidation.

sulfidation

The reaction of a metal or alloy with a sulfur-containing species to produce a sulfur compound that forms on or beneath the surface of the metal or alloy.

sulfide stress cracking, SSC

Brittle failure by cracking under the combined action of tensile stress and corrosion in the presence of water and hydrogen sulfide.

T

tangent modulus

The slope of the stress-strain curve at any specified stress or strain. See alsomodulus of elasticity. mpare to secant modulus.

tearing fracture

Microscale ductile fracture created by microvoid coalescence. Often results in a dull/matte flat fracture surface on a macroscale plane perpendicular to a tensile stress in axial or bending loading but could also apply to ductile fracture in mode II or mode III loading.

tear ridges

Thin ridges observed in what used to be called quasi-cleavage fracture. In some cases, the ridges are wide enough to show dimpled rupture on the ridge.

tempered martensite embrittlement (TME), or 300 to 350 °C (570 to 660 °F) embrittlement

A phenomenon is thought to be due to precipitation of carbides at martensite plate boundaries. It produces a low-energy trough in the room-temperature impact energy versus tempering-temperature graph. Contrast to temper embrittlement, which shifts the ductile-brittle transition temperature and thus might not affect the actual energy absorbed in a room-temperature impact test. Fracture is transgranular. In some cases, the ranges of TME and TE can overlap, creating mixed intergranular and transgranular fractures.

temper embrittlement (TE)

The brittleness that results when certain steels are held within, or are cooled slowly through, a certain range of temperature below the transformation range. The brittleness is manifested as an upward shift in ductile-to-brittle transition temperature but only rarely produces a low value of reduction of area in a smooth-bar tension test of the embrittled material. Heavy sections are particularly prone to this problem, because they cannot be cooled quickly from the tempering temperature. The temperature range can be anywhere from 400 to 600 °C (750 to 1110 °F) but is generally more restrictive for particular alloys. This phenomenon is thought to be related to the concentration of low-melting-point elements (phosphorus, antimony, tin, and sulfur) in the grain boundaries, and the crack path is intergranular. Also known as temper brittleness.

tensile strength

In tension testing, the ratio of maximum load to the original cross-sectional area. See also ultimate strength; compare with yield strength.

tensile stress

A stress that causes two parts of an elastic body, on either side of a typical stress plane, to pull apart. Contrast with compressive stress.

tension

The force or load that produces elongation.

tension testing

A method of determining the behavior of materials subjected to uniaxial loading, which tends to stretch the metal. A longitudinal specimen of known length and diameter is gripped at both ends and stretched at a slow, controlled rate until rupture occurs. Also known as tensile testing.

tertiary creep

The third stage of creep deformation. See also creep.

texture

In a polycrystalline aggregate, the nonrandom distribution of crystal orientations. In the usual sense, it is synonymous with preferred orientation, in which the distribution is not random. See also fiber and preferred orientation.

theoretical stress-concentration factor

See stress-concentration factor.

thermal fatigue

Fracture resulting from the presence of temperature gradients that vary with time in such a manner as to produce cyclic strains in a structure.

thermal shock

The development of a steep temperature gradient and accompanying high stresses within a structure.

thermal stresses

Stresses in metal resulting from nonuniform temperature distribution.

thumbnail

A feature often noted at the crack initiation site that has a crescent shape similar to a human thumbnail. If it is discolored in comparison to the rest of the fracture surface, it may be an indication that it preexisted in service conditions.

tide marks

See beach marks.

tire tracks

A microscale fractographic feature found especially for cyclic loading conditions in which particulate debris is caught between the two fracture surfaces and causes subsequent imprinting of the surface as the particle(s) moves across the surface.

T-L orientation, T-S

See crack plane orientation.

tongue

A microscale fractographic feature created in materials that mechanically twin. The feature is created when a propagating cleavage crack (for example, of the {1,0,0} family in body-centered cubic material) deviates onto the composition plane (K_I plane) ({1,1,2}) in steel. See also mechanical twin (deformation twin).

torsion

A twisting action applied to a prismatic or cylindrical member. The twisting may be either reversed (back and forth) or unidirectional (one way).

torsional stress

The shear stress on transverse and longitudinal planes resulting from a twisting action. The elastic shear stress is given by:

$$t = \frac{Tr}{J}$$

where T is torque, r is the distance from the axis, and J is the polar moment of inertia. For a solid cylindrical section, $J = (B/2)(r^4)$.

transcrystalline

See transgranular.

transcrystalline cracking

See transgranular cracking or fracture.

transgranular

Through or across crystals or grains. Also known as intracrystalline or transcrystalline.

transgranular cracking or fracture

Cracking or fracturing that occurs through or across a crystal or grain. Also known as transcrystalline cracking. Contrast with intergranular cracking.

transient creep

The first stage of creep deformation; also known as primary creep. See also creep.

transition scarp

A rib mark generated when a crack changes from one mode of growth to another, as when a wet crack accelerates abruptly from region II (plateau) to region III (dry) of a crack acceleration curve.

transverse direction

Literally, “across,” usually signifying a direction or plane perpendicular to the direction of working or the axis of a geometric section. In rolled plate or sheet, the direction across the width is often called long transverse; the direction through the thickness, short transverse. In a rod, the transverse plane is perpendicular to the axis. Compare with longitudinal direction.

Tresca yield criterion

Prediction of yielding in ductile materials when the maximum shear stress on any plane reaches a critical value, $\tau = \tau_c$.

triaxial stress

A term often used to imply the presence of a hydrostatic stress. The presence of a triaxial stress state implies only that stresses act in three directions. Those stresses could be a combination of shear stresses and normal stresses or only normal stresses; therefore, triaxial stress is not equivalent to hydrostatic stress.

tribology

The science concerned with the design, friction, lubrication, and wear of contacting surfaces that move relative to each other.

tuberculation

The formation of localized corrosion products that appear on a surface as knoblike prominences (tubercules).

twin

Two portions of a crystal with a definite crystallographic orientation relationship; one may be regarded as the parent, the other as the twin. The orientation of the twin is a mirror image of the orientation of the parent across a twinning plane. The orientation can sometimes be derived by rotating the twin portion about a twinning axis (simple shear twinning). In other cases (hexagonal close-packed lattices, for example), simple shear does not place all twinned atoms in mirror positions, so that a second set of additional "shuffle" movements are required. See also annealing or growth twin and mechanical twin (deformation twin).

twist hackle (ceramics, glassy materials)

A hackle that separates portions of a crack surface, each of which has rotated from the original crack plane in response to a twist in the axis of principal tension. In a single crystal, a twist hackle separates portions of the crack surface, each of which follows the same cleavage plane, the normal to the cleavage plane being inclined to the principal tension. In a bicrystal or polycrystalline material, a hackle is initiated at a twist grain boundary.

U

ultimate strength

The maximum nominal stress (tensile, compressive, or shear) based on the original cross-sectional area that a material can sustain without fracture; determined by dividing maximum load by the original cross-sectional area of the specimen. Also known as nominal strength, ultimate tensile strength (UTS), or maximum strength.

underfilm corrosion

Corrosion that occurs under organic films in the form of randomly distributed threadlike filaments or spots. In many cases, this is identical to filiform corrosion.

uniform corrosion

(1) A type of corrosion attack (deterioration) uniformly distributed over a metal surface. (2) Corrosion that proceeds at approximately the same rate over a metal surface. Also known as general corrosion.

V

Vickers hardness number, HV

A number related to the applied load and the surface area of the permanent impression made by a square-based pyramidal diamond indenter having included face angles of 136°, computed from:

$$HV = 2P\sin\left(\frac{a/2}{d^2}\right) = \frac{1.8544P}{d^2}$$

where P is applied load (kgf), d is mean diagonal of the impression (mm), and α is the face angle of the indenter (136°).

Vickers hardness test

An indentation hardness test employing a 136° diamond pyramid indenter (Vickers) and variable loads, enabling the use of one hardness scale for all ranges of hardness—from very soft lead to tungsten carbide. Also known as diamond pyramid hardness test.

voids

A term generally applied to paints to describe holidays, holes, and skips in a film. Also used to describe shrinkage in castings and welds.

volumetric modulus of elasticity

See bulk modulus of elasticity.

von Mises stress

A stress calculated using the *von Mises* equation, often for consideration of the von Mises yield criterion

von Mises yield criterion

A criterion to predict the yield strength of material based on the distortion energy available (total energy less the hydrostatic energy):

$$2s_e^2 = \left[\left(s_y - s_z\right)^2 + \left(s_z - s_x\right)^2 + \left(s_x - s_y\right)^2 + 6\left(s_{yz}^2 + s_{zx}^2 + s_{xy}^2\right) \right]$$

Mathematically equivalent to the octahedral shear stress criterion. See also effective stress. Contrast to Tresca yield criterion, Coulomb-Mohn fracture criterion and Hill yield criterion.

W

wake hackle (ceramic, glassy materials)
A hackle line extending from a singularity at the crack front in the direction of cracking, such as on encounter with an inclusion.

Wallner line
A rib mark with wavelike contour caused by temporary excursion of the crack front out of plane in response to a tilt in the axis of principal tension induced by an elastic pulse. Such marks frequently appear as a series of curved lines, indicating the direction of propagation of the fracture from the concave to the convex side of a given Wallner line, and are sometimes observed when viewing brittle fracture surfaces at high magnification in an electron microscope. Wallner lines are attributed to interaction between a shock wave and a brittle crack front propagating at high velocity. Sometimes a Wallner line is misinterpreted as a fatigue striation. Also known as ripple marks.

wear
Damage to a solid surface, generally involving progressive loss of material, due to relative motion between that surface and a contacting surface or substance.

wear rate
The rate of material removal or dimensional change due to wear per unit of exposure parameter—for example, quantity of material removed (mass, volume, thickness) in unit distance of sliding or unit time.

whisker
See striation.

work hardening
See strain hardening.

Y

yield
Plastic deformationwhich occurs as material is loaded above the elastic limit; see also yield strength, creep, and flow.

yield point
The first stress in a material, usually less than the maximum attainable stress, at which an increase in strain occurs without an increase in stress. Only certain metals—those that exhibit a localized, heterogeneous type of transition from elastic to plastic deformation—produce a yield point. If there is a decrease in stress after yielding, a distinction may be made between upper and lower yield points. The load at which a sudden drop in the flow curve occurs is called the upper yield point. The constant load on the flow curve is the lower yield point.

yield strength (offset yield strength)
The stress required to produce a specified amount of permanent deformation. The most common value is indexed at 0.2% permanent deformation (known as the 0.2% offset yield strength). Compare with tensile strength.

yield stress
The stress level of ductile materials at which permanent deformation initiates.

Young's modulus
See modulus of elasticity