Metals Handbook® Ninth Edition

Volume 11 Failure Analysis and Prevention

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Ninth Edition

Volume 11
Failure Analysis and Prevention

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Comments, criticisms, and suggestions are invited, and should be forwarded to the American Society for Metals.

Foreword

Volume 11 of the 9th Edition of *Metals Handbook* is a tribute to the science of failure analysis, a science that benefits all of us every day. Although the word "failure" conjures up negative images—anything from a snapped lawnmower bolt to a major airline disaster—the analysis of failures is the most positive of disciplines. By systematically identifying, exploring, understanding, and finally solving problems, the failure analyst rewards us with improved product reliability and safety.

This Volume continues the *Metals Handbook* tradition of providing its readers with practical information that can be used on the job. The hundreds of case histories described in this Handbook guide you through detailed, step-by-step analyses of actual service failures—concluding with recommendations for preventing similar failures in the future.

It should be noted that in this Handbook the term "failure" is used as a technical term, as are many other terms relating to failure. As a technical term, "failure" means cessation of function or usefulness. Failures may stem from many causes, but the term carries no implication of negligence or malfeasance.

Handbook Coordinators Gordon Powell and Salah Mahmoud are to be congratulated for recruiting a fine array of knowledgeable contributors and for successfully pulling a large undertaking together. Thanks to the many authors and reviewers who volunteered their expertise to this project. We also appreciate the assistance of ASM's Handbook Committee and Failure Analysis Committee (a special nod to former chairman Ray Fessler and member Bruce Christ) and the hard work of the ASM editorial staff. As always, it is the combined efforts of dedicated individuals that make *Metals Handbook* a valued reference source.

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Preface

Failure Analysis and Prevention was published initially in 1975 as Volume 10 of the 8th Edition of *Metals Handbook*. That Volume has served as the best single source of information on the failure modes and service failures of metallic materials. This new Volume is an updated and expanded version of its predecessor.

The present Handbook essentially maintains the format used in the 8th Edition—beginning with a review of the engineering aspects of failure, following with in-depth studies of various failure mechanisms and related environmental factors, and concluding with extensive analyses of hundreds of actual service failures. Nearly all of the articles have been significantly revised and expanded, and brand-new articles on solid metal induced embrittlement, failures in sour gas environments, and failures of bridge components, pipelines, and locomotives axles have been included.

This edition also includes, for the first time, articles on the failure analysis of ceramics, polymers, and continuous fiber reinforced composites; this change is in keeping with ASM's commitment to being a society for materials. Another article that represents a step forward for the Handbook in terms of increased coverage is concerned with failure analysis of integrated circuits.

On behalf of ASM, we express our appreciation to the authors for their time and effort expended in the preparation of this Volume and for their willingness to share with its readers their knowledge and the lessons derived from practical experience. Most of the contributors have established national and international reputations in their respective fields; several are authors of noteworthy textbooks. Each article has also undergone review by members of the ASM Handbook Committee and by other experts from industry and universities. We extend thanks to all of them.

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Policy on
Units of Measure

By a resolution of its Board of Trustees, the American Society for Metals has adopted the practice of publishing data in both metric and customary U.S. units of measure. In preparing this Handbook, the editors have attempted to present data primarily in metric units based on Système International d'Unités (SI), with secondary mention of the corresponding values in customary U.S. units. The decision to use SI as the primary system of units was based on the aforementioned resolution of the Board of Trustees, the widespread use of metric units throughout the world, and the expectation that the use of metric units in the United States will increase substantially during the anticipated lifetime of this Handbook.

For the most part, numerical engineering data in the text and in tables are presented in SI-based units with the customary U.S. equivalents in parentheses (text) or adjoining columns (tables). For example, pressure, stress, and strength are shown both in SI units, which are pascals (Pa) with a suitable prefix, and in customary U.S. units, which are pounds per square inch (psi). To save space, large values of psi have been converted to kips per square inch (ksi), where 1 kip = 1000 lb. Some strictly scientific data are presented in SI units only.

To clarify some illustrations that depict machine parts described in the text, only one set of dimensions is presented on artwork. References in the accompanying text to dimensions in the illustrations are presented in both SI-based and customary U.S. units.

On graphs and charts, grids correspond to SI-based units, which appear along the left and bottom edges; where appropriate, corresponding customary U.S. units appear along the top and right edges. Some illustrations previously published in the 8th Edition, particularly graphs illustrating mechanical property values, have been reproduced in their original form. In some instances, only customary U.S. units have been used.

Data pertaining to a specification published by a specification-writing group may be given in only the units used in that specification or in dual units, depending on the nature of the data. For example, the typical yield strength of aluminum sheet made to a specification written in customary U.S. units would be presented in dual units, but the thickness specified in that specification might be presented only in inches.

Data obtained according to standardized test methods for which the standard recommends a particular system of units are presented in the units of that system. Wherever feasible, equivalent units are also presented.

Conversions and rounding have been done in accordance with ASTM Standard E 380, with careful attention to the number of significant digits in the original data. For example, an annealing temperature of 1575 °F contains three significant digits. In this instance, the equivalent temperature would be given as 855 °C; the exact conversion to 857.22 °C would not be appropriate. For an invariant physical phenomenon that occurs at a precise temperature (such as the melting of pure silver), it would be appropriate to report the temperature as 961.93 °C or 1763.5 °F. In many instances (especially in tables and data compilations), temperature values in °C and °F are alternatives rather than conversions.

The policy on units of measure in this Handbook contains several exceptions to strict conformance to ASTM E 380; in each instance, the exception has been made to improve the clarity of the Handbook. The most notable exception is the use of MPa$\sqrt{m}$ rather than MN · m$^{-3/2}$ or MPa · m$^{0.5}$ as the SI unit of measure for fracture toughness. Other examples of such exceptions are the use of "L" rather than "l" as the abbreviation for liter and the use of g/cm^3 rather than kg/m^3 as the unit of measure for density (mass per unit volume).

SI practice requires that only one virgule (diagonal) appear in units formed by combination of several basic units. Therefore, all of the units preceding the virgule are in the numerator and all units following the virgule are in the denominator of the expression; no parentheses are required to prevent ambiguity.

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Contents

Glossary of Terms

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*.

alligatoring. The longitudinal splitting of flat slabs in a plane parallel to the rolled surface. Also called fishmouthing.

alligator skin. See *orange peel*.

ambient. Surrounding; usually used in relation to temperature, as "ambient temperature" surrounding a certain part or assembly.

annealing twin. A *twin* formed in a crystal during recrystallization.

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

arrest lines (marks). See *beach marks*.

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.

axial strain. Increase (or decrease) in length resulting from a stress acting parallel to the longitudinal axis of a test specimen.

B

banded structure. A segregated structure consisting of alternating, nearly parallel bands of different composition, typically aligned in the direction of primary hot working.

beach marks. Macroscopic (visible) progression marks on a fracture surface that indicate successive position of the advancing crack front. The classic appearance is of irregular elliptical or semielliptical rings, radiating outward from one or more origins. 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 or alternating stress. Not to be confused with *striations*, which are microscopic and form differently.

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:

$$HB = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})}$$

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 it under a specified load. 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.

brittle crack propagation. A very sudden propagation of a crack with the absorption of no energy except that stored elastically in the body. Microscopic examination may reveal some deformation 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 plastic deformation. Typically, brittle fracture occurs by rapid crack propagation with less expenditure of energy than for *ductile fracture*.

brittleness. The tendency of a material to fracture without first undergoing significant *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.

buckling. A compression 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 form.

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 to the corresponding unit change in volume. This elastic constant can be expressed by:

$$K = \frac{\sigma_m}{\Delta} = \frac{-p}{\Delta} = \frac{1}{\beta}$$

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

C

carbon flotation. Segregation in which free graphite has separated from the molten iron. This defect tends to occur at the upper surfaces of the cope of the castings.

casting shrinkage. See *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.

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). Also known as caustic embrittlement.

caustic embrittlement. See *caustic cracking.*

cavitation. 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.*

cavitation damage. The degradation of a solid body resulting from its exposure to cavitation. This may include loss of material, surface deformation, or changes in properties or appearance.

cavitation erosion. See *cavitation damage.*

centerline shrinkage. Shrinkage or porosity occurring along the central plane or axis of a cast metal section.

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

Charpy test. An impact test in which a V-notched, keyhole-notched, or U-notched specimen, supported at both ends, is struck 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.*

chevron pattern. A fractographic pattern of radial marks (shear ledges) that looks like nested letters "V"; sometimes called a herringbone pattern. Chevron patterns are typically found on brittle fracture surfaces in parts whose widths are considerably greater than their thicknesses. The points of the chevrons can be traced back to the fracture origin.

chill. A white iron structure that is produced by rapid solidification.

chord modulus. The slope of the chord drawn between any two specific points on a stress-strain curve. See also *modulus of elasticity.*

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.

cleavage crack. A crack that extends along a plane of easy *cleavage* in a crystalline material.

cleavage fracture. A fracture, usually of a polycrystalline metal, in which most of the grains have failed by *cleavage*, resulting in bright reflecting facets. It is one type of *crystalline fracture* and is associated with *low-energy brittle fracture*. Contrast with *shear fracture.*

cleavage plane. A characteristic crystallographic plane or set of planes in a crystal on which *cleavage fracture* occurs easily.

cold shot. A small globule of metal that solidified prematurely and is embedded in but not entirely fused with the surface of the casting.

cold shut. 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.

columnar structure. A coarse structure of parallel, elongated grains formed by unidirectional growth that is most often observed in castings. This results from diffusional growth accompanied by a solid-state transformation.

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 or filament of a high-melting substance embedded in a metal or nonmetal matrix.

compression modulus. See *bulk modulus of elasticity.*

compressive. Pertaining to forces on a body or part of a body that tend to crush, or compress, the body.

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 an elastic 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 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.

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 at lower stress levels or fewer cycles than would be required in the absence of a corrosive environment.

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

crack extension, Δa. An increase in crack size. See also *crack length, effective crack size, original crack size,* and *physical crack size.*

crack length (depth), a. In *fatigue* and *stress-corrosion cracking*, 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. See also *crack size.*

crack mouth opening displacement (CMOD). See *crack opening displacement.*

crack opening displacement (COD). On a K_{Ic} specimen, the opening displacement of the notch surfaces at the notch and in the direction perpendicular to the plane of the notch and the crack. The displacement at the tip is called the crack tip opening displacement (CTOD); at the mouth, it is called the crack mouth opening displacement (CMOD).

crack plane orientation. An identification of the plane and direction of a fracture in relation to product geometry. This identification is designated by a hyphenated code, the first letter(s) representing the direction normal to the crack plane and the second letter(s) designating the expected direction of crack propagation.

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 (depth).*

crack tip opening displacement (CTOD). See *crack opening displacement*.

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; that occurring at a minimum and almost constant rate, secondary or steady-rate creep; that occurring at an accelerating rate, tertiary creep.

creep rate. The slope of the creep-time curve at a given time determined from a Cartesian plot.

creep-rupture strength. The stress that will cause 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 (extension plus initial gage length) produced by applied stress during a creep test.

creep strength. The stress that will cause 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. An indentation in a casting surface due to displacement of sand into the mold cavity when the mold is closed.

crystalline fracture. A pattern of brightly reflecting crystal facets on the fracture surface of a polycrystalline metal, resulting from *cleavage fracture* of many individual crystals. Contrast with *fibrous fracture* and *silky fracture*; see also *granular fracture*.

cup fracture (cup-and-cone fracture). A mixed-mode fracture, often seen in tension test specimens of a ductile material, where the central portion undergoes plane-strain fracture and the surrounding region undergoes plane-stress fracture. One of the mating fracture surfaces looks like a miniature cup; it has a central depressed flat-face region surrounded by a shear lip. The other fracture surface looks like 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.

cycle, N. In fatigue, one complete sequence of values of applied load that is repeated periodically.

cyclic load. (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 repeating sequence of change.

cyclic stressing. See *cyclic load*.

D

decarburization. Loss of carbon from the surface layer of a carbon-containing alloy due to reaction with one or more chemical substances in a medium that contacts the surface.

deformation. A change in the form of a body due to stress, thermal change, change in moisture, or other causes. Measured in units of length.

deformation bands. Bands produced within individual grains during cold working which differ variably in orientation from the matrix.

deformation curve. See *stress-strain diagram*.

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. See *poultice corrosion*.

deposit corrosion. See *poultice corrosion*.

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*.

dimpled rupture fracture. A fractographic term describing *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*.

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 (i.e., 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. Fracture characterized by tearing of metal accompanied by appreciable gross *plastic deformation* and expenditure of considerable energy. 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 *cupping* 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 (>0.1 s^{-1}) testing of metal specimens. Contrast with *static*.

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.

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. A change in dimensions directly proportional to and in phase with an increase or decrease in applied force.

elastic limit. The maximum *stress* a material is capable of sustaining without any permanent *strain* (deformation) remaining upon complete release of the stress. See also *proportional limit*.

elastic strain. See *elastic deformation*.

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

elongation. A term used in mechanical testing to describe the amount of extension of a test piece when stressed. See also *elongation, percent* and *stress*.

elongation, percent. The extension of a uniform section of a specimen expressed as percentage of the original gage length:

$$\text{Elongation, \%} = \frac{L_f - L_o}{L_o} \times 100$$

where L_o is original gage length and L_f is final gage length. See also *elongation*.

embrittlement. The severe loss of ductility and/or toughness of a material, usually a metal or alloy.

endurance limit. 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.

exfoliation. *Corrosion* that proceeds laterally from the sites of initiation along planes parallel to the surface, generally at grain boundaries, forming corrosion products that force metal away from the body of the material, giving rise to a layered appearance.

F

failure. A general term used to imply that a part in service (1) has become completely inoperable, (2) is still operable but is incapable of satisfactorily performing its intended function, or (3) has deteriorated seriously to the point that it has become unreliable or unsafe for continued use.

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* under repeated or fluctuating stresses having a maximum value less than the ultimate tensile strength of the material. See also *fatigue failure, high-cycle fatigue, low-cycle fatigue*, 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.

fatigue failure. Failure that occurs when a specimen undergoing fatigue completely fractures into two parts or has softened or been otherwise significantly reduced in stiffness by thermal heating or cracking. Fatigue failure generally occurs at loads which applied statically would produce little perceptible effect. Fatigue failures are progressive, beginning as minute cracks that grow under the action of the fluctuating stress.

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

fatigue limit. 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*.

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 effect of a notch 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. See *striation*.

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

fiber. (1) The characteristic of wrought metal that indicates directional properties. It is revealed by etching of a longitudinal section or is manifested by the fibrous or woody appearance of a fracture. It is caused chiefly by extension of the constituents of the metal, both metallic and nonmetallic, in the direction of working. (2) The pattern of *preferred orientation* of metal crystals after a given deformation process, usually wiredrawing. See also *texture*.

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* through 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. A gray and amorphous *fracture* that results when a metal is sufficiently ductile for the crystals to elongate before fracture occurs. When a fibrous fracture is obtained in an impact test, it may be regarded as definite evidence of toughness of the metal. See also *crystalline fracture* and *silky fracture*.

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 discontinuity found on the fracture surface of a weld in steel that consists of a small pore or inclusion surrounded by an approximately round, bright area.

fishmouthing. See *alligatoring*.

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 termed 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. Texture showing the direction of metal flow during hot or cold working. Flow lines often can be revealed by etching the surface or a section of a metal part.

fluting. 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.

fold. A defect in metal, usually on or near the surface, caused by continued fabrication of overlapping surfaces.

fractography. Descriptive explanation of a fracture process, especially in metals, with specific reference to photographs of the fracture surface. Macrofractography involves low magnification (<25×); microfractography, at high magnification (>25×).

fracture. The irregular surface produced when a piece of metal is broken. See also *crystalline fracture*, *fibrous fracture*, *granular fracture*, *intergranular fracture*, *silky fracture*, and *transgranular fracture*.

fracture mechanics. See *linear elastic fracture mechanics*.

fracture stress. See *rupture stress*.

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 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 commonly includes 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 *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 *spalling* 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 or in clusters, or may 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 deterioration that is distributed more or less uniformly over a surface. See also *corrosion*.

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*.

grain-boundary corrosion. Same as *intergranular corrosion*; see also *corrosion* and *interdendritic corrosion*.

grain flow. Fiberlike lines on polished and etched sections of forgings caused by orientation of the constituents of the metal in the direction of working during forging. Grain flow produced by proper die design can improve required *mechanical properties* of forgings.

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 gray 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.

H

hairline crack. See *flake*.

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*, *Scleroscope*, and *Vickers hardness tests*.

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 *chevron pattern*.

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 about 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*.

Hooke's law. A material in which *stress* is linearly proportional to *strain* is said to obey Hooke's law. 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 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, etc.

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 hydrogen-induced 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.

hydrostatic modulus. See *bulk modulus of elasticity*.

I

impact energy. The amount of energy required to fracture a material, usually measured by means of an *Izod test* or *Charpy 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*.

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

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. Inclusions are usually considered undesirable, although in some cases—such as in free-machining metals—manganese sulfides, phosphorus, selenium, or tellurium may be deliberately introduced to improve machinability.

intercrystalline. See *intergranular*.

intercrystalline cracking. See *intergranular cracking*.

intercrystalline corrosion. See *intergranular corrosion*.

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. See also *corrosion*.

interface. The boundary between two contacting parts or regions of parts.

intergranular. Between crystals or grains. Also termed intercrystalline. Contrast with *transgranular*.

intergranular corrosion. *Corrosion* occurring preferentially at grain boundaries, usually with slight or negligible attack on the adjacent grains. See also *interdendritic corrosion*.

intergranular cracking. Cracking or fracturing that occurs between the grains or crystals in a polycrystalline aggregate. Contrast with *transgranular cracking*.

intergranular fracture. Brittle fracture of a metal in which the fracture is between the grains, or crystals, that form the metal. Contrast with *transgranular fracture*.

intergranular stress-corrosion cracking. *Stress-corrosion cracking* in which the cracking occurs along grain boundaries.

internal oxidation. (1) The formation of isolated particles of *corrosion* products beneath the metal surface. This occurs as the result of preferential oxidation of certain alloy constituents by inward diffusion of oxygen, nitrogen, sulfur, etc. Also called subsurface cor-

rosion. (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*.

intracrystalline cracking. See *transgranular cracking*.

Izod test. A type of impact test in which a V-notched specimen, mounted vertically, 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 test*.

J

J-integral. A mathematical expression; a line or surface integral that encloses the crack front from one crack surface to the other, used to characterize the *fracture toughness* of a material having appreciable plasticity before fracture. The J-integral eliminates the need to describe the behavior of the material near the crack tip by considering the local stress-strain field around the crack front; J_{Ic} is the critical value of the J-integral required to initiate growth of a pre-existing crack.

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′ and 130° 0′ computed from the equation:

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

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. (1) A type of discontinuity with separation or weakness generally aligned parallel to the worked surface of a metal. (2) In electrical components such as motors, a blanked piece of electrical sheet that is stacked up with several other identical pieces to make a stator or rotor.

lap. (1) A surface imperfection on 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. (2) A flat surface that holds an abrasive for polishing operations.

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 crack-like flaw of known size and shape. See also *stress-intensity factor*.

liquid metal embrittlement. The decrease in *ductility* of a metal caused by contact with a liquid metal.

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

longitudinal direction. That direction parallel to the direction of maximum elongation in a worked material. See also *normal direction* and *transverse direction*.

low-cycle fatigue. *Fatigue* that occurs at relatively small numbers of cycles ($<10^4$ cycles). Low-cycle fatigue may be accompanied by some plastic, or permanent, deformation. Compare with *high-cycle fatigue*.

Lüders lines. Elongated surface markings or depressions, often visible to the unaided eye, 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×.

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* in compression without fracture. See also *ductility*.

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