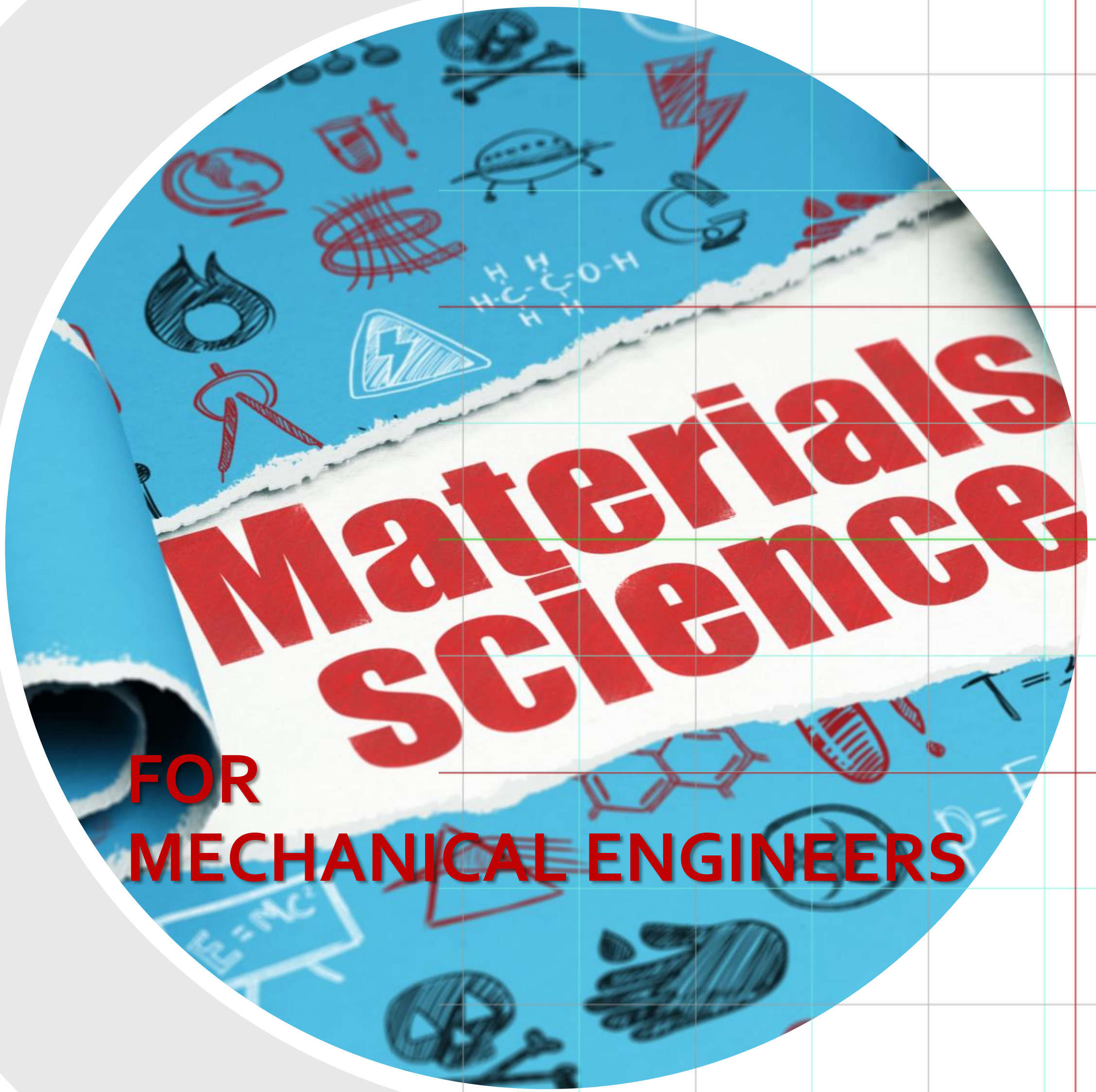


FOR
MECHANICAL ENGINEERS

Failure

SPRING 2022-2023

Aloha Airlines flight 243

INTRODUCTION

Learning Objectives

- Describe the mechanism of crack propagation for both ductile and brittle modes of fracture.
- Explain why the strengths of brittle materials are much lower than predicted by theoretical calculations.
- Define fracture toughness in terms of (a) a brief statement and (b) an equation; define all parameters in this equation.
- Make a distinction between *fracture toughness* and *plane strain fracture toughness.*
- Name and describe the two impact fracture testing techniques.
- Define *fatigue* and specify the conditions under which it occurs.
- From a fatigue plot for some material, determine (a) the fatigue lifetime (at a specified stress level) and (b) the fatigue strength (at a specified number of cycles).
- Define *creep* and specify the conditions under which it occurs.
- Given a creep plot for some material, determine (a) the steady-state creep rate and (b) the rupture lifetime.

INTRODUCTION

The failure of engineering materials is almost always an undesirable event for several reasons; these include:

- putting human lives in jeopardy,
- causing economic losses, and
- interfering with the availability of products and services.

Even though the causes of failure and the behaviour of materials may be known, prevention of failures is difficult to guarantee.

The usual causes are:

- improper materials selection and processing.
- inadequate design of the component or its misuse.

Also, damage can occur to structural parts during service, and regular inspection and repair or replacement are critical to safe design.

It is the responsibility of the engineer to anticipate and plan for possible failure and, in the event that failure does occur, to assess its cause and then take appropriate preventive measures against future incidents.

FUNDAMENTALS OF FRACTURE

Simple fracture is the separation of a body into two or more pieces in response to an imposed stress that is static (i.e., constant or slowly changing with time) and at temperatures that are low relative to the melting temperature of the material.

Fracture can also occur from fatigue (when cyclic stresses are imposed) and creep (time-dependent deformation, normally at elevated temperatures).

Although applied stresses may be tensile, compressive, shear, or torsional (or combinations of these), the present discussion will be confined to fractures that result from uniaxial tensile loads.

For metals, two fracture modes are possible: **ductile** and **brittle.** Classification is based on the ability of a material to experience plastic deformation.

Ductile metals typically exhibit substantial plastic deformation with high energy absorption before fracture. However, there is normally little or no plastic deformation with low energy absorption accompanying a brittle fracture.

Ductile and *brittle* are relative terms; whether a particular fracture is one mode or the other depends on the situation. Ductility may be quantified in terms of percent elongation and percent reduction in area.

Furthermore, ductility is a function of temperature of the material, the strain rate, and the stress state.

FUNDAMENTALS OF FRACTURE

Any fracture process involves two steps:

- crack formation and
- crack propagation

In response to an imposed stress.

The mode of fracture is highly dependent on the mechanism of crack propagation. Ductile fracture is characterized by extensive plastic deformation in the vicinity of an advancing crack.

The process proceeds relatively slowly as the crack length is extended. Such a crack is often said to be *stable*—that is, it resists any further extension unless there is an increase in the applied stress.

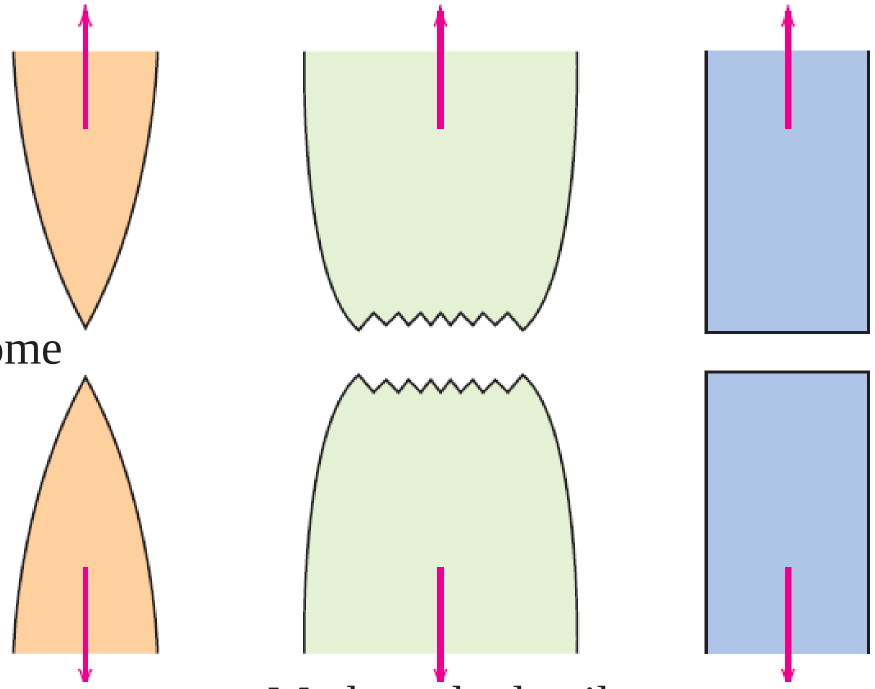
In addition, there typically is evidence of appreciable gross deformation at the fracture surfaces (e.g., twisting and tearing). However, for brittle fracture, cracks may spread extremely rapidly, with very little accompanying plastic deformation. Such cracks may be said to be *unstable*, and crack propagation, once started, continues spontaneously without an increase in magnitude of the applied stress.

FUNDAMENTALS OF FRACTURE

Ductile fracture is almost always preferred to brittle fracture for two reasons:

- First, brittle fracture occurs suddenly and catastrophically without any warning; this is a consequence of the spontaneous and rapid crack propagation. By contrast, in ductile fracture, the presence of plastic deformation gives warning that failure is imminent, allowing preventive measures to be taken.
- Second, more strain energy is required to induce ductile fracture inasmuch as these materials are generally tougher. Under the action of an applied tensile stress, many metal alloys are ductile, whereas ceramics are typically brittle, and polymers may exhibit a range of behaviours.

Moderately ductile fracture after some necking.



Brittle fracture without any plastic deformation.

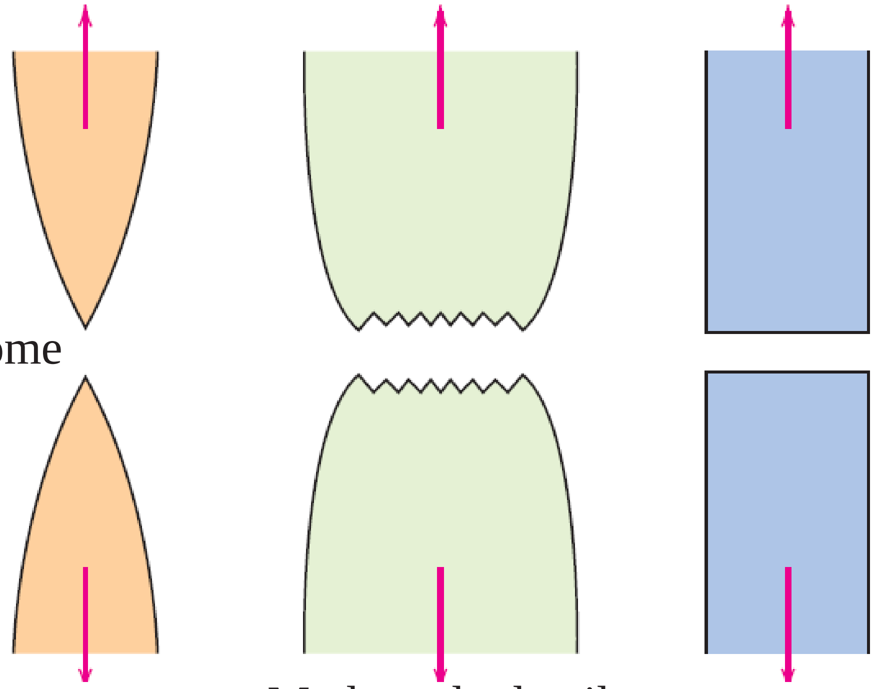
Moderately ductile fracture after some necking.

DUCTILE FRACTURE

Ductile fracture surfaces have distinctive features on both macroscopic and microscopic levels.

The configuration shown is found for extremely soft metals, such as pure gold and lead at room temperature, and other metals, polymers, and inorganic glasses at elevated temperatures. These highly ductile materials neck down to a point fracture, showing virtually 100% reduction in area.

The most common type of tensile fracture profile for ductile metals is where fracture is preceded by only a moderate amount of necking.



Moderately ductile fracture after some necking.

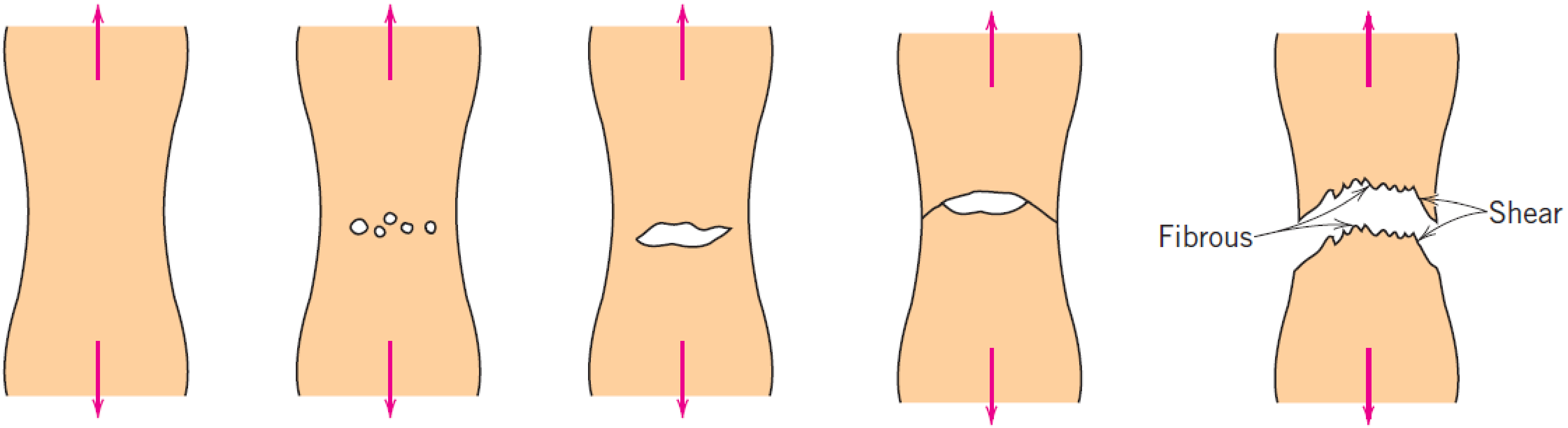
Moderately ductile fracture after some necking.

Brittle fracture without any plastic deformation.

DUCTILE FRACTURE

The fracture process normally occurs in several stages:

1. First, after necking begins, small cavities, or *microvoids,* form in the interior of the cross section.
2. Next, as deformation continues, these microvoids enlarge, come together, and coalesce to form an elliptical crack, which has its long axis perpendicular to the stress direction.
3. The crack continues to grow in a direction parallel to its major axis by this microvoid coalescence process.
4. Finally, fracture ensues by the rapid propagation of a crack around the outer perimeter of the neck by shear deformation at an angle of about 45° with the *tensile axis*—the angle at which the shear stress is a maximum.



DUCTILE FRACTURE

Sometimes a fracture having this characteristic surface contour is termed a *cup-and-cone fracture* because one of the mating surfaces is in the form of a cup and the other like a cone.

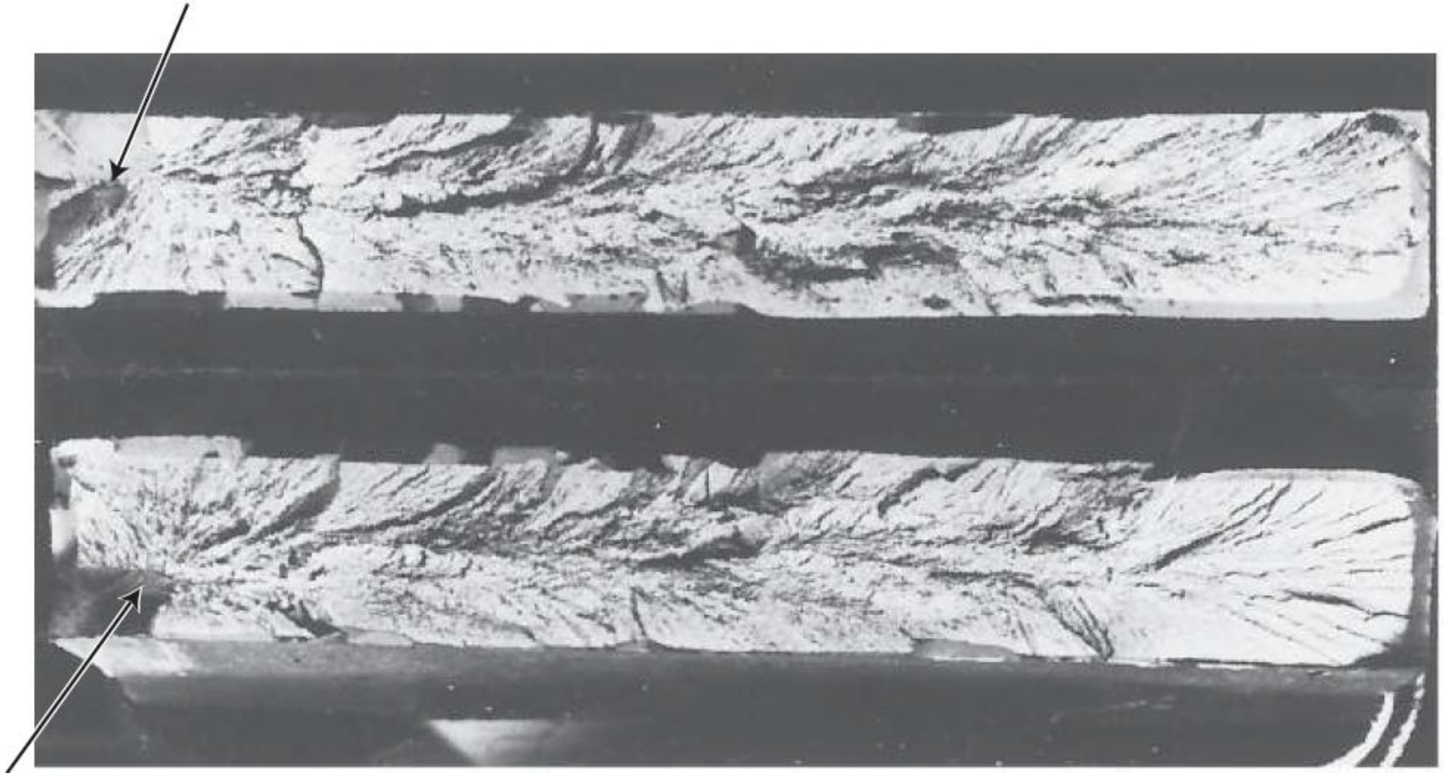
In this type of fractured specimen, the central interior region of the surface has an irregular and fibrous appearance, which is indicative of plastic deformation.

BRITTLE FRACTURE

Brittle fracture takes place without any appreciable deformation and by rapid crack propagation. The direction of crack motion is very nearly perpendicular to the direction of the applied tensile stress and yields a relatively flat fracture surface.

Fracture surfaces of materials that fail in a brittle manner have distinctive patterns; any signs of gross plastic deformation are absent.

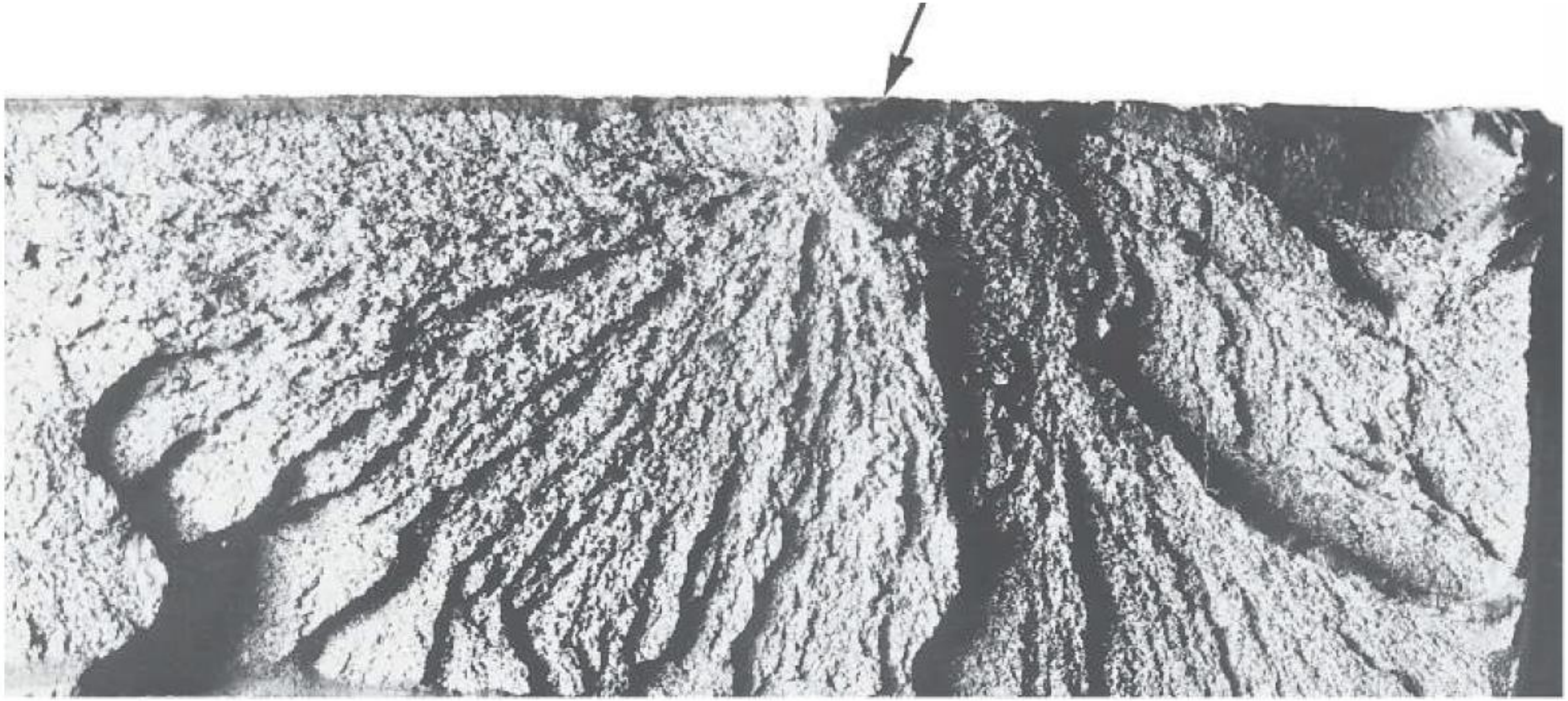
For example, in some steel pieces, a series of V-shaped “chevron” markings may form near the centre of the fracture cross section that point back toward the crack initiation site.



BRITTLE FRACTURE

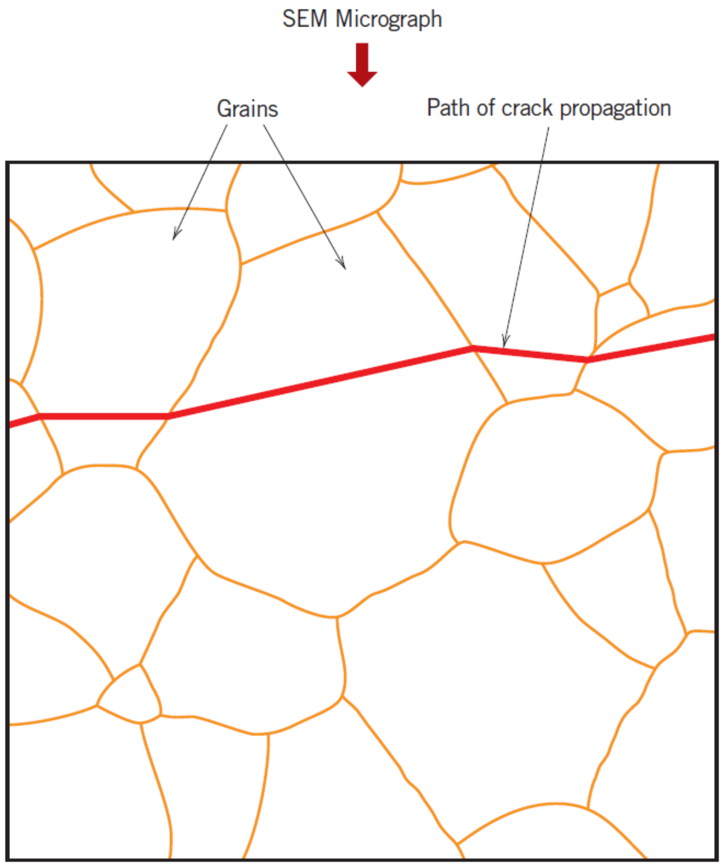
Other brittle fracture surfaces contain lines or ridges that radiate from the origin of the crack in a fanlike pattern. Often, both of these marking patterns are sufficiently coarse to be discerned with the naked eye.

For very hard and fine-grained metals, there is no discernible fracture pattern. Brittle fracture in amorphous materials, such as ceramic glasses, yields a relatively shiny and smooth surface.



BRITTLE FRACTURE

For most brittle crystalline materials, crack propagation corresponds to the successive and repeated breaking of atomic bonds along specific crystallographic planes; such a process is termed *cleavage*.

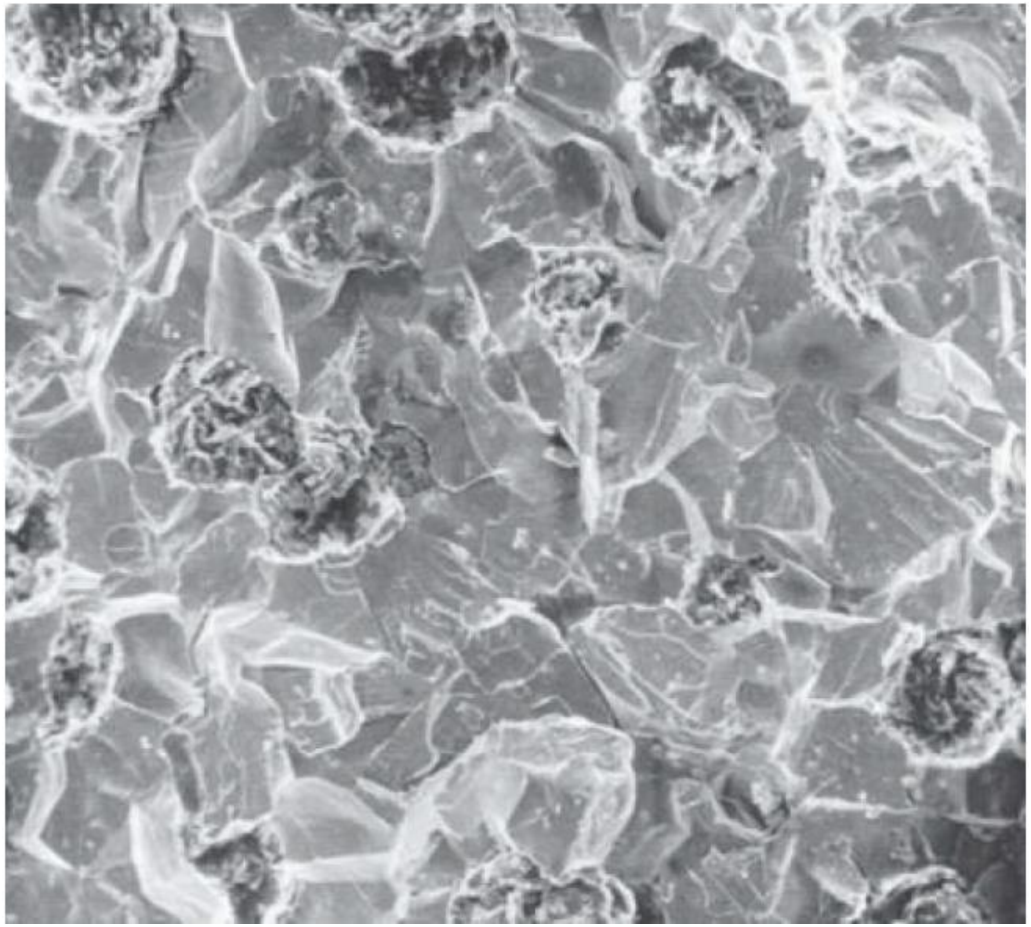


This type of fracture is said to be **transgranular** (or *transcrystalline*) because the fracture cracks pass through the grains.

BRITTLE FRACTURE

Macroscopically, the fracture surface may have a grainy or faceted texture as a result of changes in orientation of the cleavage planes from grain to grain.

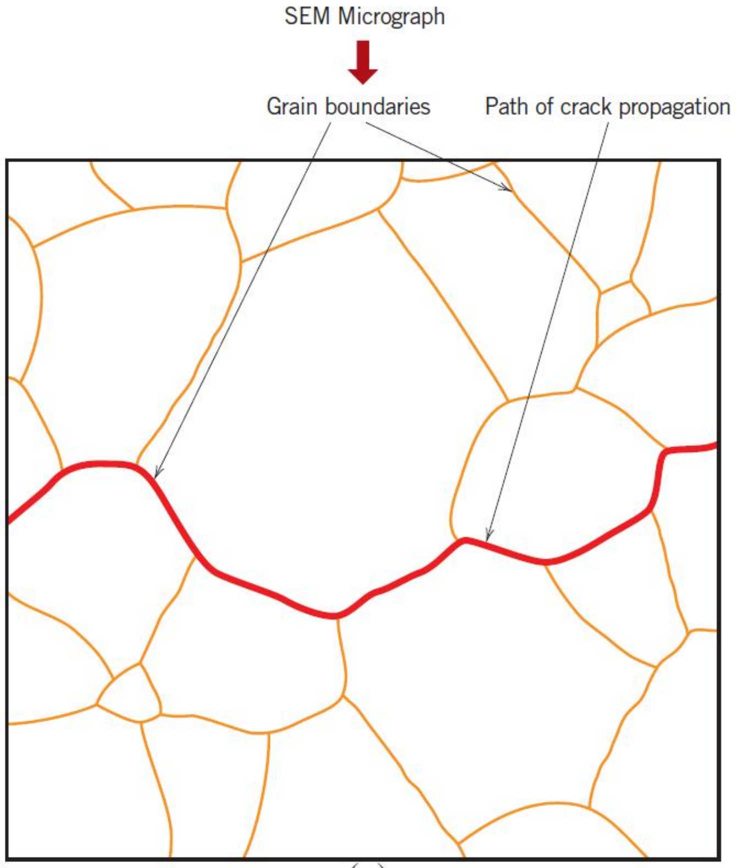
This cleavage feature is shown at a higher magnification in the scanning electron micrograph.



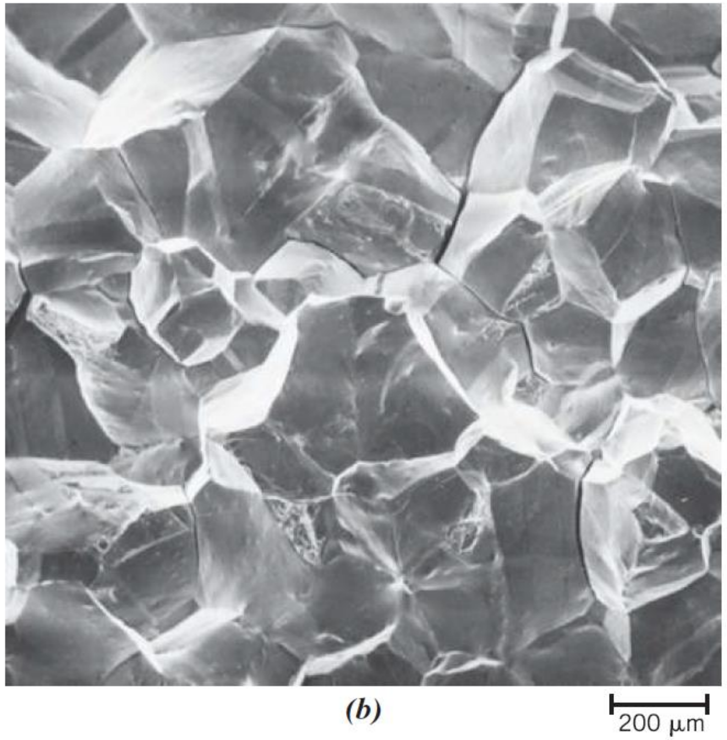
BRITTLE FRACTURE

In some alloys, crack propagation is along grain boundaries; this fracture is termed **intergranular.** Figure *b* is a scanning electron micrograph showing a typical intergranular fracture, in which the three-dimensional nature of the grains may be seen.

This type of fracture normally results subsequent to the occurrence of processes that weaken or embrittle grain boundary regions.



(*a*)



(*b*)

BRITTLE FRACTURE

Stress Concentration

The measured fracture strengths for most materials are significantly lower than those predicted by theoretical calculations based on atomic bonding energies.

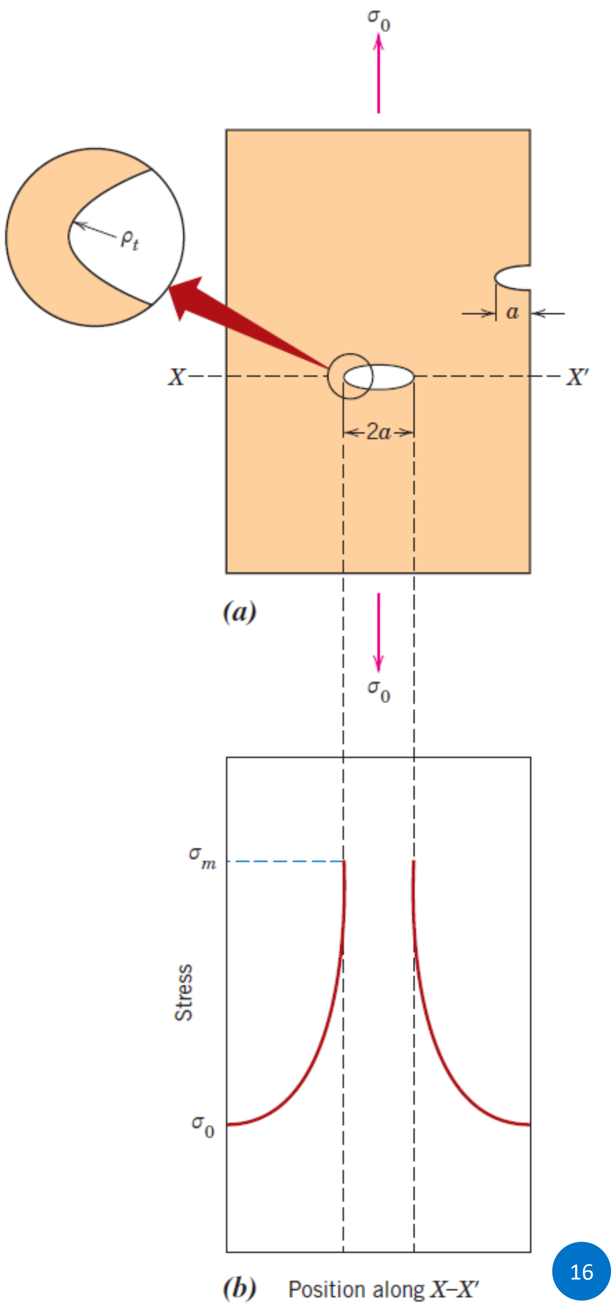
This discrepancy is explained by the presence of microscopic flaws or cracks that always exist under normal conditions at the surface and within the interior of a body of material.

These flaws are a detriment to the fracture strength because an applied stress may be amplified or concentrated at the tip, the magnitude of this amplification depending on crack orientation and geometry.

This phenomenon is demonstrated: a stress profile across a cross section containing an internal crack. As indicated by this profile, the magnitude of this localized stress decreases with distance away from the crack tip.

At positions far removed, the stress is just the nominal stress σ_0, or the applied load divided by the specimen cross-sectional area (perpendicular to this load).

Because of their ability to amplify an applied stress in their locale, these flaws are sometimes called **stress raisers.**



BRITTLE FRACTURE

If it is assumed that a crack is similar to an elliptical hole through a plate and is oriented perpendicular to the applied stress, the maximum stress, σ_m, occurs at the crack tip and may be approximated by:

$$\sigma_m = 2\sigma_0\left(\frac{a}{\rho_t}\right)^{1/2}$$

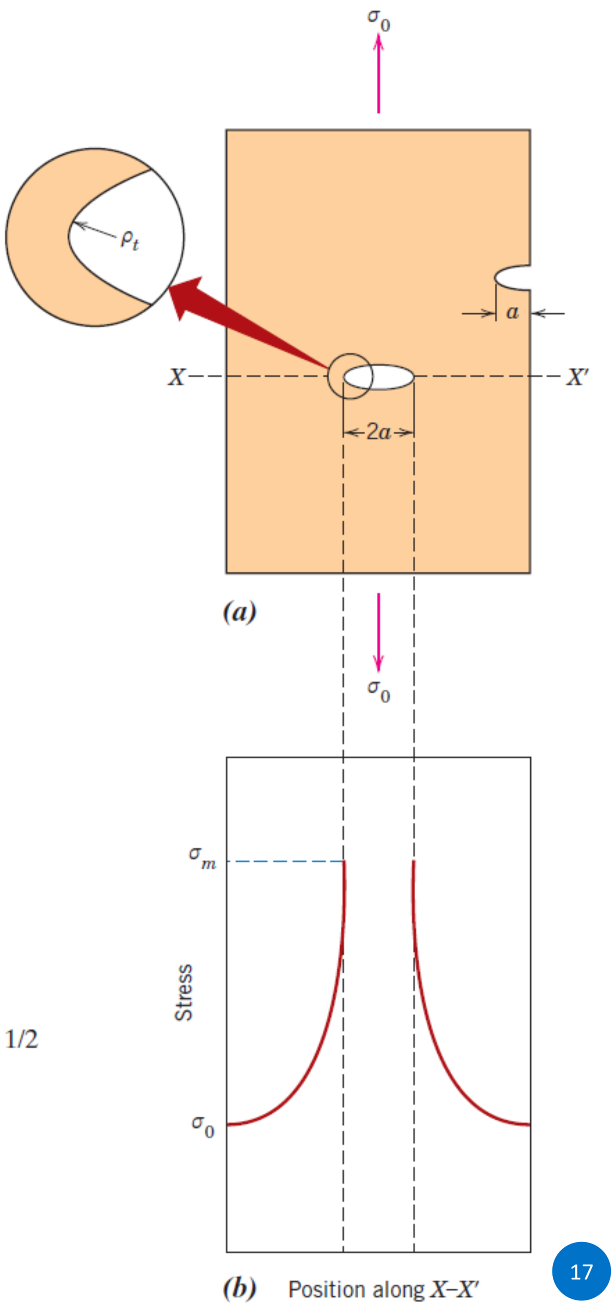
where σ_0 is the magnitude of the nominal applied tensile stress, ρ_t is the radius of curvature of the crack tip, and a represents the length of a surface crack, or half of the length of an internal crack.

For a relatively long microcrack that has a small tip radius of curvature, the factor $(a/\rho_t)^{1/2}$ may be very large.

This yields a value of σ_m that is many times the value of σ_0.

Sometimes the ratio σ_m/σ_0 is denoted the *stress concentration factor* K_t: $K_t = \frac{\sigma_m}{\sigma_0} = 2\left(\frac{a}{\rho_t}\right)^{1/2}$

which is simply a measure of the degree to which an external stress is amplified at the tip of a crack.



BRITTLE FRACTURE

Note that stress amplification is not restricted to these microscopic defects; it may occur at macroscopic internal discontinuities (e.g., voids or inclusions), sharp corners, scratches, and notches.

Furthermore, the effect of a stress raiser is more significant in brittle than in ductile materials. For a ductile metal, plastic deformation ensues when the maximum stress exceeds the yield strength. This leads to a more uniform distribution of stress in the vicinity of the stress raiser and to the development of a maximum stress concentration factor less than the theoretical value.

Such yielding and stress redistribution do not occur to any appreciable extent around flaws and discontinuities in brittle materials; therefore, essentially the theoretical stress concentration results.

Using principles of fracture mechanics, it is possible to show that the critical stress σ_c required for crack propagation in a brittle material is described by the expression:

$$\sigma_c = \left(\frac{2E\gamma_s}{\pi a}\right)^{1/2}$$

where E is modulus of elasticity, γ_s is the specific surface energy, and a is one-half the length of an internal crack.

All brittle materials contain a population of small cracks and flaws that have a variety of sizes, geometries, and orientations. When the magnitude of a tensile stress at the tip of one of these flaws exceeds the value of this critical stress, a crack forms and then propagates, which results in fracture. Very small and virtually defect-free metallic and ceramic whiskers have been grown with fracture strengths that approach their theoretical values.

BRITTLE FRACTURE

Fracture Toughness

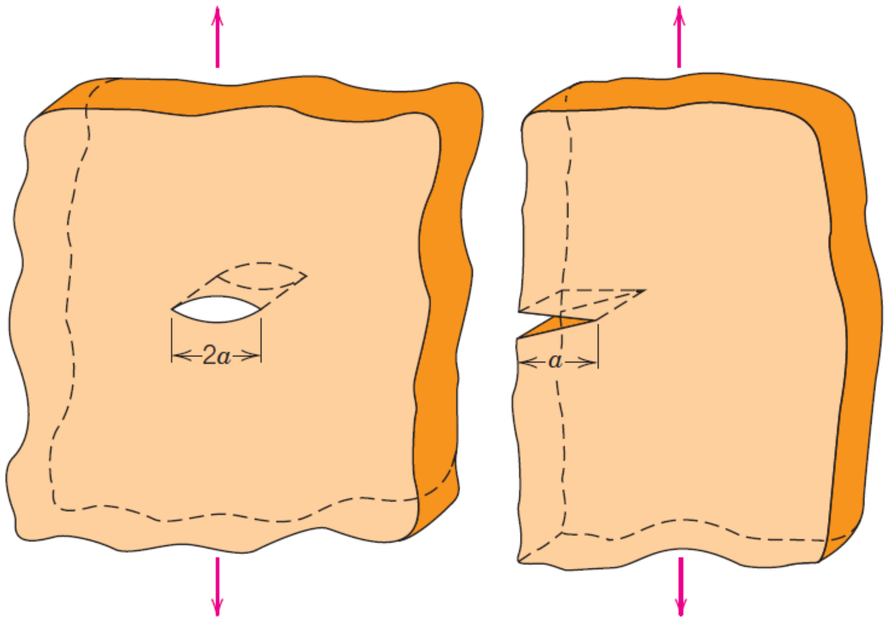
Using fracture mechanical principles, an expression has been developed that relates this critical stress for crack propagation (σ_c) and crack length (a) as: $K_c = Y\sigma_c\sqrt{\pi a}$

In this expression *Kc* is the **fracture toughness,** a property that is a measure of a material's resistance to brittle fracture when a crack is present. *Kc* has the unusual units of MPa√m or psi√in. (alternatively, ksi√in.).

Here, *Y* is a dimensionless parameter or function that depends on both crack and specimen sizes and geometries as well as on the manner of load application.

Relative to this *Y* parameter, for planar specimens containing cracks that are much shorter than the specimen width, *Y* has a value of approximately unity. For example, for a plate of infinite width having a through-thickness crack, $Y = 1.0$, whereas for a plate of semi-infinite width containing an edge crack of length a, $Y \cong 1.1$.

Mathematical expressions for *Y* have been determined for a variety of crack specimen geometries; these expressions are often relatively complex.



BRITTLE FRACTURE

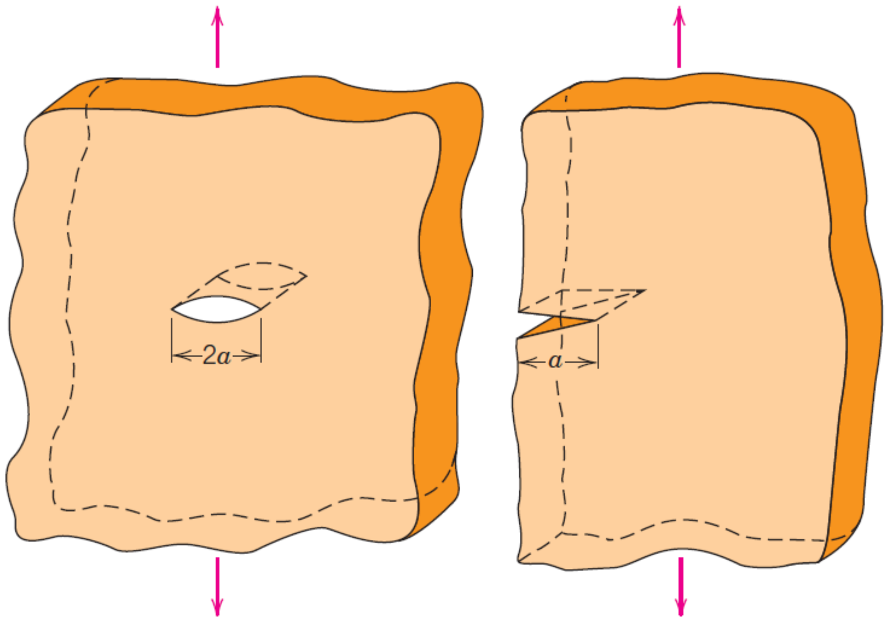
For relatively thin specimens, the value of K_c depends on specimen thickness.

However, when specimen thickness is much greater than the crack dimensions, K_c becomes independent of thickness; under these conditions a condition of **plane strain** exists.

By *plane strain*, we mean that when a load operates on a crack in the manner represented there is no strain component perpendicular to the front and back faces.

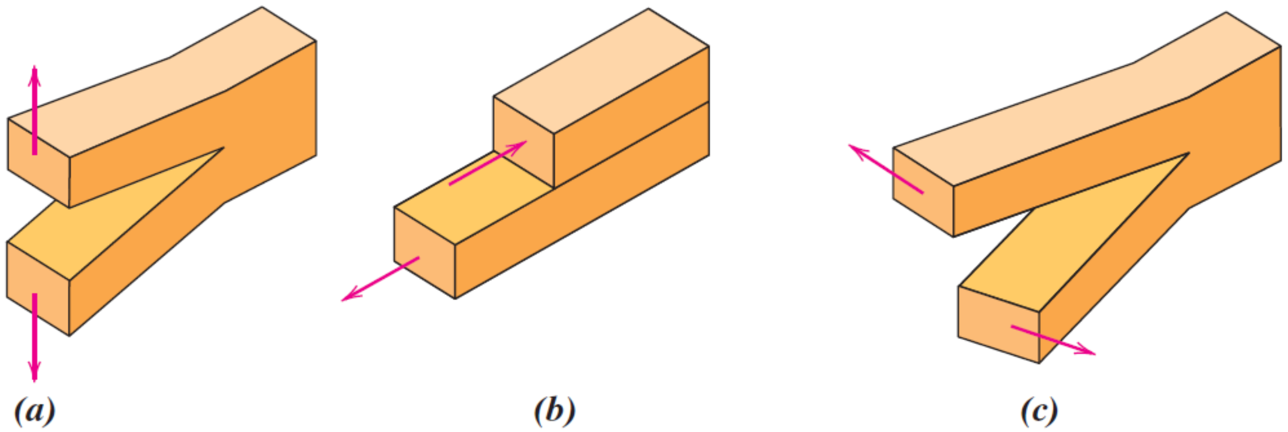
The K_c value for this thick-specimen situation is known as the **plane strain fracture toughness,** K_{Ic}; it is also defined by: $K_{Ic} = Y\sigma\sqrt{\pi a}$

K_{Ic} is the fracture toughness cited for most situations.



BRITTLE FRACTURE

The *I* (i.e., Roman Numeral "one") subscript for K_{Ic} denotes that the plane strain fracture toughness is for mode I crack displacement, as illustrated in **a**.



The three modes of crack surface displacement. (*a*) Mode I, opening or tensile mode; (*b*) mode II, sliding mode; and (*c*) mode III, tearing mode.

Brittle materials, for which appreciable plastic deformation is not possible in front of an advancing crack, have low K_{Ic} values and are vulnerable to catastrophic failure. However, K_{Ic} values are relatively large for ductile materials. Fracture mechanics is especially useful in predicting catastrophic failure in materials having intermediate ductilities. Plane strain fracture toughness values for a number of different materials are presented Tables.

BRITTLE FRACTURE

The plane strain fracture toughness K_{Ic} is a fundamental material property that depends on many factors, the most influential of which are temperature, strain rate, and microstructure. The magnitude of K_{Ic} decreases with increasing strain rate and decreasing temperature.

Furthermore, an enhancement in yield strength wrought by solid solution or dispersion additions or by strain hardening generally produces a corresponding decrease in K_{Ic}. In addition, K_{Ic} normally increases with reduction in grain size as composition and other microstructural variables are maintained constant.

	Yield Strength		K_{Ic}	
Material	***MPa***	***ksi***	$MPa\sqrt{m}$	$ksi\sqrt{in.}$
	Metals			
Aluminum alloy[a] (7075-T651)	495	72	24	22
Aluminum alloy[a] (2024-T3)	345	50	44	40
Titanium alloy[a] (Ti-6Al-4V)	910	132	55	50
Alloy steel[a] (4340 tempered @ 260°C)	1640	238	50.0	45.8
Alloy steel[a] (4340 tempered @ 425°C)	1420	206	87.4	80.0
	Ceramics			
Concrete	—	—	0.2–1.4	0.18–1.27
Soda-lime glass	—	—	0.7–0.8	0.64–0.73
Aluminum oxide	—	—	2.7–5.0	2.5–4.6
	Polymers			
Polystyrene (PS)	25.0–69.0	3.63–10.0	0.7–1.1	0.64–1.0
Poly(methyl methacrylate) (PMMA)	53.8–73.1	7.8–10.6	0.7–1.6	0.64–1.5
Polycarbonate (PC)	62.1	9.0	2.2	2.0

BRITTLE FRACTURE

Design Using Fracture Mechanics

Three variables must be considered relative to the possibility for fracture of some structural component:

- fracture toughness (K_c) or plane strain fracture toughness (K_{Ic}),
- the imposed stress (σ), and
- the flaw size (a) assuming, of course, that Y has been determined.

When designing a component, it is first important to decide which of these variables are constrained by the application and which are subject to design control.

For example, material selection (and hence K_c or K_{Ic}) is often dictated by factors such as density (for lightweight applications) or the corrosion characteristics of the environment.

Alternatively, the allowable flaw size is either measured or specified by the limitations of available flaw detection techniques. It is important to realize, however, that once any combination of two of the preceding parameters is prescribed, the third becomes fixed.

For example, assume that K_{Ic} and the magnitude of a are specified by application constraints; therefore, the design (or critical) stress σ_c is given by:

$$\sigma_c = \frac{K_{Ic}}{Y\sqrt{\pi a}}$$

BRITTLE FRACTURE

However, if stress level and plane strain fracture toughness are fixed by the design situation, then the maximum allowable flaw size a_c is given by:

$$a_c = \frac{1}{\pi}\left(\frac{K_{Ic}}{\sigma Y}\right)^2$$

A number of non-destructive test (NDT) techniques have been developed that permit detection and measurement of both internal and surface flaws. Such techniques are used to examine structural components that are in service for defects and flaws that could lead to premature failure; in addition, NDTs are used as a means of quality control for manufacturing processes. As the name implies, these techniques do not destroy the material/structure being examined. Furthermore, some testing methods must be conducted in a laboratory setting; others may be adapted for use in the field.

Technique	*Defect Location*	*Defect Size Sensitivity (mm)*	*Testing Location*
Scanning electron microscopy (SEM)	Surface	>0.001	Laboratory
Dye penetrant	Surface	0.025–0.25	Laboratory/in-field
Ultrasonics	Subsurface	>0.050	Laboratory/in-field
Optical microscopy	Surface	0.1–0.5	Laboratory
Visual inspection	Surface	>0.1	Laboratory/in-field
Acoustic emission	Surface/subsurface	>0.1	Laboratory/in-field
Radiography (x-ray/gamma ray)	Subsurface	>2% of specimen thickness	Laboratory/in-field

FRACTURE TOUGHNESS TESTING

Prior to the advent of fracture mechanics as a scientific discipline, impact testing techniques were established to ascertain the fracture characteristics of materials at high loading rates.

It was realized that the results of laboratory tensile tests (at low loading rates) could not be extrapolated to predict fracture behaviour.

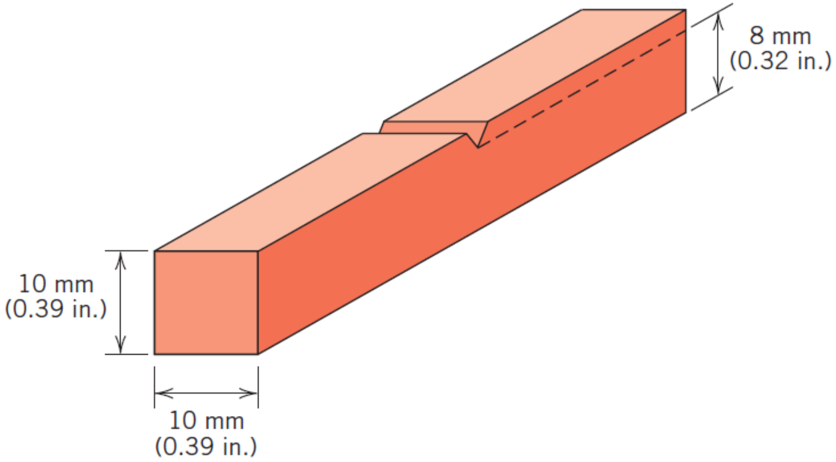
For example, under some circumstances, normally ductile metals fracture abruptly and with very little plastic deformation under high loading rates.

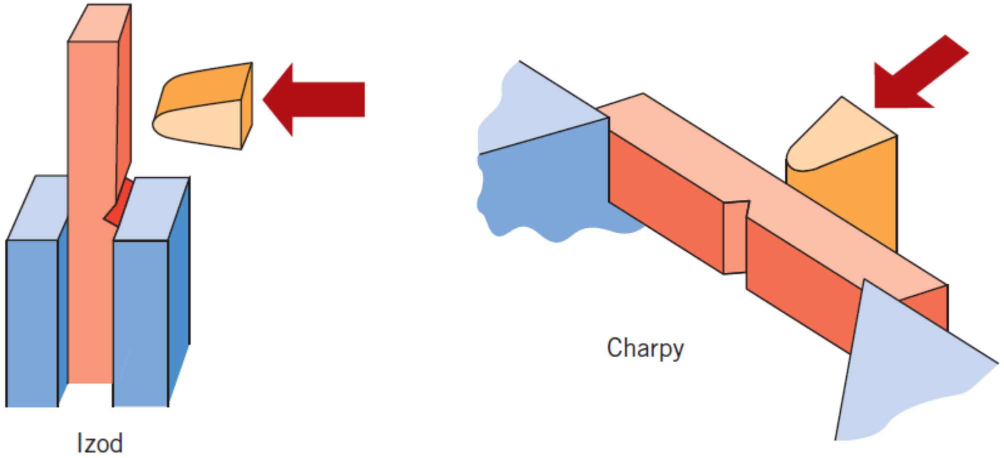
Impact test conditions were chosen to represent those most severe relative to the potential for fracture—namely,
(1) deformation at a relatively low temperature,
(2) a high strain rate (i.e., rate of deformation), and
(3) a triaxial stress state (which may be introduced by the presence of a notch).

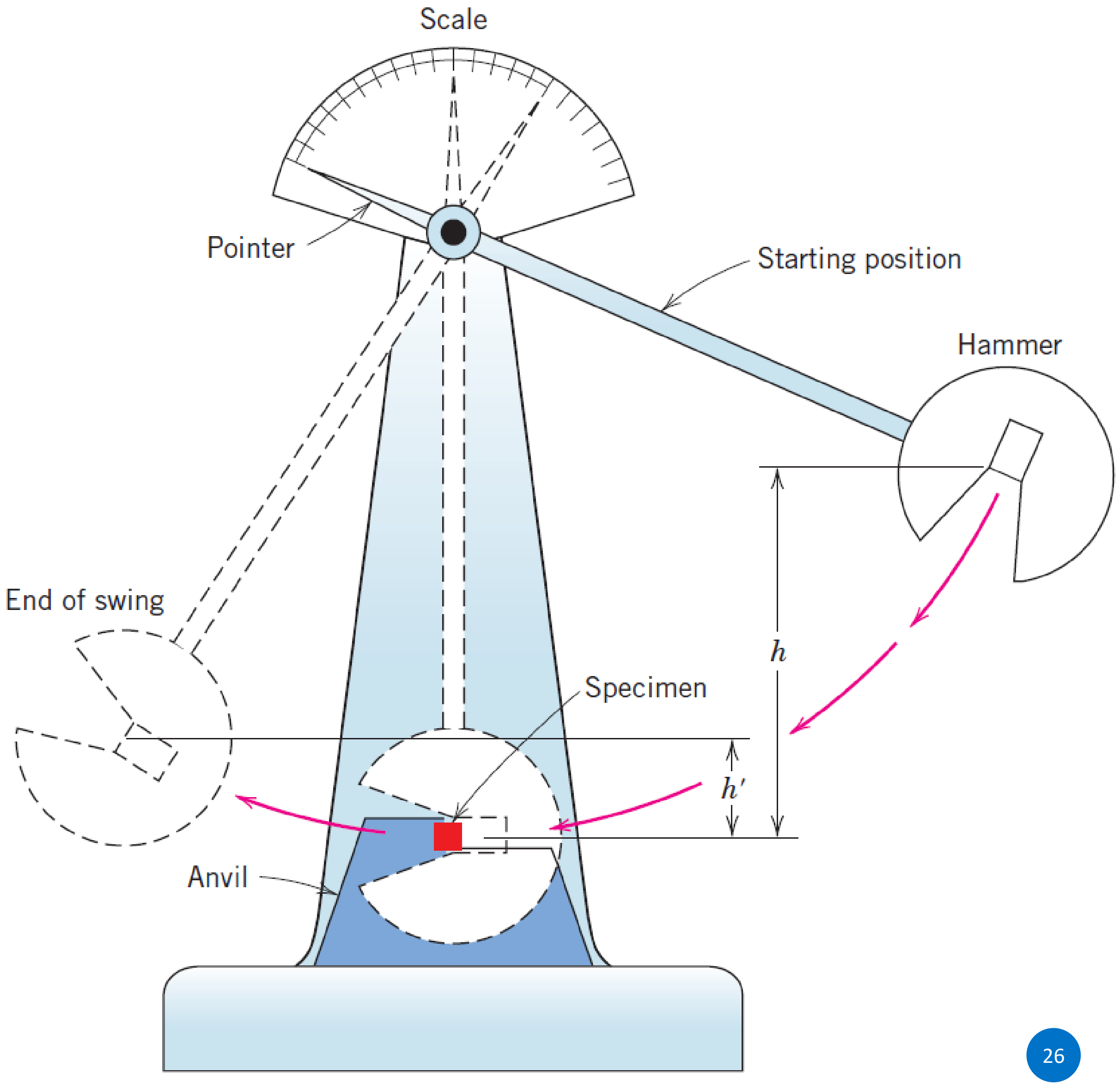
Two standardized tests, the **Charpy** and the **Izod,** are used to measure the **impact energy** (sometimes also termed *notch toughness*).

One of the primary functions of the Charpy and the Izod tests is to determine whether a material experiences a **ductile-to-brittle transition** with decreasing temperature and, if so, the range of temperatures over which it occurs.

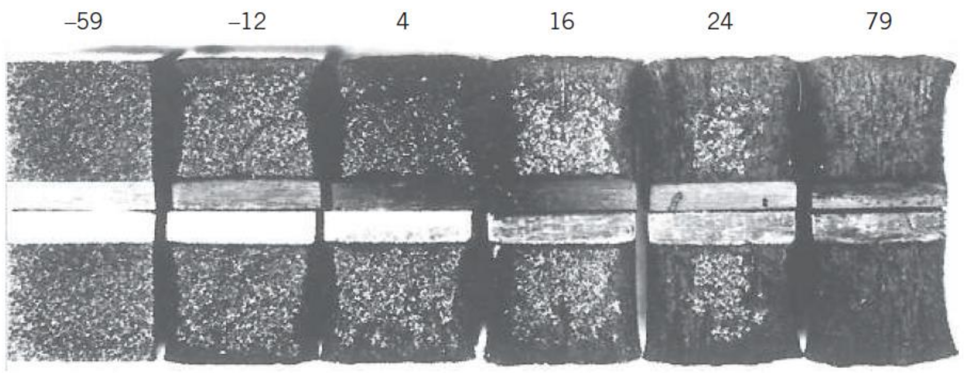
FRACTURE TOUGHNESS TESTING



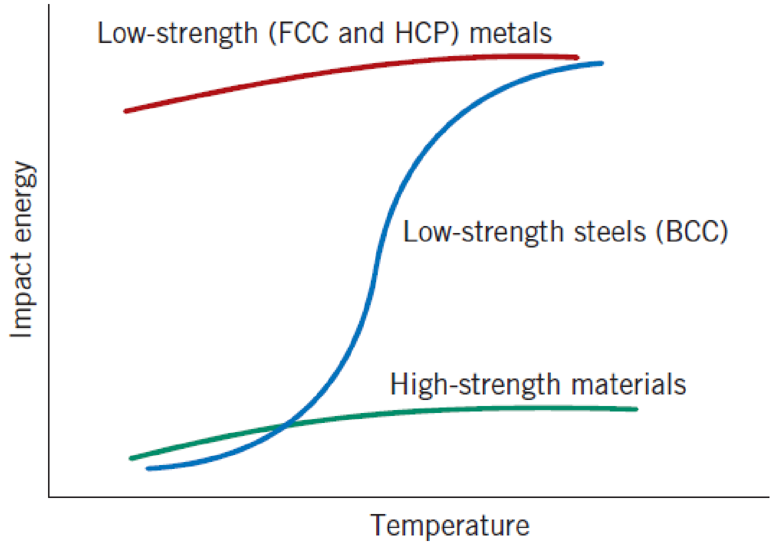


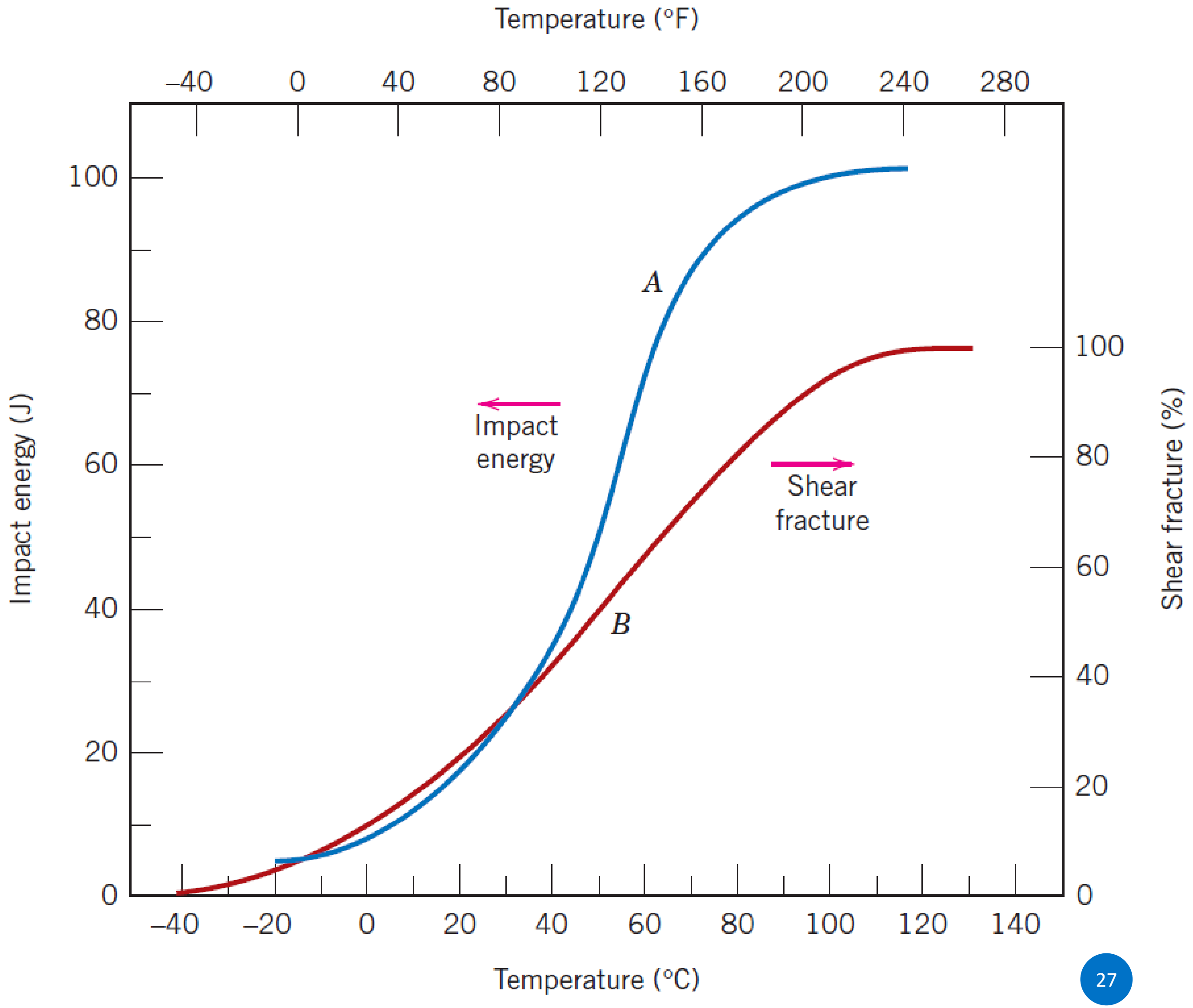


FRACTURE TOUGHNESS TESTING



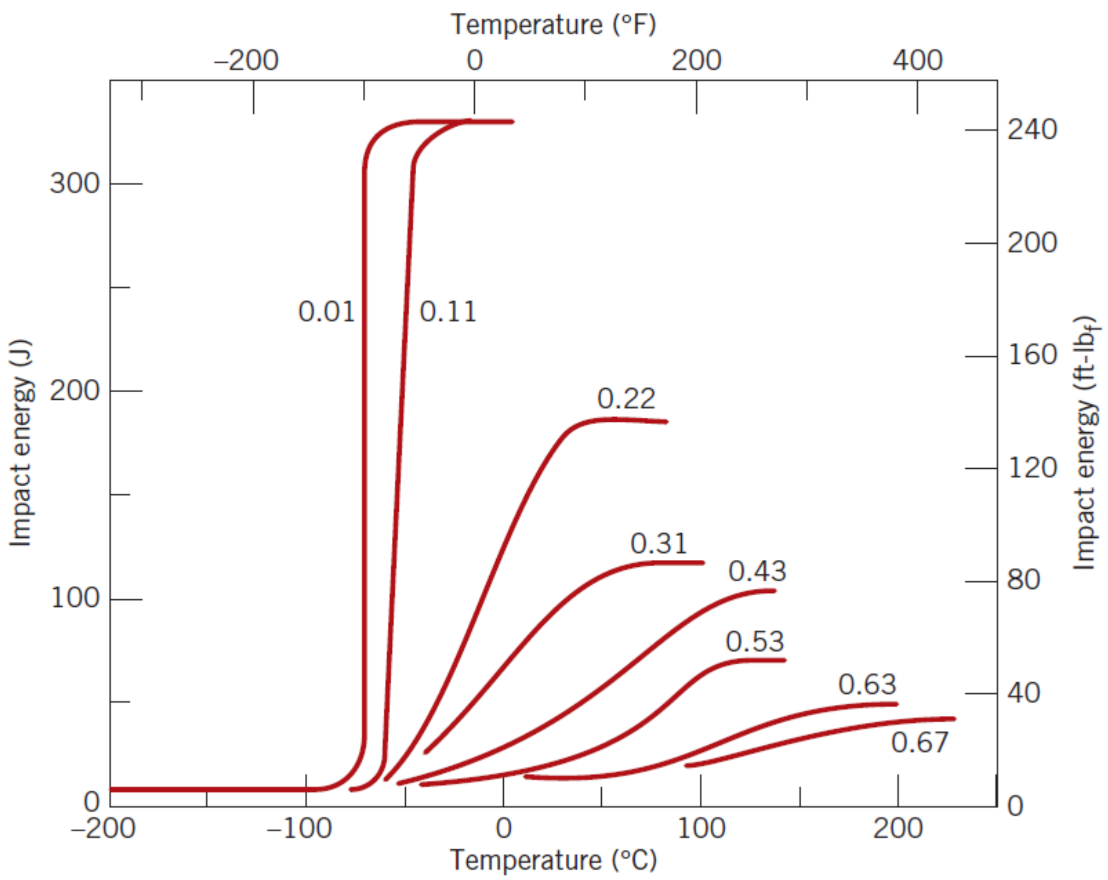
Photograph of fracture surfaces of A36 steel Charpy V-notch specimens tested at indicated temperatures (in °C).





FRACTURE TOUGHNESS TESTING

Influence of carbon content on the Charpy V-notch energy–versus–temperature behaviour for steel.



FATIGUE

Fatigue is a form of failure that occurs in structures subjected to dynamic and fluctuating stresses (e.g., bridges, aircraft, machine components). Under these circumstances, it is possible for failure to occur at a stress level considerably lower than the tensile or yield strength for a static load.

The term *fatigue* is used because this type of failure normally occurs after a lengthy period of repeated stress or strain cycling. Fatigue is important inasmuch as it is the single largest cause of failure in metals, estimated to be involved in approximately 90% of all metallic failures; polymers and ceramics (except for glasses) are also susceptible to this type of failure.

Furthermore, fatigue is catastrophic and insidious, occurring very suddenly and without warning.

Fatigue failure is brittle-like in nature even in normally ductile metals in that there is very little, if any, gross plastic deformation associated with failure.

The process occurs by the initiation and propagation of cracks, and typically the fracture surface is perpendicular to the direction of an applied tensile stress.

FATIGUE

CYCLIC STRESSES

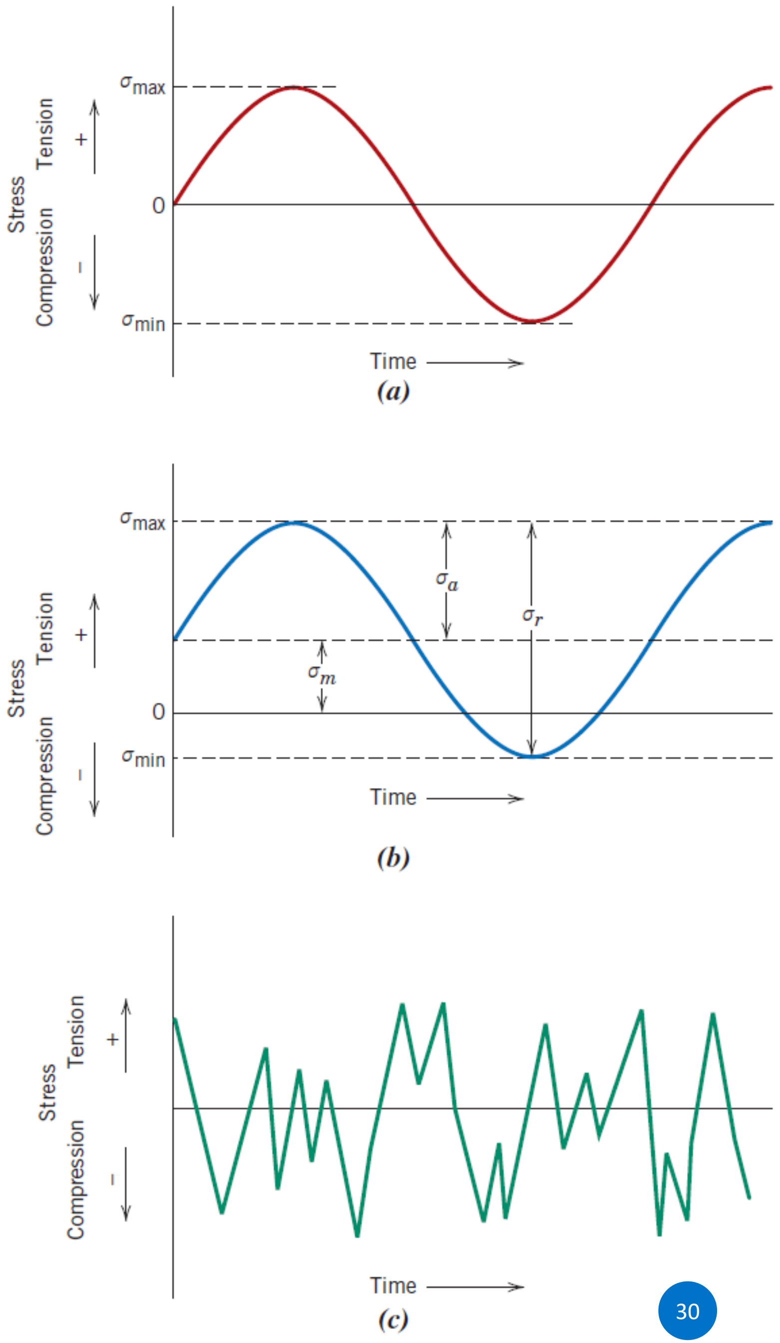
The applied stress may be axial (tension–compression), flexural (bending), or torsional (twisting) in nature.

In general, three different fluctuating stress–time modes are possible. One is represented schematically by a regular and sinusoidal time dependence in Figure *a*, where the amplitude is symmetrical about a mean zero stress level, for example, alternating from a maximum tensile stress (σ_{max}) to a minimum compressive stress (σ_{min}) of equal magnitude; this is referred to as a *reversed stress cycle*.

Another type, termed a *repeated stress cycle*, is illustrated in Figure *b*; the maxima and minima are asymmetrical relative to the zero stress level.

Finally, the stress level may vary randomly in amplitude and frequency, as exemplified in Figure *c*.

Also indicated in Figure *b* are several parameters used to characterize the fluctuating stress cycle.



FATIGUE

The stress amplitude alternates about a *mean stress* σ_m, defined as the average of the maximum and minimum stresses in the cycle, or:

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}$$

The *range of stress* σ_r is the difference between σmax and σmin, namely,

$$\sigma_r = \sigma_{max} - \sigma_{min}$$

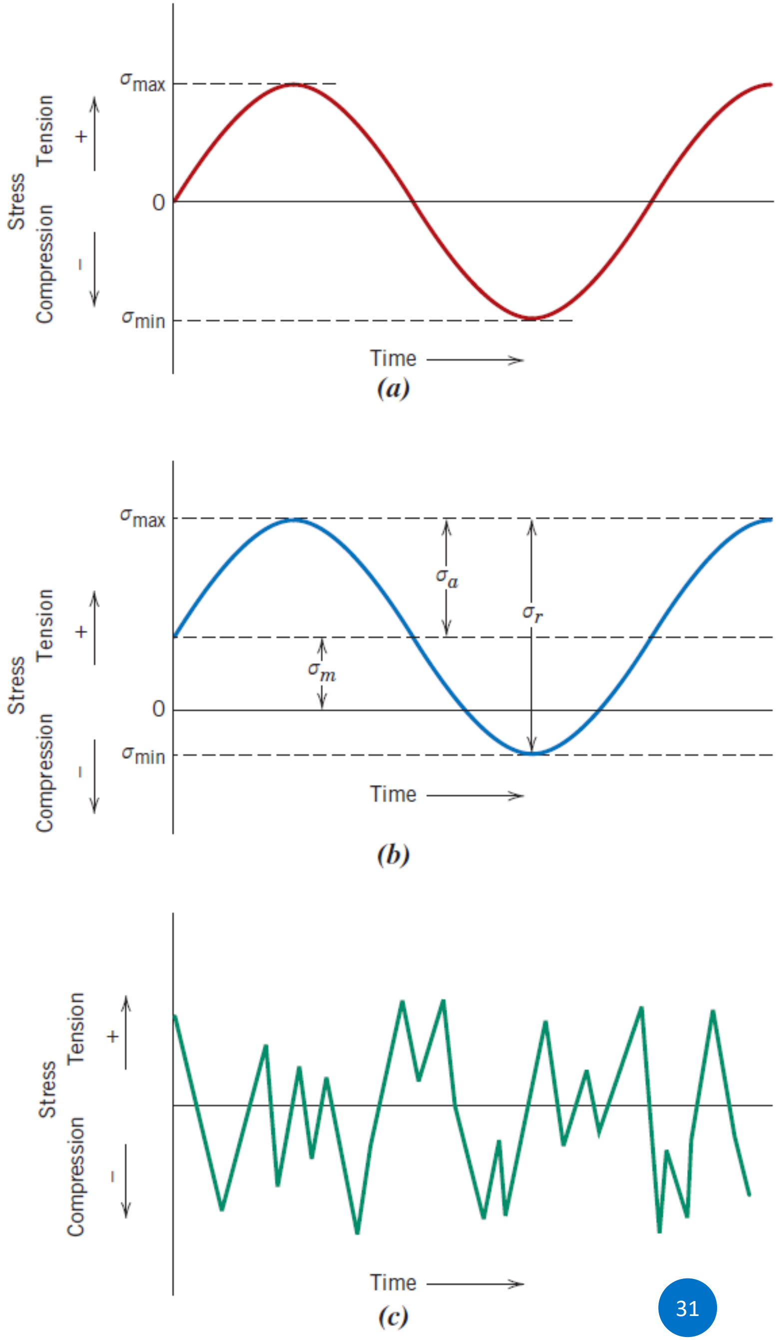
Stress amplitude σ_a is one-half of this range of stress, or

$$\sigma_a = \frac{\sigma_r}{2} = \frac{\sigma_{max} - \sigma_{min}}{2}$$

Finally, the *stress ratio R* is the ratio of minimum and maximum stress amplitudes:

$$R = \frac{\sigma_{min}}{\sigma_{max}}$$

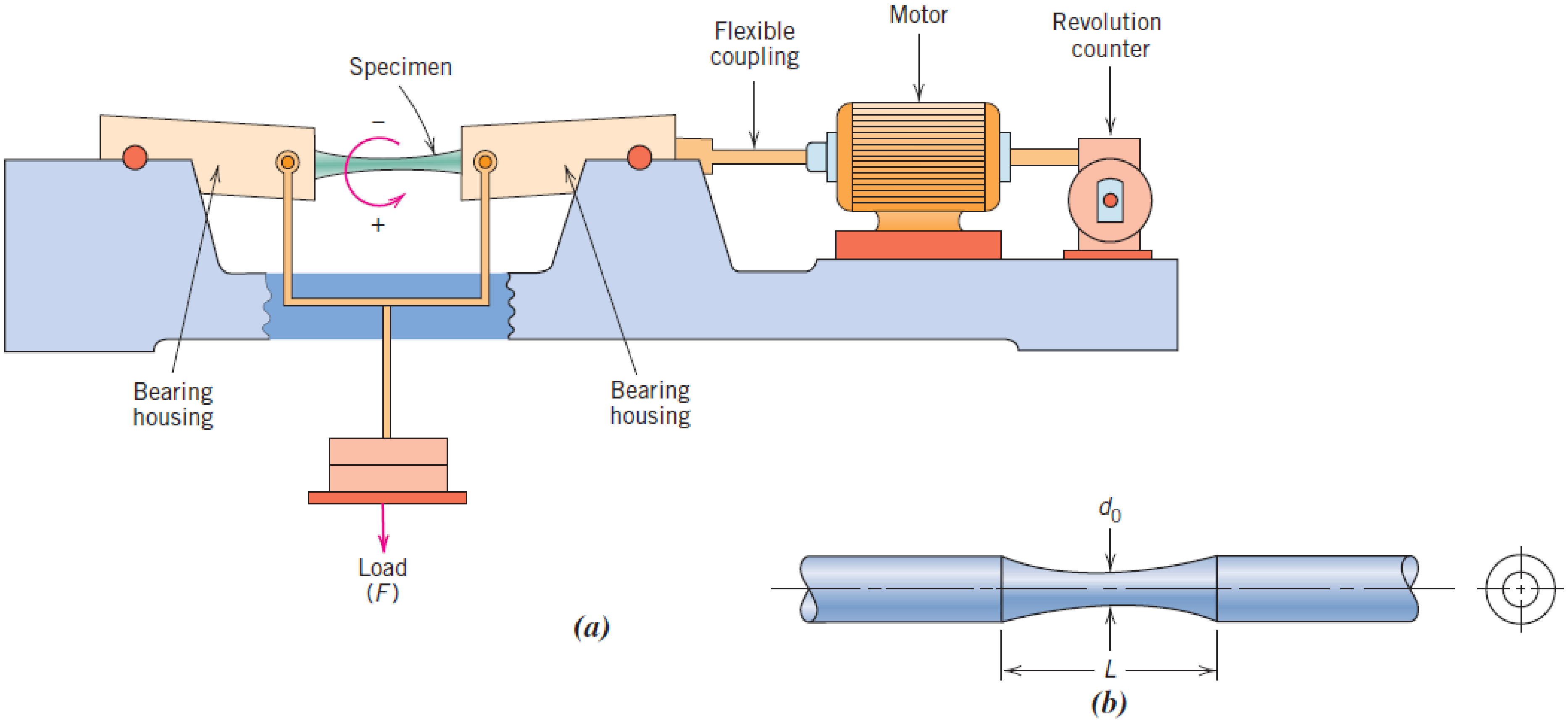
By convention, tensile stresses are positive and compressive stresses are negative. For example, for the reversed stress cycle, the value of *R* is −1.



FATIGUE

THE *S–N* CURVE

As with other mechanical characteristics, the fatigue properties of materials can be determined from laboratory simulation tests.



FATIGUE

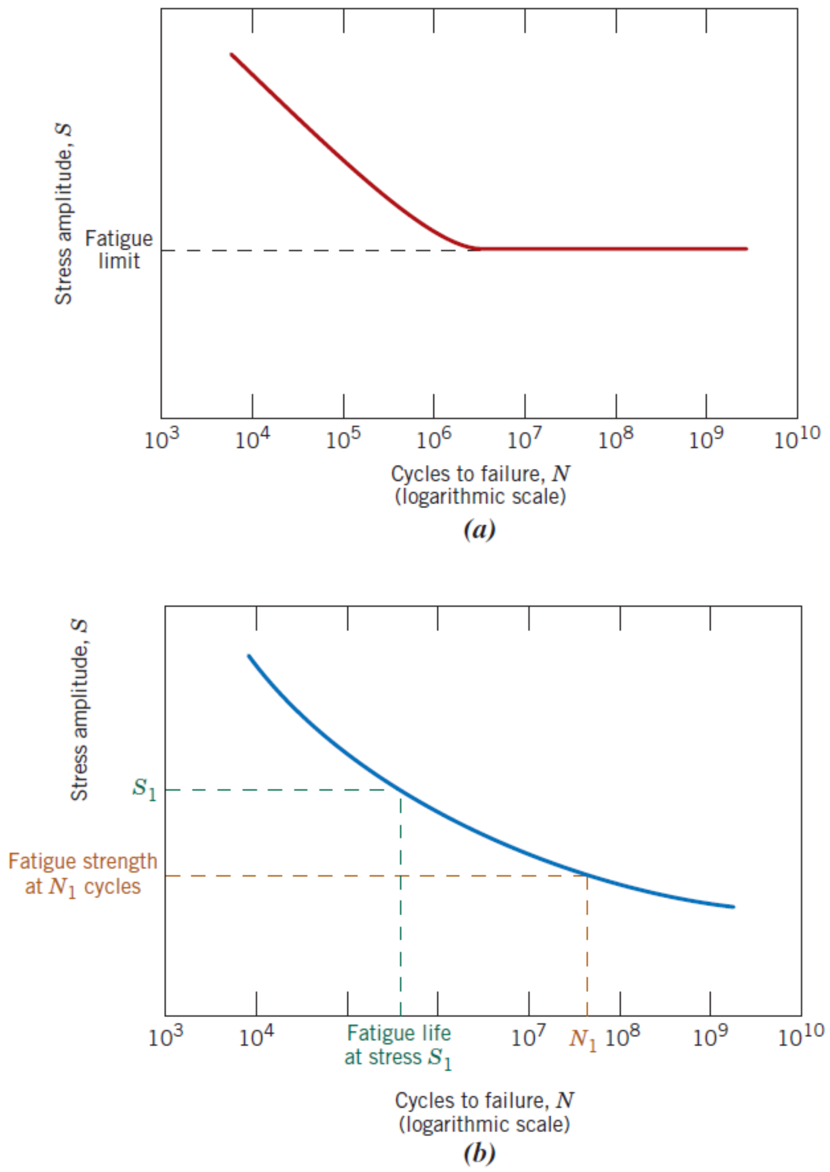
A series of tests is commenced by subjecting a specimen to stress cycling at a relatively large maximum stress (σ_{max}), usually on the order of two-thirds of the static tensile strength; number of cycles to failure is counted and recorded.

This procedure is repeated on other specimens at progressively decreasing maximum stress levels. Data are plotted as stress *S* versus the logarithm of the number *N* of cycles to failure for each of the specimens. The *S* parameter is normally taken as either maximum stress (σ_{max}) or stress amplitude (σ_a).

Two distinct types of *S*–*N* behaviour are observed and are represented schematically in.

As these plots indicate, the higher the magnitude of the stress, the smaller the number of cycles the material is capable of sustaining before failure.

For some ferrous (iron-base) and titanium alloys, the *S*–*N* curve (Figure *a*) becomes horizontal at higher *N* values; there is a limiting stress level, called the **fatigue limit** (also sometimes called the *endurance limit*), below which fatigue failure will not occur. This fatigue limit represents the largest value of fluctuating stress that will *not* cause failure for essentially an infinite number of cycles. For many steels, fatigue limits range between 35% and 60% of the tensile strength.

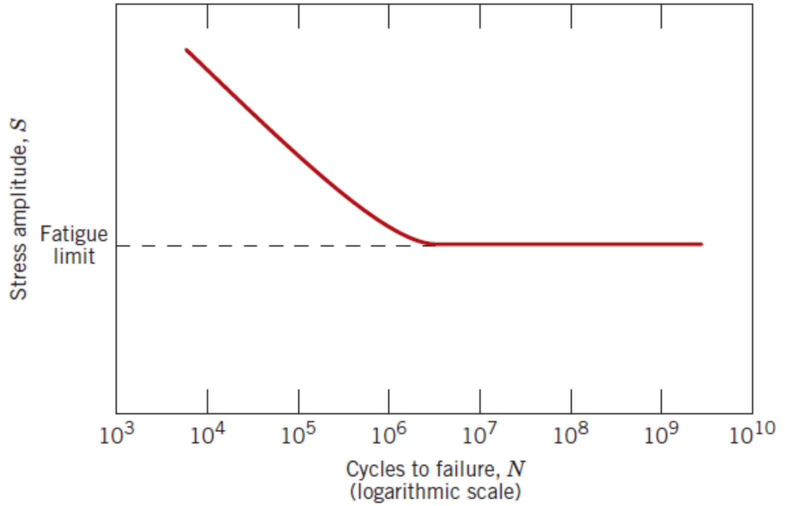


FATIGUE

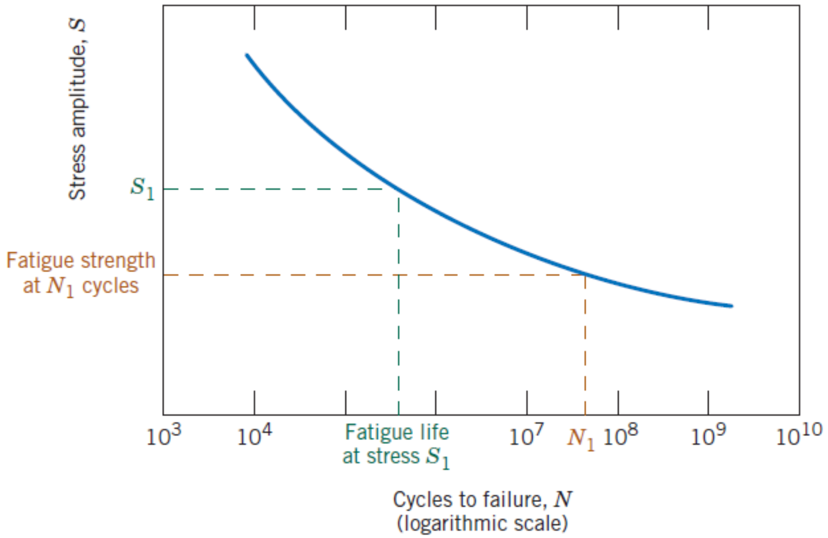
Most nonferrous alloys (e.g., aluminium, copper) do not have a fatigue limit, in that the *S*–*N* curve continues its downward trend at increasingly greater *N* values (Figure *b*).

Thus, fatigue ultimately occurs regardless of the magnitude of the stress. For these materials, the fatigue response is specified as **fatigue strength,** which is defined as the stress level at which failure will occur for some specified number of cycles (e.g., 10^7 cycles).

Another important parameter that characterizes a material's fatigue behaviour is **fatigue life** N_f. It is the number of cycles to cause failure at a specified stress level, as taken from the *S*–*N* plot (Figure *b*)



(a)

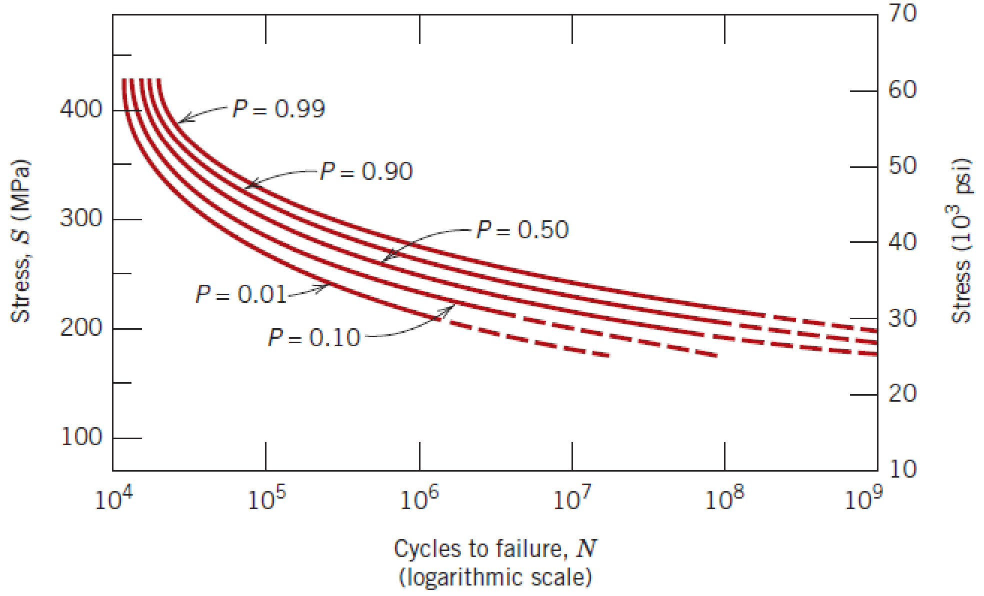


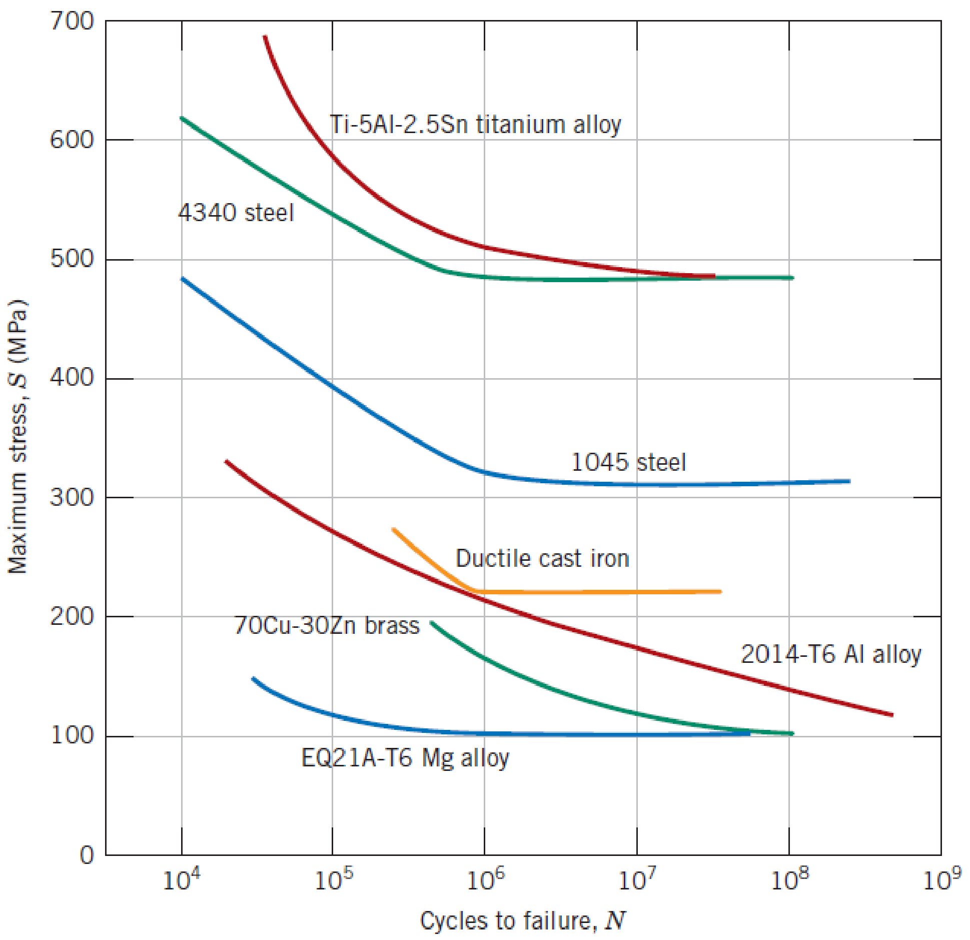
(b)

FATIGUE

Fatigue *S–N* curves shown represent "best-fit" curves that have been drawn through average-value data points. It is a little unsettling to realize that approximately one-half of the specimens tested actually failed at stress levels lying nearly 25% below the curve (as determined on the basis of statistical treatments).

Several statistical techniques have been developed to specify fatigue life and fatigue limit in terms of probabilities. One convenient way of representing data treated in this manner is with a series of constant probability curves, several of which are plotted below. The *P* value associated with each curve represents the probability of failure.

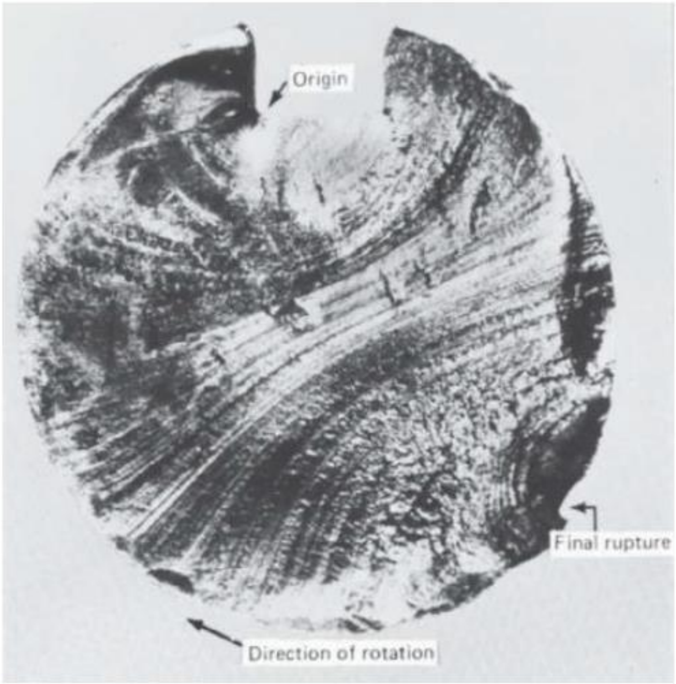


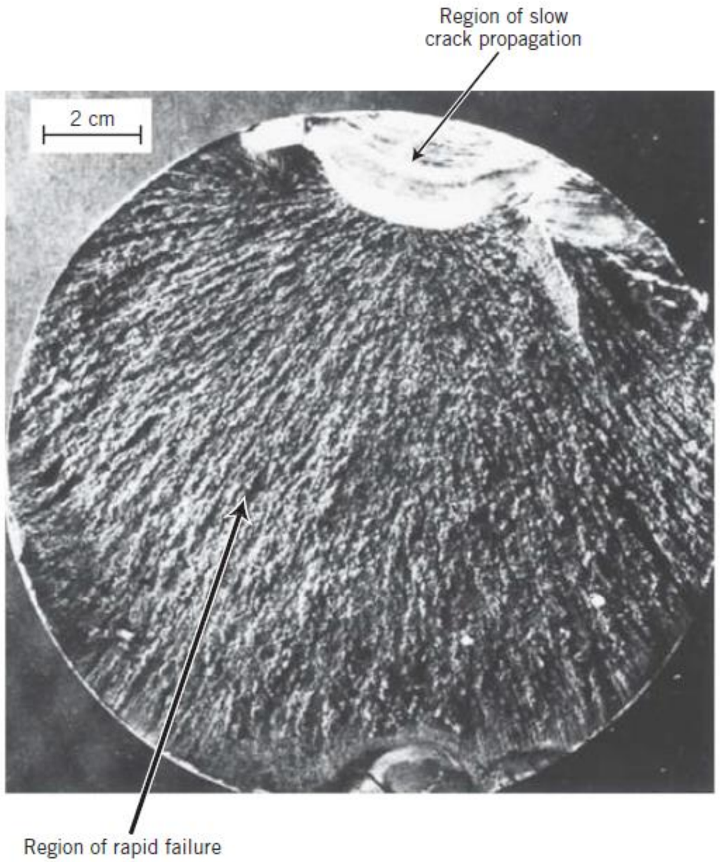


For example, at a stress of 200 MPa (30,000 psi), we would expect 1% of the specimens to fail at about 10^6 cycles, 50% to fail at about 2×10^7 cycles.

FATIGUE

CRACK INITIATION AND PROPAGATION

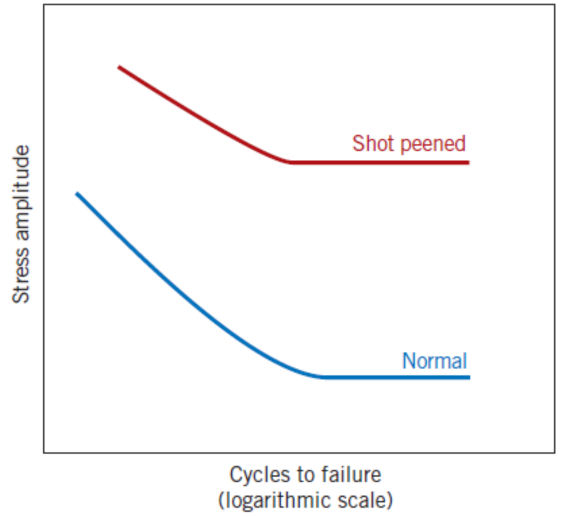


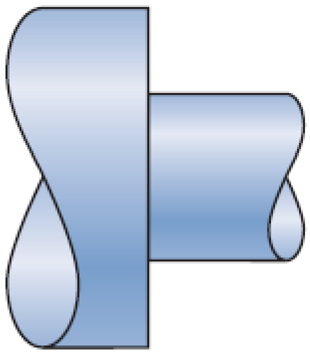


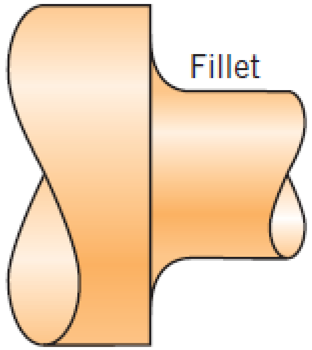
(1) crack initiation, in which a small crack forms at some point of high stress concentration;
(2) crack propagation, during which this crack advances incrementally with each stress cycle; and
(3) final failure, which occurs very rapidly once the advancing crack has reached a critical size.

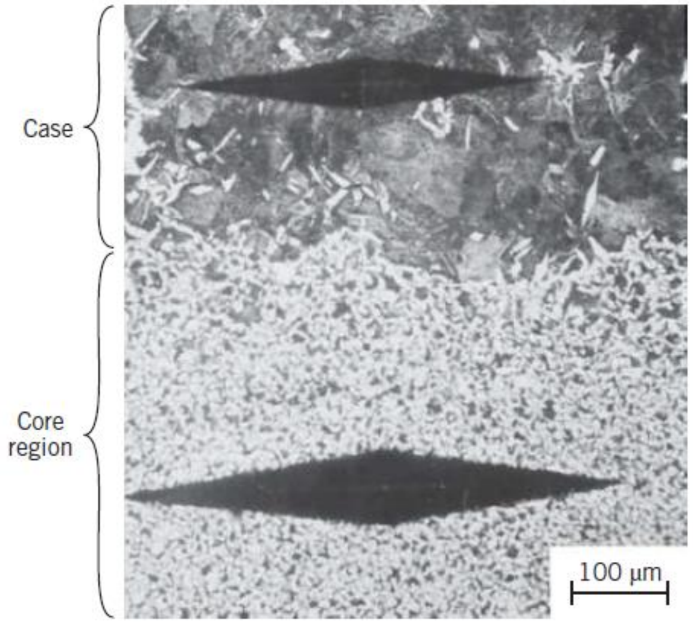
FATIGUE

WHAT ARE THE FACTORS THAT AFFECT FATIGUE LIFE









CREEP

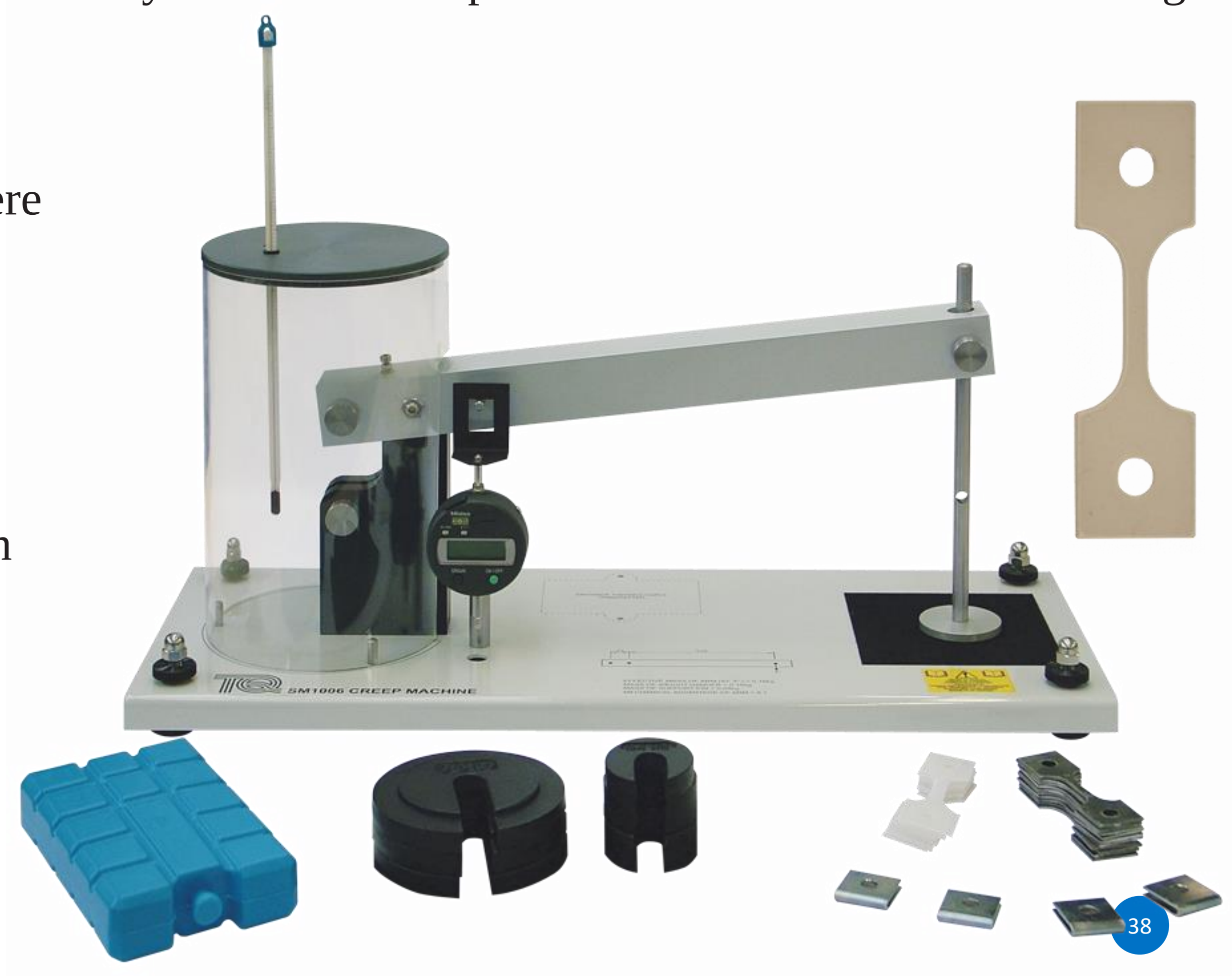
Materials are often placed in service at elevated temperatures and exposed to static mechanical stresses (e.g., turbine rotors in jet engines and steam generators that experience centrifugal stresses; high-pressure steam lines).

Deformation under such circumstances is termed **creep.** Defined as the time-dependent and permanent deformation of materials when subjected to a constant load or stress, creep is normally an undesirable phenomenon and is often the limiting factor in the lifetime of a part.

It is observed in all materials types; for metals, it becomes important only for temperatures greater than about $0.4T_m$, where T_m is the absolute melting temperature.

Amorphous polymers, which include plastics and rubbers, are especially sensitive to creep deformation.

Several theoretical mechanisms have been proposed to explain the creep behaviour for various materials; these mechanisms involve stress-induced vacancy diffusion, grain boundary diffusion, dislocation motion, and grain boundary sliding.



CREEP

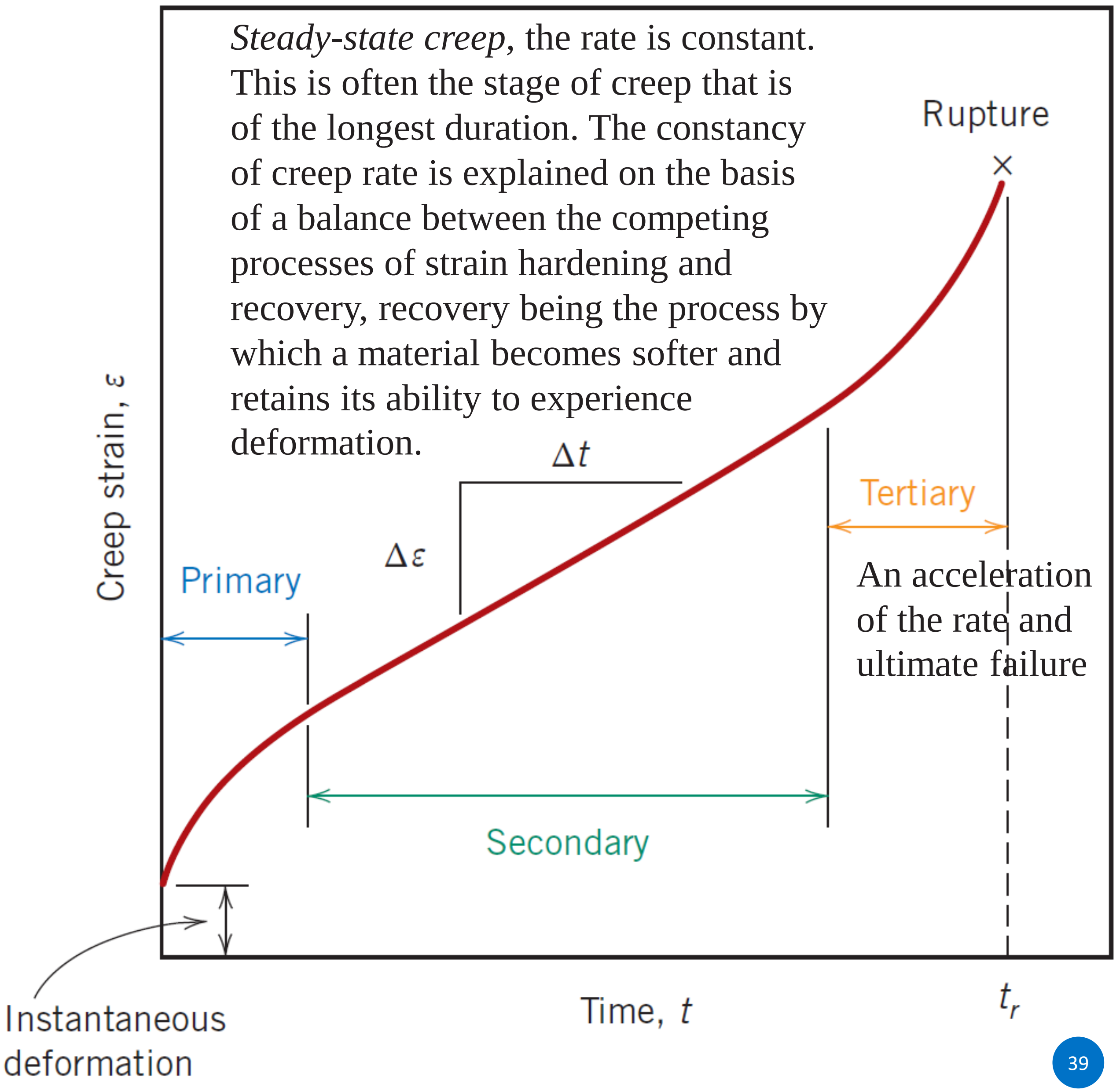
A typical creep test consists of subjecting a specimen to a constant load or stress while maintaining the temperature constant; deformation or strain is measured and plotted as a function of elapsed time.

continuously decreasing creep rate: the material is experiencing an increase in creep resistance or strain hardening: deformation becomes more difficult as the material is strained.

Steady-state creep, the rate is constant. This is often the stage of creep that is of the longest duration. The constancy of creep rate is explained on the basis of a balance between the competing processes of strain hardening and recovery, recovery being the process by which a material becomes softer and retains its ability to experience deformation.

An acceleration of the rate and ultimate failure

Upon application of the load, there is an instantaneous deformation, that is totally elastic.



CREEP

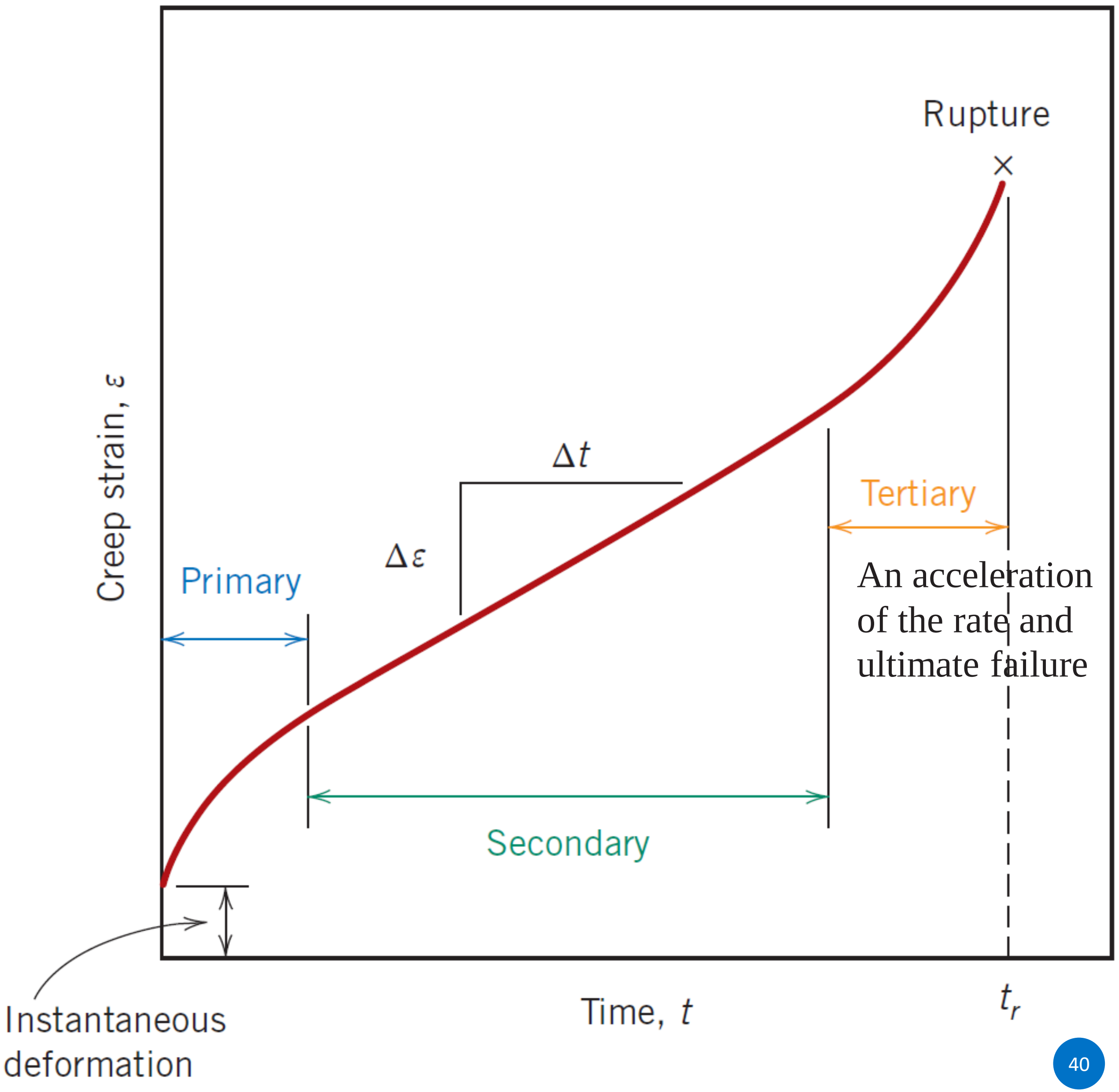
Creep failure is frequently termed *rupture* and results from microstructural and/or metallurgical changes—for example, grain boundary separation, and the formation of internal cracks, cavities, and voids.

Also, for tensile loads, a neck may form at some point within the deformation region.

These all lead to a decrease in the effective cross-sectional area and an increase in strain rate.

Possibly the most important parameter from a creep test is the slope of the secondary portion of the creep curve ($\Delta\varepsilon/\Delta t$); this is often called the minimum or *steady-state creep rate* $\dot{\varepsilon}_s$.

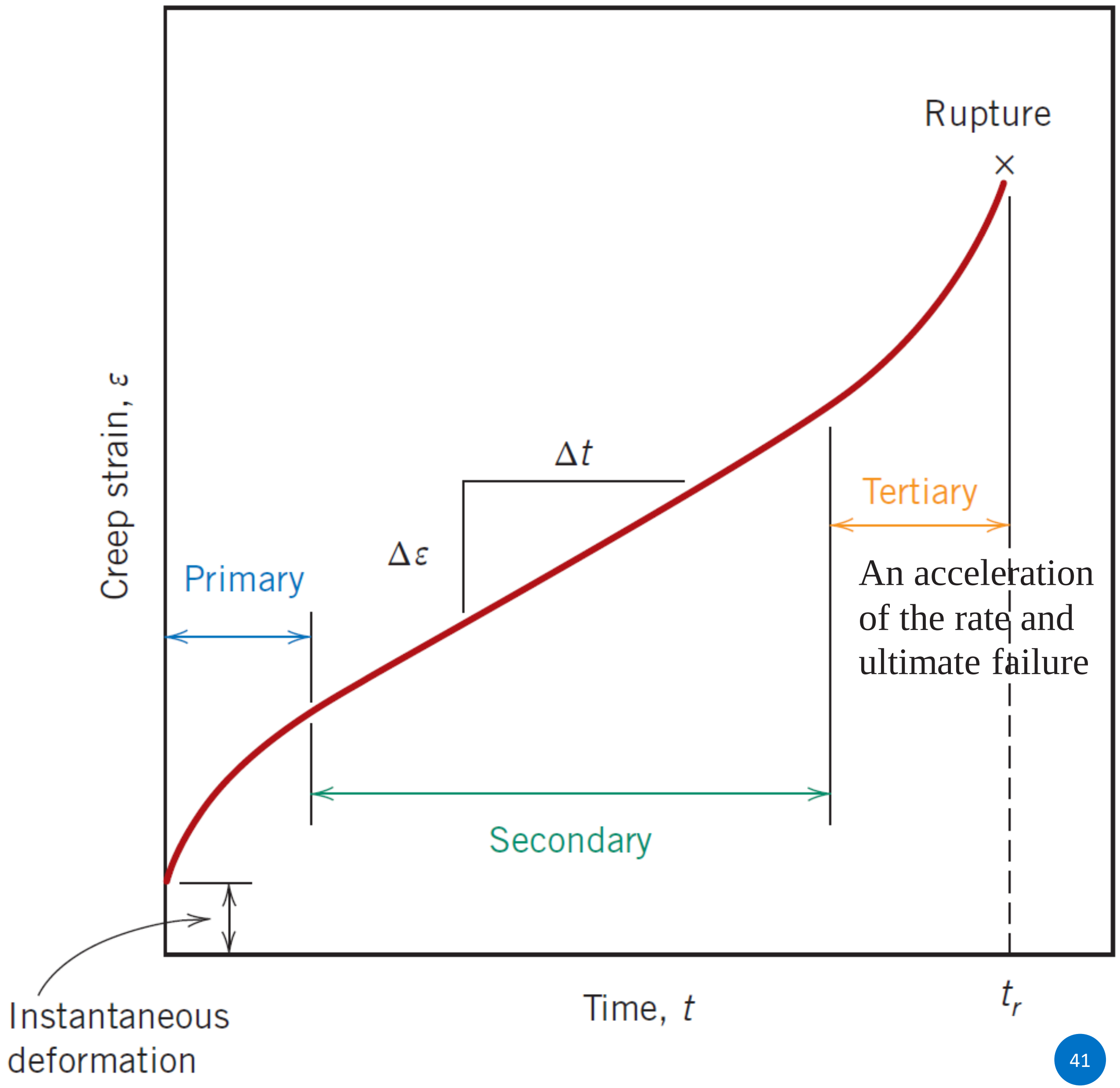
It is the engineering design parameter that is considered for long-life applications, such as a nuclear power plant component that is scheduled to operate for several decades, and when failure or too much strain is not an option.



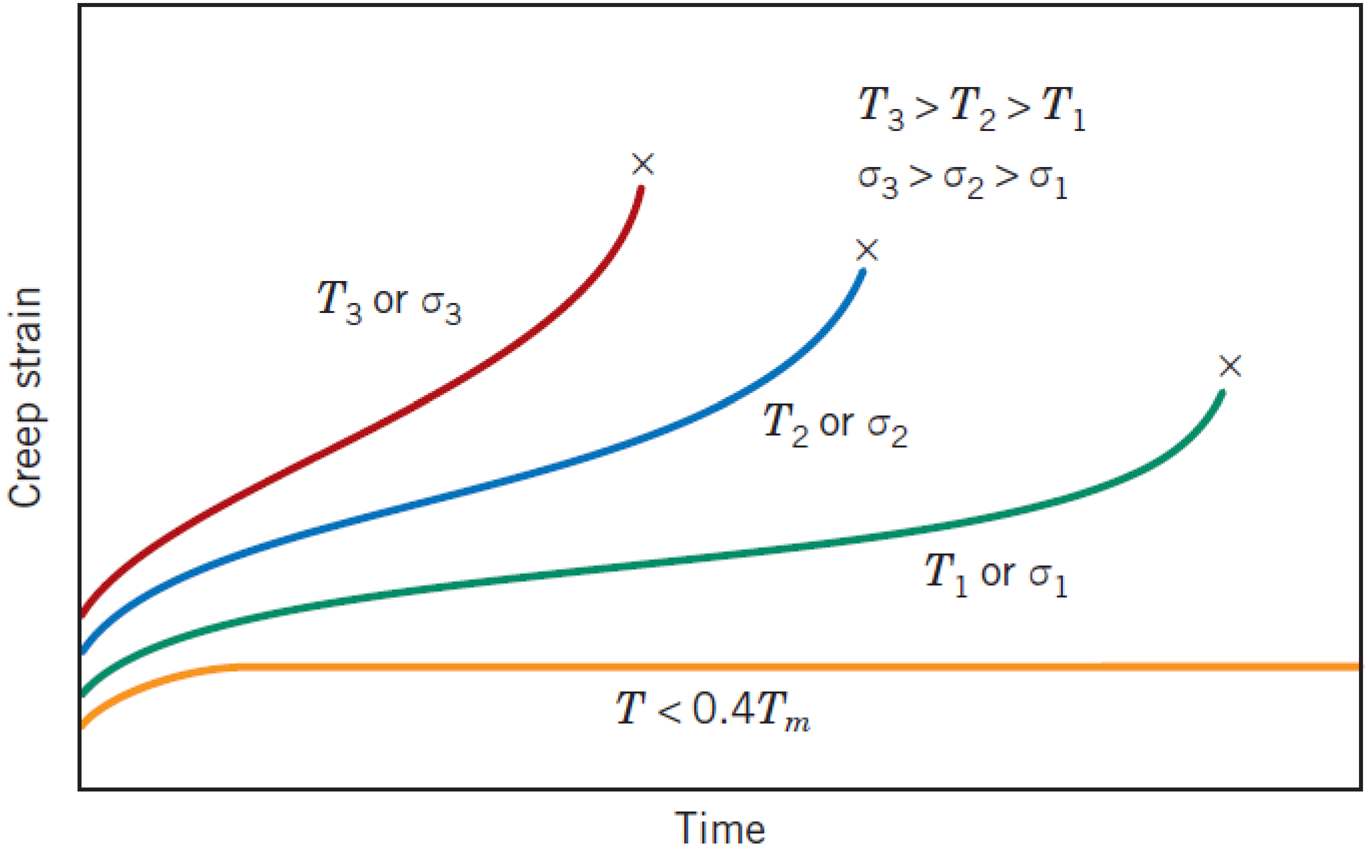
CREEP

For many relatively short-life creep situations (e.g., turbine blades in military aircraft and rocket motor nozzles), *time to rupture*, or the *rupture lifetime* t_r, is the dominant design consideration.

Thus, knowledge of these creep characteristics of a material allows the design engineer to ascertain its suitability for a specific application.



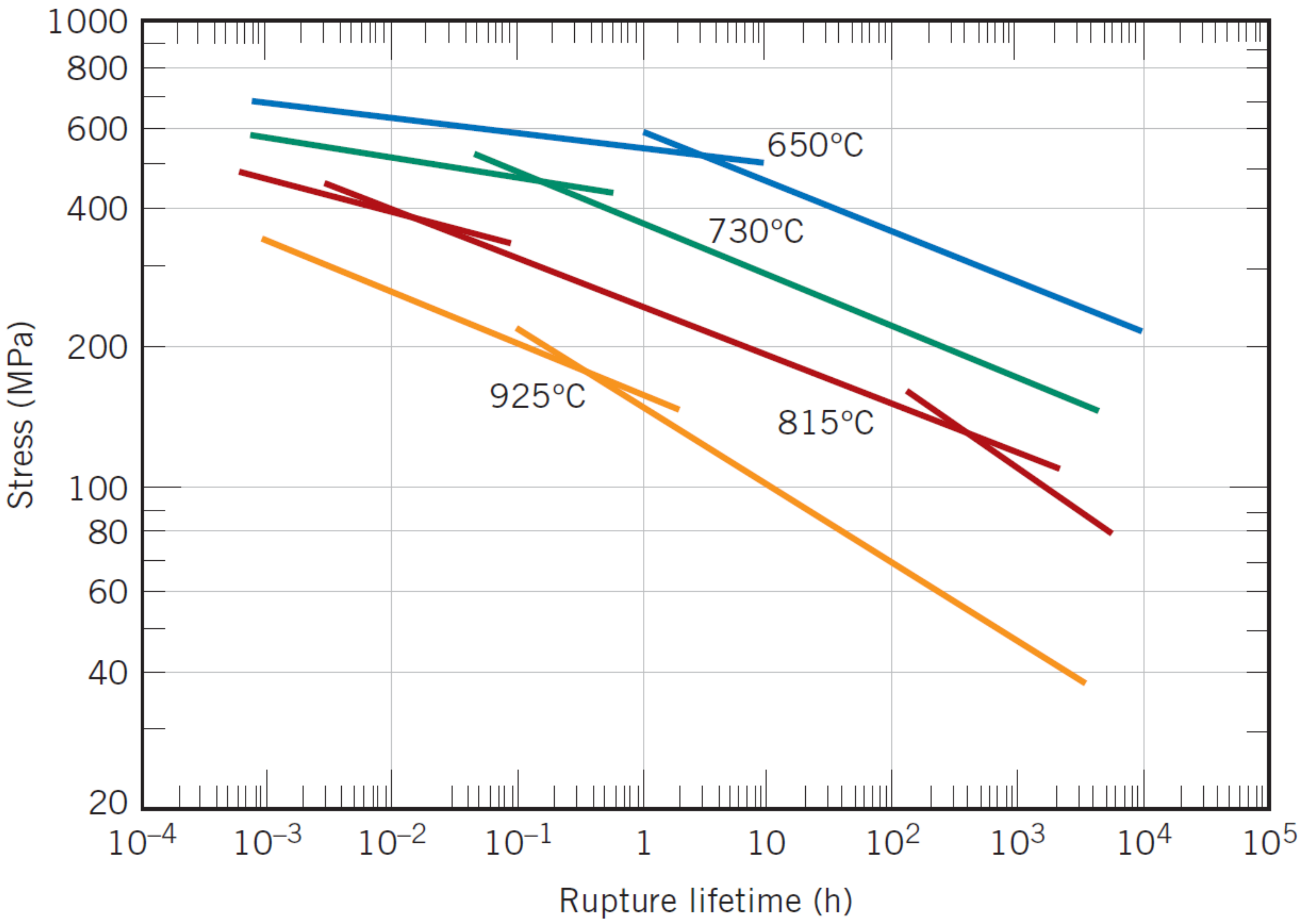
CREEP



Influence of stress σ and temperature T on creep behaviour.

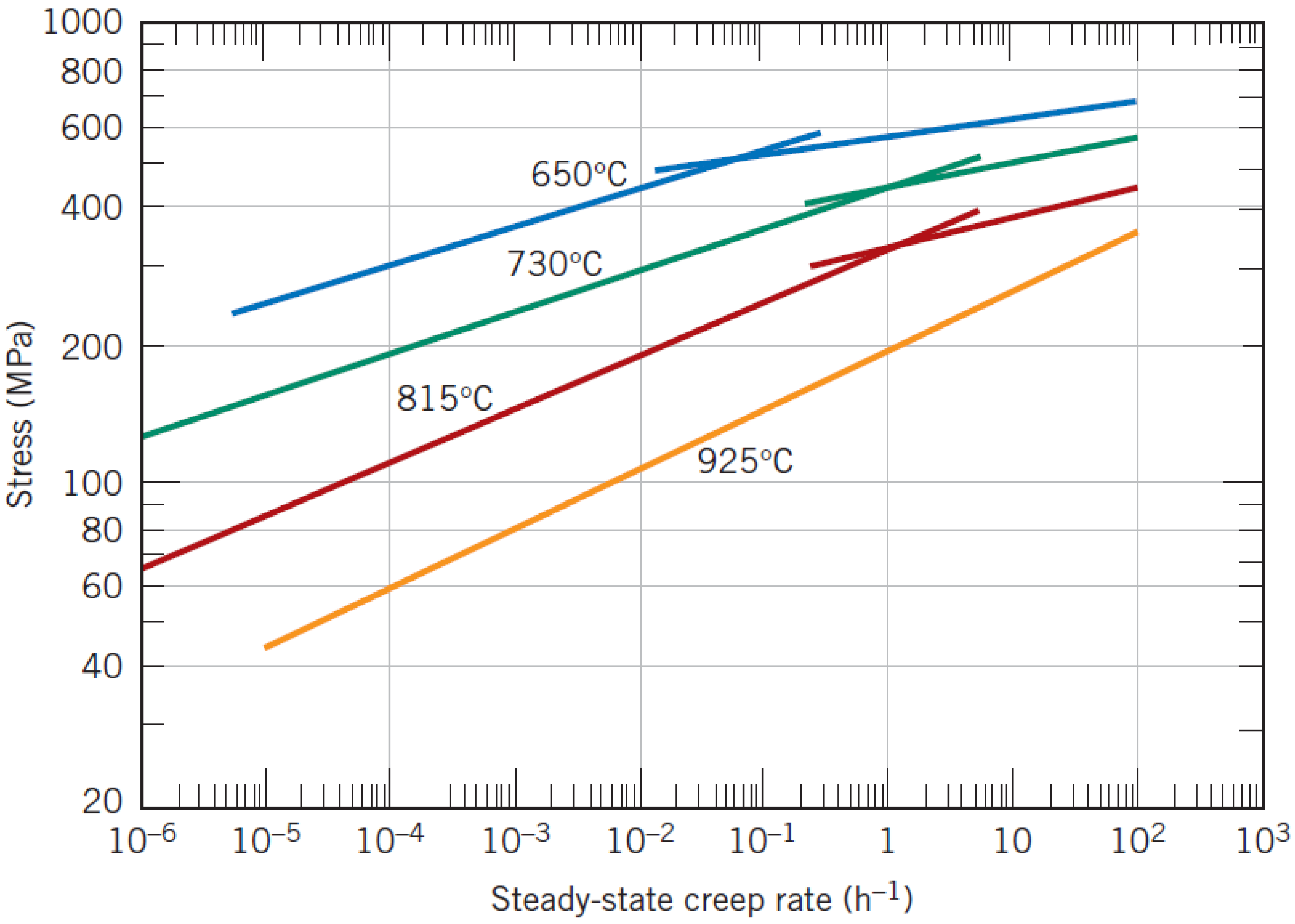
$$\dot{\varepsilon}_s = K_1 \sigma^n$$

CREEP



1000
800
600
400
200
100
80
60
40
20
Stress (MPa)
650°C
730°C
815°C
925°C
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
10^{5}
Rupture lifetime (h)

CREEP



$$\dot{\varepsilon}_s = K_2 \sigma^n \exp\left(-\frac{Q_c}{RT}\right)$$

K_2 and Q_c are constants; Q_c is the *activation energy for creep;* also R is the gas constant, 8.31 J·mol/K.

CREEP

The need often arises for engineering creep data that are impractical to collect from normal laboratory tests.

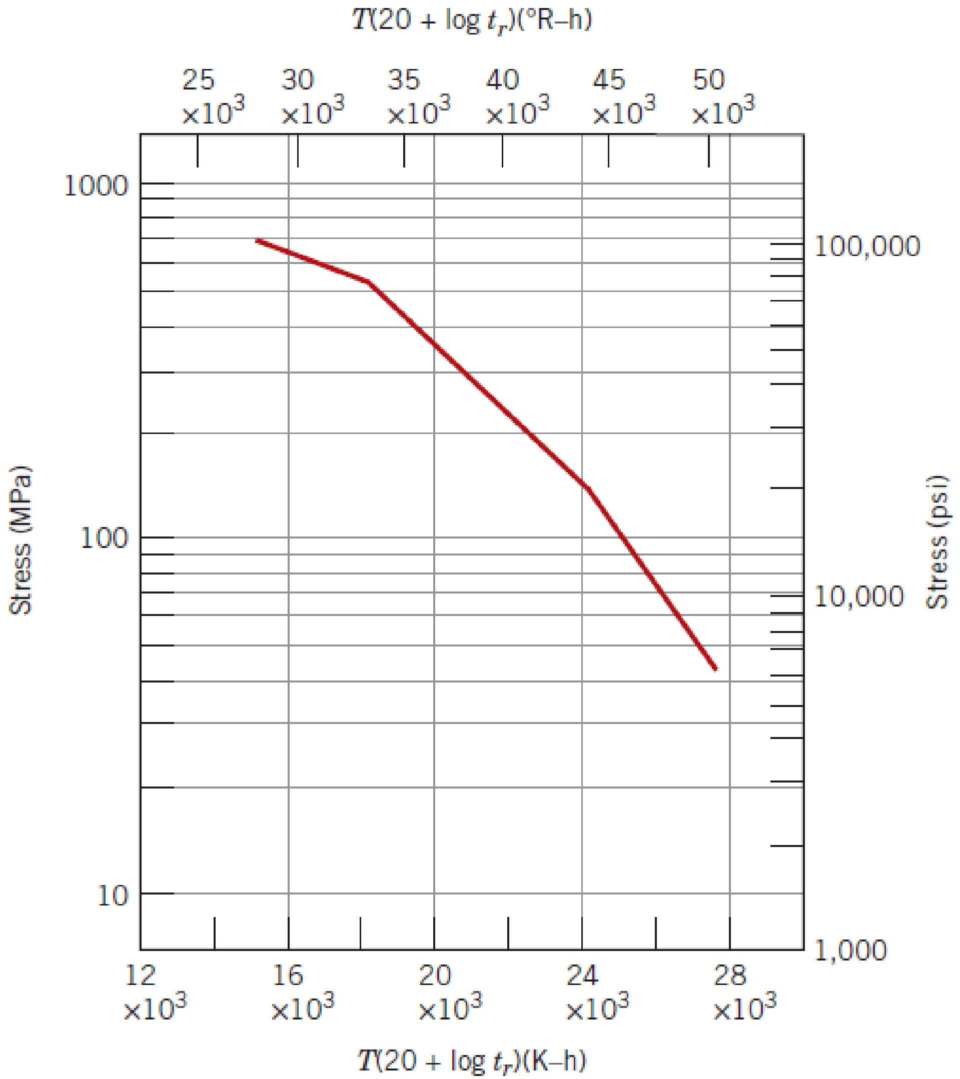
This is especially true for prolonged exposures (on the order of years).

One solution to this problem involves performing creep and/or creep rupture tests at temperatures in excess of those required, for shorter time periods, and at a comparable stress level, and then making a suitable extrapolation to the in-service condition.

A commonly used extrapolation procedure employs the Larson–Miller parameter, m, defined as: $m = T(C + \log t_r)$.

Where C is a constant (usually on the order of 20), for T in Kelvin and the rupture lifetime t_r in hours.

The rupture lifetime of a given material measured at some specific stress level varies with temperature such that this parameter remains constant.



Logarithm of stress versus the Larson–Miller parameter for an S-590 alloy.

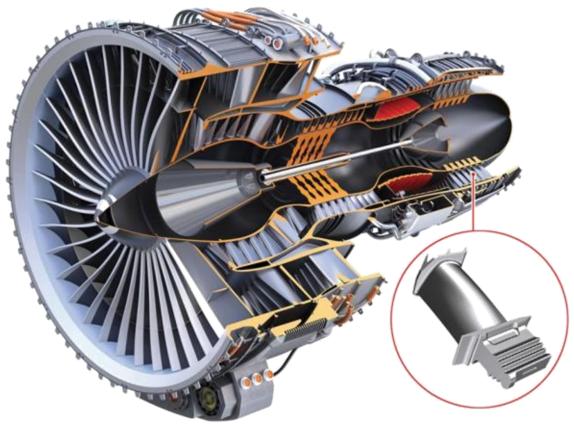
CREEP

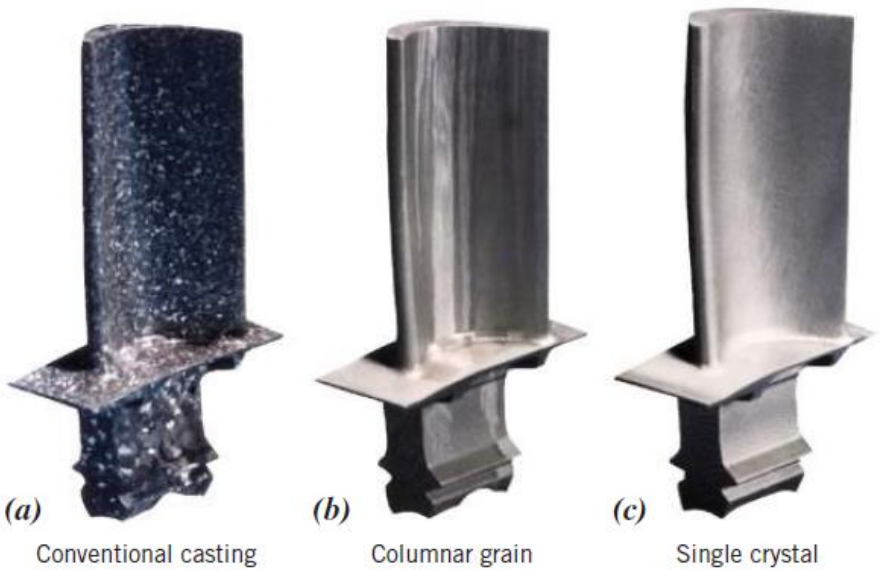
Several factors affect the creep characteristics of metals. These include melting temperature, elastic modulus, and grain size.

In general, the higher the melting temperature, the greater the elastic modulus, the larger the grain size, the better a material's resistance to creep.

Relative to grain size, smaller grains permit more grain boundary sliding, which results in higher creep rates.

This effect may be contrasted to the influence of grain size on the mechanical behaviour at low temperatures [i.e., increase in both strength and toughness.





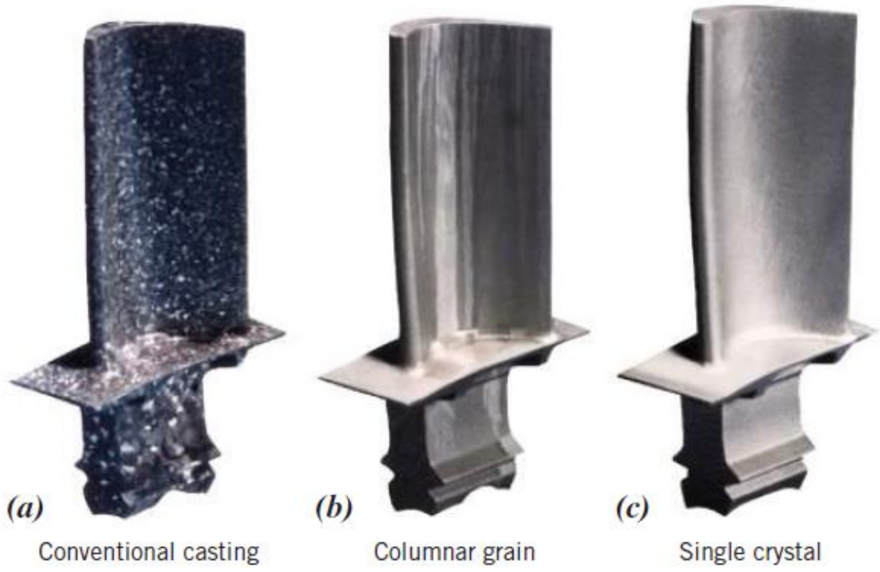
(*a*) Polycrystalline turbine blade that was produced by a conventional casting technique. High-temperature creep resistance is improved as a result of an oriented columnar grain structure (*b*) produced by a sophisticated directional solidification technique. Creep resistance is further enhanced when single-crystal blades (*c*) are used.

CREEP

Stainless steels and the superalloys are especially resilient to creep and are commonly employed in high-temperature service applications.

The creep resistance of the superalloys is enhanced by solid-solution alloying and also by the formation of precipitate phases. In addition, advanced processing techniques have been utilized; one such technique is directional solidification, which produces either highly elongated grains or single-crystal components.

(*a*) Polycrystalline turbine blade that was produced by a conventional casting technique. High-temperature creep resistance is improved as a result of an oriented columnar grain structure (*b*) produced by a sophisticated directional solidification technique. Creep resistance is further enhanced when single-crystal blades (*c*) are used.



HOMEWORK

In aviation, failure due to fatigue and creep is closely studied and investigated. Identify the components of an aircraft where fatigue and creep failure can occur. Be as thorough as possible. Discuss your work and findings.