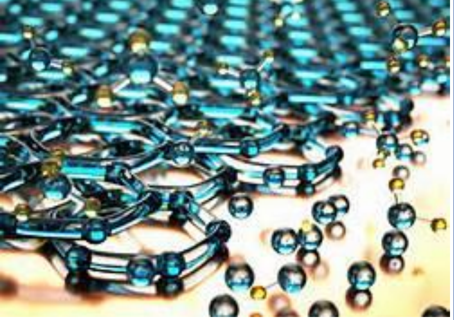


Materials Science

Lecture 18

Lebanese University - Faculty of Engineering – Branch 3

Fall 2022

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Contents

Lecture 18:

Chap6: Failure

6.5. Principles of Fracture Mechanics

Design Using Fracture Mechanics

- According to the previous equations (K_c and K_{Ic}), **three** variables must be **considered** relative to the possibility for fracture of some structural component—namely, the 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** (Equations of K_c *and* K_{Ic}).

6.5. Principles of Fracture Mechanics

Design Using Fracture Mechanics

- 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:

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

- 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:

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

6.5. Principles of Fracture Mechanics

Design Using Fracture Mechanics

- A **number of nondestructive 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**.

- One important example of the use of **NDT** is for the detection of cracks and leaks in the walls of **oil pipelines** in remote areas such as **Alaska**. **Ultrasonic** analysis is utilized in conjunction with a "**robotic analyzer**" that can travel relatively long distances within a pipeline.

6.5. Principles of Fracture Mechanics

Design Using Fracture Mechanics

- Several commonly employed NDT techniques and their characteristics are listed in the next table:

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

A List of Several Common Nondestructive Testing Techniques

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Chap6: Failure

6.6. Fracture Toughness Testing

- A number of **different standardized tests** have been devised to measure the **fracture toughness values** for structural materials.

- In the **United States**, these standard test methods are developed by the **ASTM** (American Society for Testing and Materials).

- **Procedures** and **specimen configurations** for most tests are relatively **complicated**, and we will not attempt to provide detailed explanations. In brief, for each test type, the specimen (of specified geometry and size) **contains** a **preexisting defect**, usually a **sharp crack** that has been introduced.

- The test **apparatus** loads the specimen at a **specified rate**, and also **measures load** and **crack displacement** values.

- **Data** are subjected to **analyses** to ensure that they meet established **criteria** before the **fracture toughness** values are deemed **acceptable**.

- **Most tests** are for **metals**, but some have also been developed for **ceramics**, **polymers**, and **composites**.

6.6. Fracture Toughness Testing

Impact Testing Techniques

- **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** behavior.

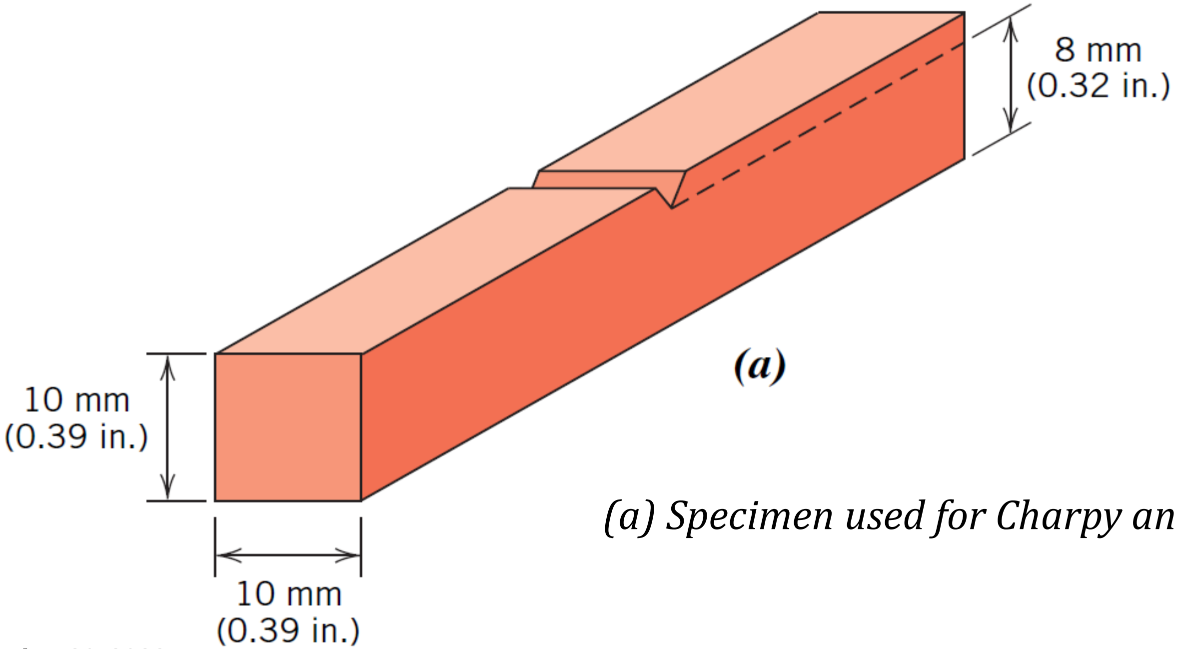
- **For example**, under some circumstances, **normally ductile metals** fracture **abruptly** and with **very little plastic deformation** under **high loading rates**.

- **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).

6.6. Fracture Toughness Testing

Impact Testing Techniques

- Two standardized tests, the **Charpy** and the **Izod**, are used to measure the **impact energy** (sometimes also termed **notch toughness**).
- The **Charpy V-notch (CVN)** technique is most **commonly** used in the **United States**.
- For both the **Charpy** and the **Izod**, the **specimen** is in the shape of a **bar** of **square** cross section, into which a **V-notch** is machined (Figure (a)).



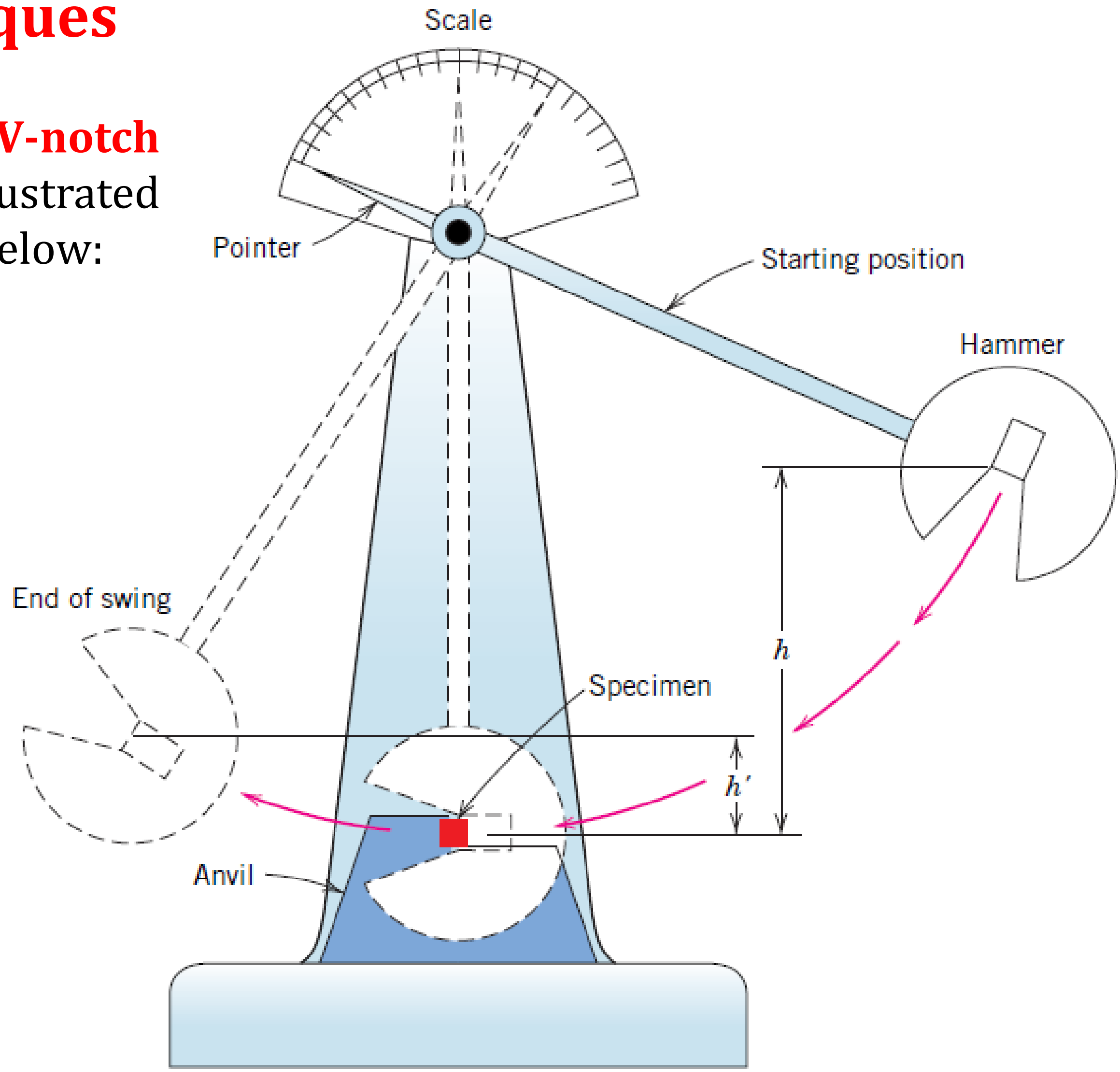
(a) Specimen used for Charpy and Izod impact tests.

6.6. Fracture Toughness Testing

Impact Testing Techniques

- The **apparatus** for making **V-notch impact tests** is illustrated schematically in the Figure below:

(b) A schematic drawing of an impact testing apparatus. The hammer is released from fixed height h and strikes the specimen; the energy expended in fracture is reflected in the difference between h and the swing height h'.

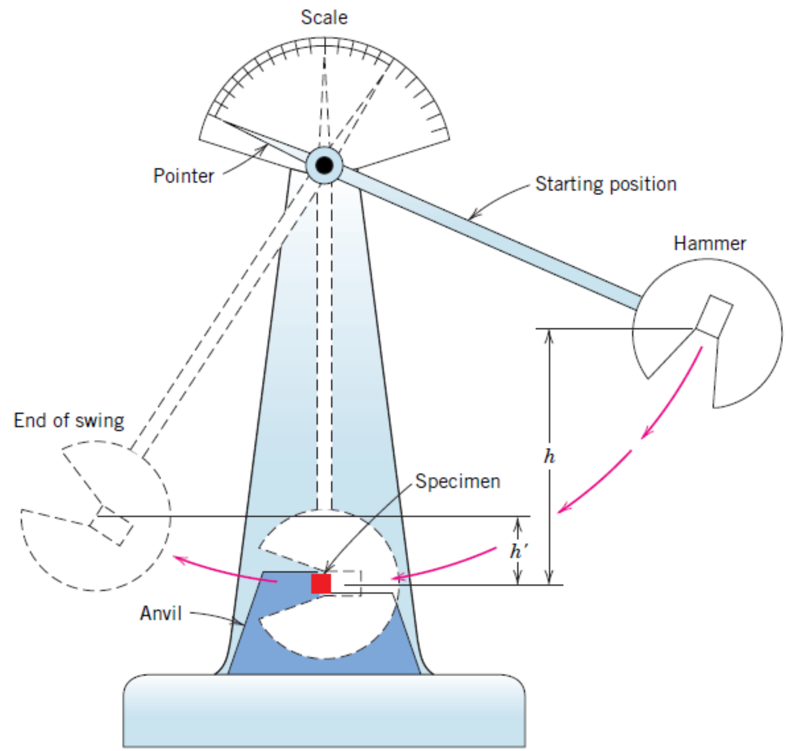


(b)

6.6. Fracture Toughness Testing

Impact Testing Techniques

- The **load** is applied as an **impact blow** from a weighted **pendulum hammer** released from a cocked position at a fixed height ***h***.
- The **specimen** is positioned at the **base**. Upon release, a **knife edge** mounted **on the pendulum strikes** and **fractures** the **specimen** at the **notch**, which acts as a point of stress concentration for this high-velocity impact blow.
- The **pendulum continues** its swing, rising to a **maximum height *h'***, which is **lower than *h***.
- The **energy absorption**, computed from the **difference** between ***h*** and ***h'***, is a measure of the **impact energy**.

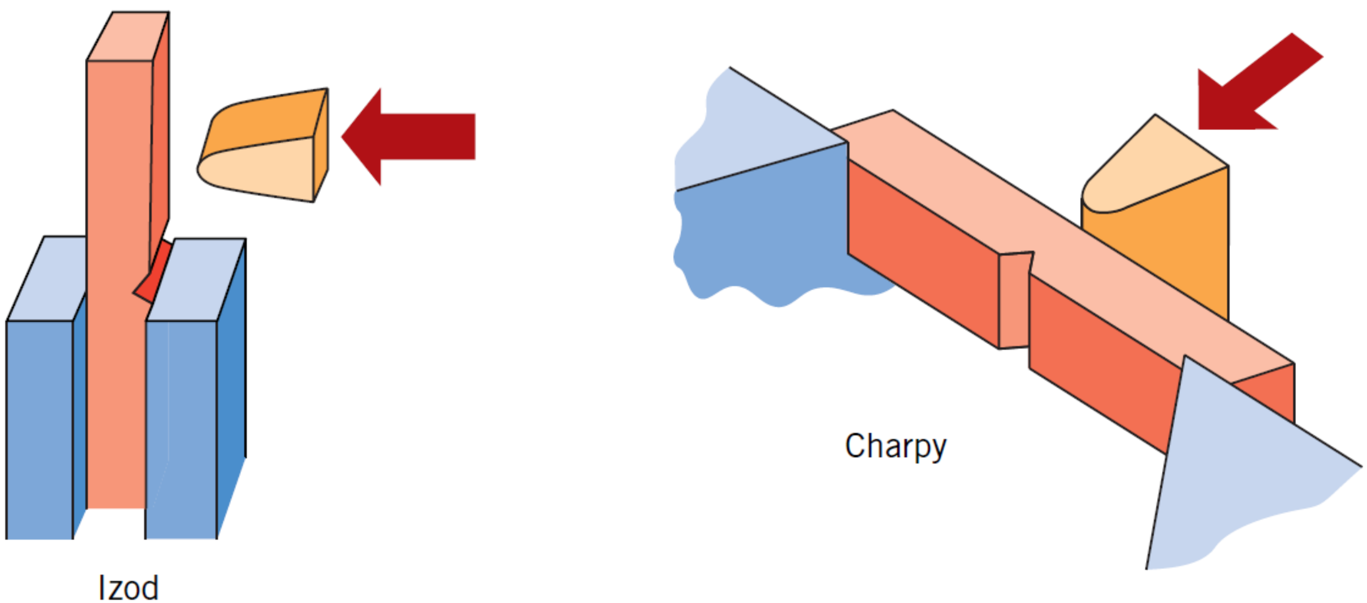


(b)

6.6. Fracture Toughness Testing

Impact Testing Techniques

- The **primary difference** between the **Charpy** and the **Izod** techniques lies in the **manner** of **specimen support** (Figure).
- These are termed **impact tests** because of the manner of **load application**.
- Several **variables**, including specimen **size** and **shape** as well as **notch configuration** and **depth**, **influence** the test **results**.



Specimen placements for both the Charpy and the Izod tests are also shown.

6.6. Fracture Toughness Testing

Impact Testing Techniques

- **Both** **plane strain fracture toughness** and these **impact tests** have been used to determine the **fracture properties** of materials.
- The former are **quantitative** in **nature**, in that a specific property of the material is determined (i.e., K_{Ic}).
- The results of the **impact tests**, however, are more **qualitative** and are of **little use for design** purposes.
- **Impact energies** are of interest **mainly** in a **relative** sense and for making **comparisons**—**absolute values are of little significance**.
- **Attempts** have been made to **correlate** **plane strain fracture toughnesses** and **CVN** energies, with only **limited success**.
- **Plane strain fracture toughness** tests are not as simple to perform as impact tests; furthermore, **equipment** and **specimens** are **more expensive**.

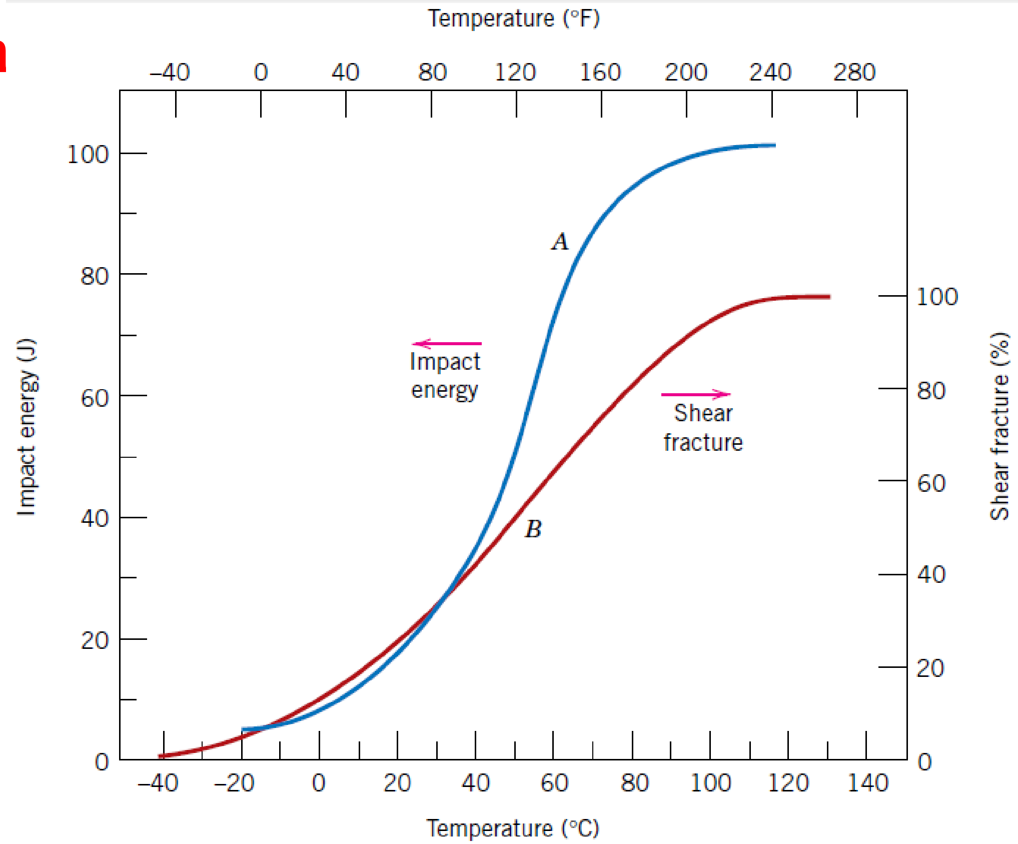
6.6. Fracture Toughness Testing

Ductile-to-Brittle Transition

- One of the primary functions of the **<u>Charpy and the Izod tests</u>** 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**.

- Widely used **steels** can exhibit this **ductile-to-brittle transition** with disastrous **consequences**.

- The ductile-to-brittle transition is **related** to the **temperature dependence** of the **measured impact energy absorption**.

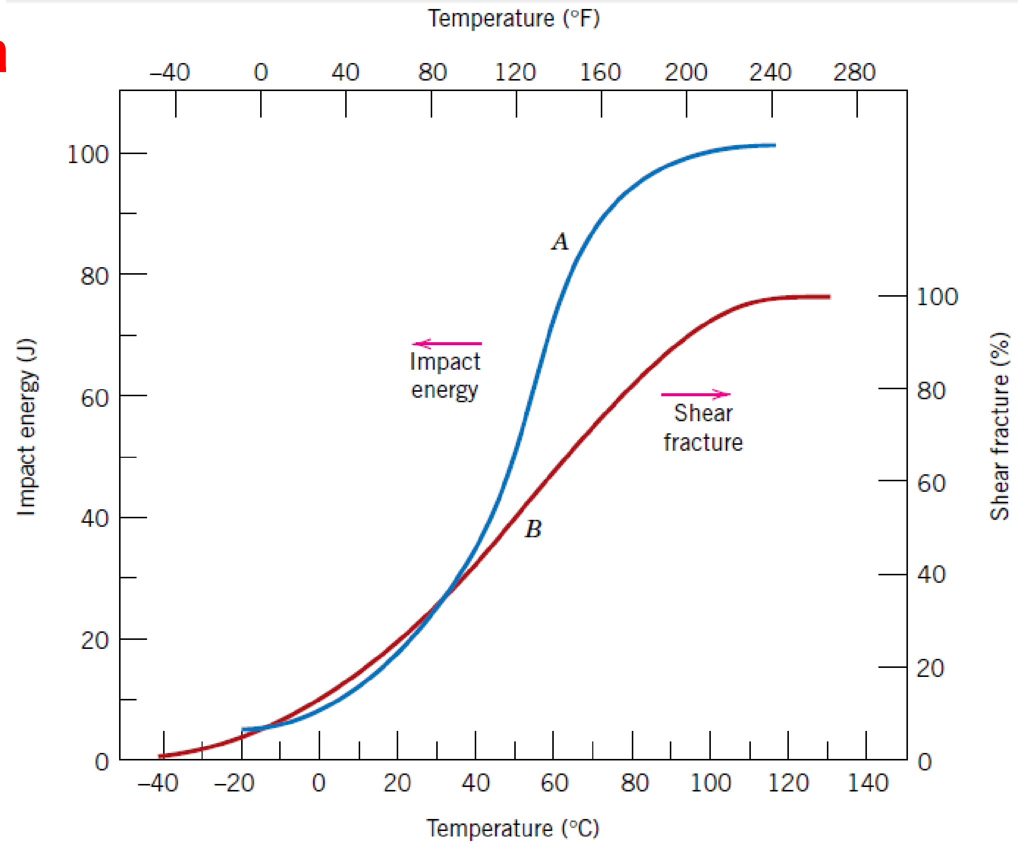


Temperature dependence of the Charpy V-notch impact energy (curve A) and percent shear fracture (curve B) for an A283 steel.

6.6. Fracture Toughness Testing

Ductile-to-Brittle Transition

- This **transition** is represented for a steel by **curve A** in the figure.
- At **higher temperatures**, the **CVN energy** is relatively **large**, corresponding to a **ductile** mode of **fracture**.
- As the **temperature** is **lowered**, the **impact energy drops suddenly** over a relatively **narrow temperature** range, below which the **energy** has a **constant** but **small value**—that is, the mode of **fracture is brittle**.
- Frequently, the **percent shear fracture** is plotted as a function of temperature—**curve B**.

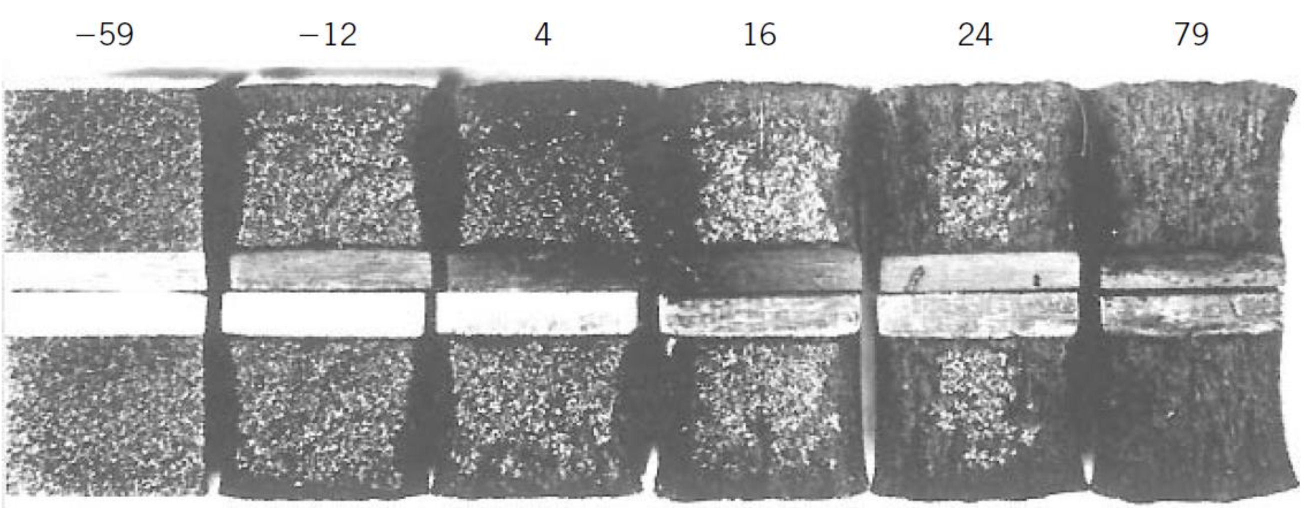


Temperature dependence of the Charpy V-notch impact energy (curve A) and percent shear fracture (curve B) for an A283 steel.

6.6. Fracture Toughness Testing

Ductile-to-Brittle Transition

- Alternatively, **appearance** of the **failure surface** is **indicative** of the nature of fracture and may be used in transition temperature determinations.
- For **ductile fracture**, this **surface** appears **fibrous** or **dull** (or of **shear character**), as in the steel specimen of the figure, which was tested at **79°C**.
- Conversely, **totally brittle surfaces** have a **granular** (shiny) texture (or **cleavage** character) like the **-59°C** specimen in the figure.
- Over the **ductile-to-brittle transition**, features of **both types** will exist (specimens tested at **-12°C, 4°C, 16°C, and 24°C**).



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

6.6. Fracture Toughness Testing

Ductile-to-Brittle Transition

- For **many alloys** there is a **range** of **temperatures** over which the **ductile-to-brittle transition occurs**; this presents **some difficulty** in **specifying** a **single** ductile-to-brittle **transition temperature**.

- **No explicit criterion** has been established, and so this temperature is **often defined** as the **temperature** at **which** the **CVN energy** assumes **some value** (e.g., **20 J**), or corresponding to **some given fracture appearance** (e.g., **50% fibrous fracture).**

- **Matters** are further **complicated** by the fact that a **different transition temperature** may be realized for **each of these criteria.**

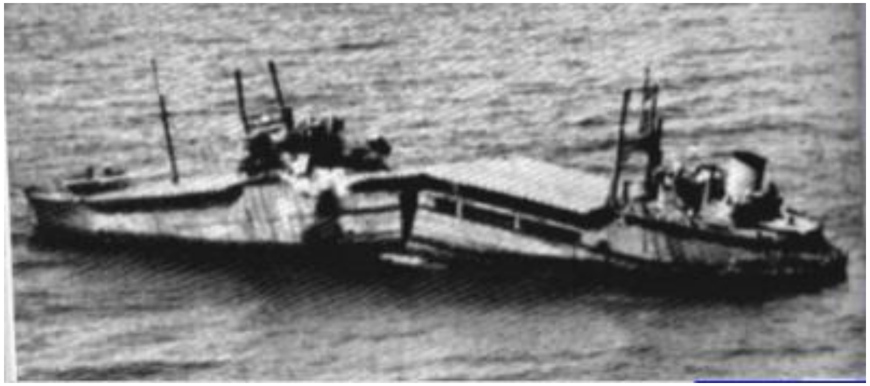
- Perhaps the **most conservative transition temperature** is that at which the **fracture surface becomes 100% fibrous**; on this basis, the transition temperature is **approximately 110°C** for the A283 steel alloy.

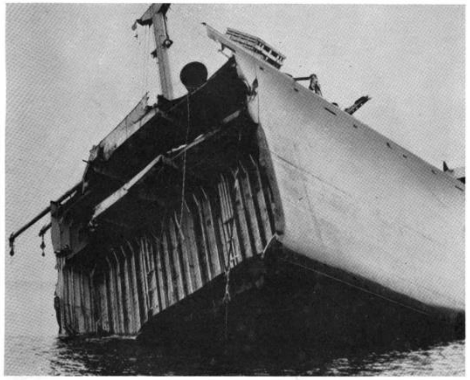
6.6. Fracture Toughness Testing

Ductile-to-Brittle Transition

- **Structures** constructed from alloys that **exhibit** this **ductile-to-brittle behavior** should be **used only** at temperatures **above** the **transition temperature** to **avoid brittle** and **catastrophic failure**.

- Classic examples: during World War II, a number of welded transport **ships** away from combat suddenly split in half. The vessels were constructed of a steel alloy that possessed adequate toughness according to room-temperature tensile tests. The **brittle fractures** occurred at relatively low ambient temperatures, at about **4°C**, in the vicinity of the **transition temperature** of the alloy. Each **fracture crack originated** at some point of **stress concentration**, probably a **sharp corner** or fabrication **defect**, and then propagated around the entire girth of the ship.



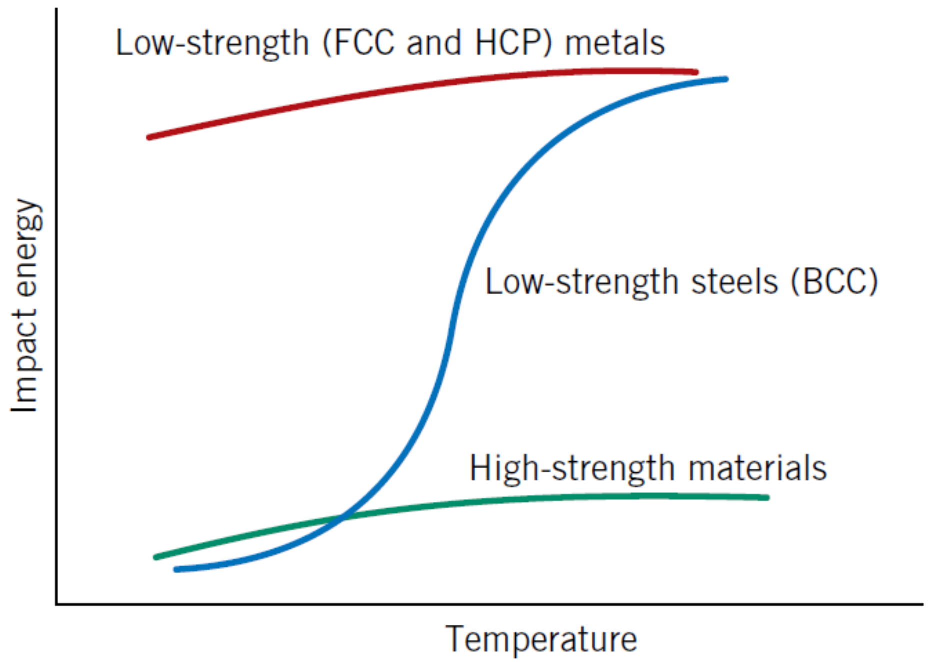


6.6. Fracture Toughness Testing

Ductile-to-Brittle Transition

- In addition to the ductile-to-brittle transition represented previously (for A283 steel), **two other general types** of **impact energy–versus–temperature behavior** have been observed; these are represented schematically by the **upper** and **lower** curves of the figure.

- Here it may be noted that **low-strength FCC** metals (**some aluminum and copper alloys**) and **most HCP** metals **do not experience** a ductile-to-brittle **transition** and retain **high impact energies** (i.e., remain tough) with decreasing temperature.



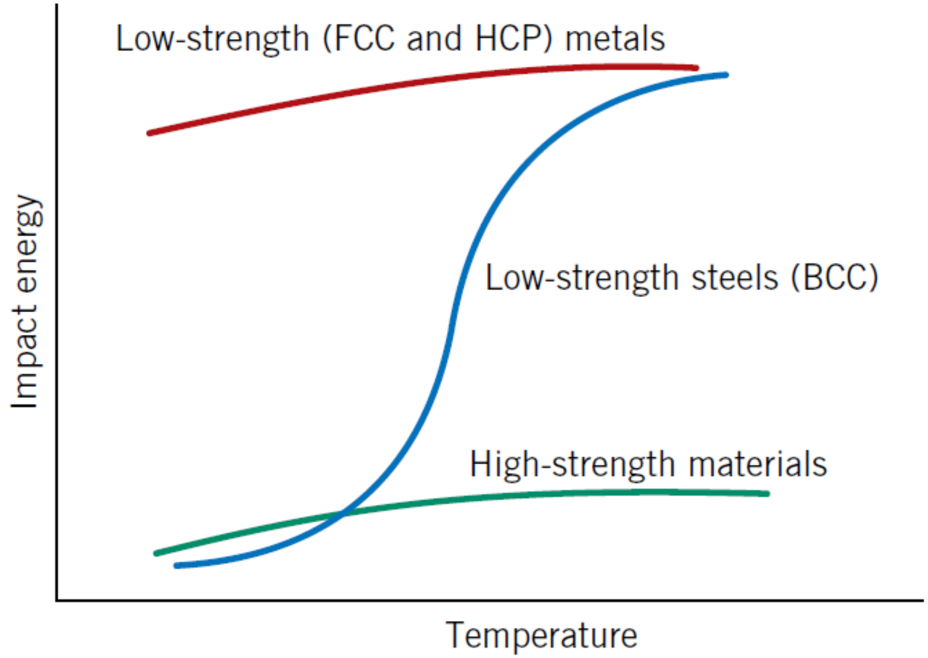
Schematic curves for the three general types of impact energy–versus temperature behavior.

Ductile-to-Brittle Transition

- For **high-strength** materials (e.g., **high-strength steels** and **titanium** alloys), the **impact energy** is also **relatively insensitive** to temperature.

- However, these materials are also **very brittle**, as reflected by their **low impact energies**.

- The characteristic **ductile-to-brittle transition** is represented by the **middle curve**. As noted, this behavior is typically found in **low-strength** steels that have the **BCC crystal structure**.



Schematic curves for the three general types of impact energy–versus temperature behavior.

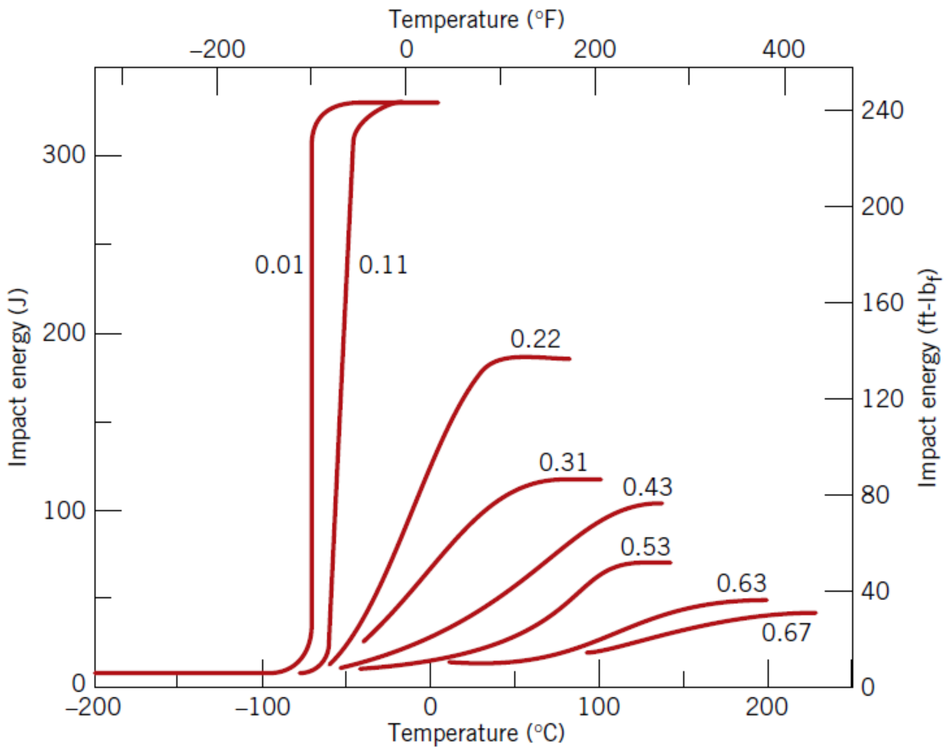
6.6. Fracture Toughness Testing

Ductile-to-Brittle Transition

- For these **low-strength steels**, the **transition temperature** is **sensitive** to both **alloy composition** and **microstructure**.

- **For example**, **decreasing** the average **grain size** results in a **lowering** of the transition temperature (<u>more ductile fracture</u>). Hence, **refining** the **grain size** both **strengthens** and **toughens** steels.

- In contrast, **increasing** the **carbon** content, although it **increases** the **strength** of steels, also **raises** their **CVN transition** (curve translated to the right, more brittle fracture), as indicated in the figure.



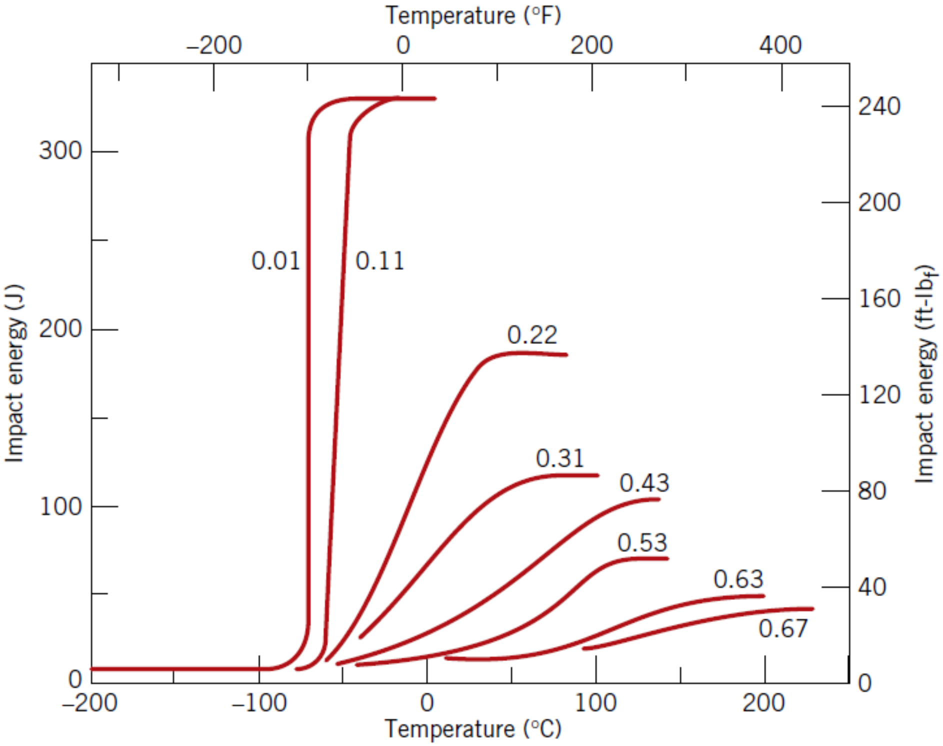
Influence of carbon content on the Charpy V-notch energy–versus–temperature behavior for steel.

6.6. Fracture Toughness Testing

Ductile-to-Brittle Transition

- Most **ceramics and polymers** also experience a ductile-to-brittle transition.

- For **ceramic** materials, the **transition** occurs only at **elevated temperatures**, ordinarily in excess of **1000°C**.



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

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Chap6: Failure

Introduction

- **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.

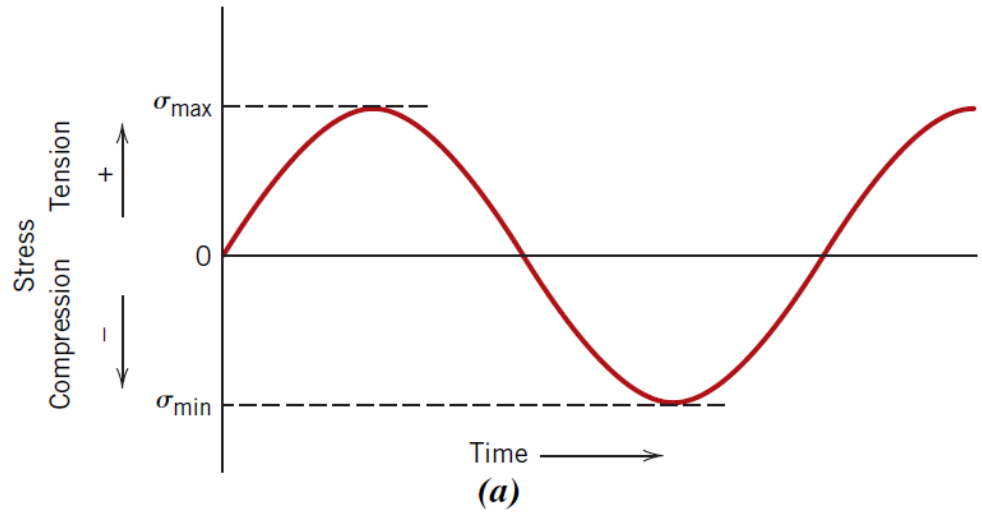
- The **process occurs** by the **initiation** and **propagation** of cracks, and typically the fracture surface is **perpendicular** to the **direction** of an **applied tensile stress**.

6.7. 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**.

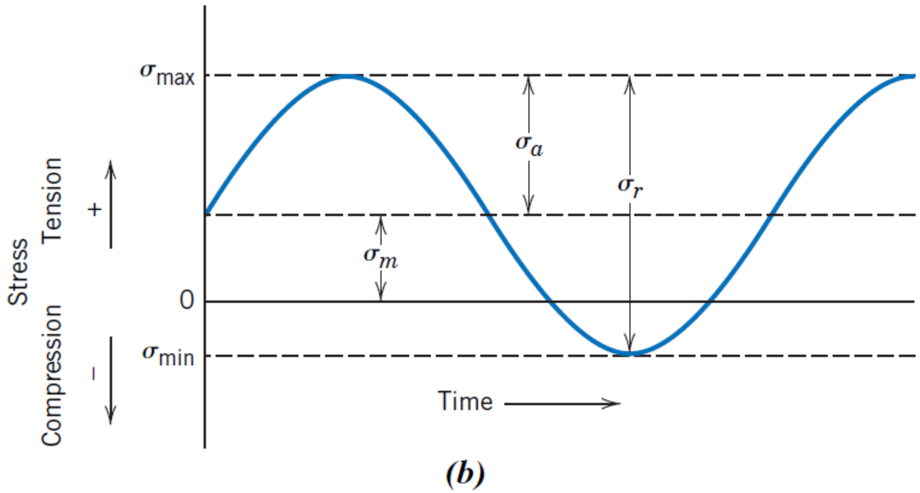
- **One** is represented schematically by a **regular** and **sinusoidal time dependence** in Figure (a), where the amplitude is **symmetrical** about a **mean zero stress level**. **For example**, alternating from a **maximum tensile stress** (**σ_{max}**) to a **minimum compressive stress** (**σ_{min}**)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



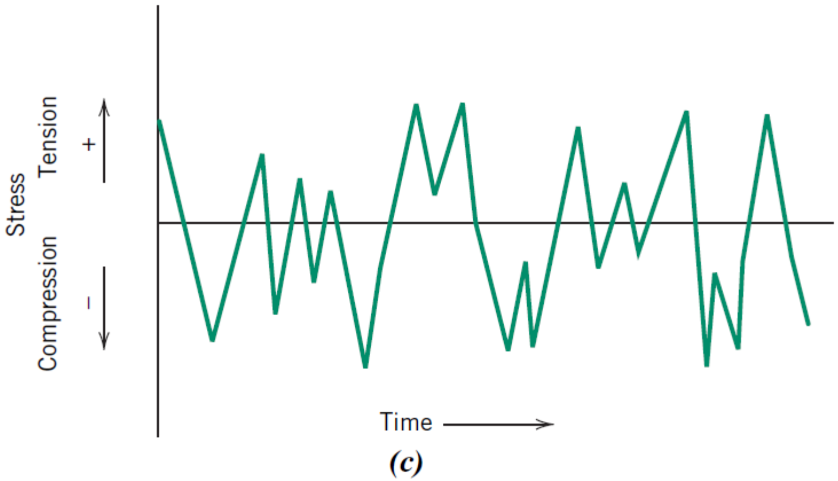
Variation of stress with time that accounts for fatigue failures. (a) Reversed stress cycle, in which the stress alternates from a maximum tensile stress (+) to a maximum compressive stress (-) of equal magnitude.

6.7. Cyclic Stresses

- 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**).



(b) Repeated stress cycle, in which maximum and minimum stresses are asymmetrical relative to the zero-stress level; mean stress σ_m, range of stress σ_r, and stress amplitude σ_a are indicated.



(c) Random stress cycle.

6.7. Cyclic Stresses

- Also indicated in Figure (b) are **several parameters** used to **characterize** the **fluctuating stress cycle**.
- 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 **σ_{max}** and **σ_{min}**, namely,

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

6.7. Cyclic Stresses

- 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**.

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6.8. The S–N Curve

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

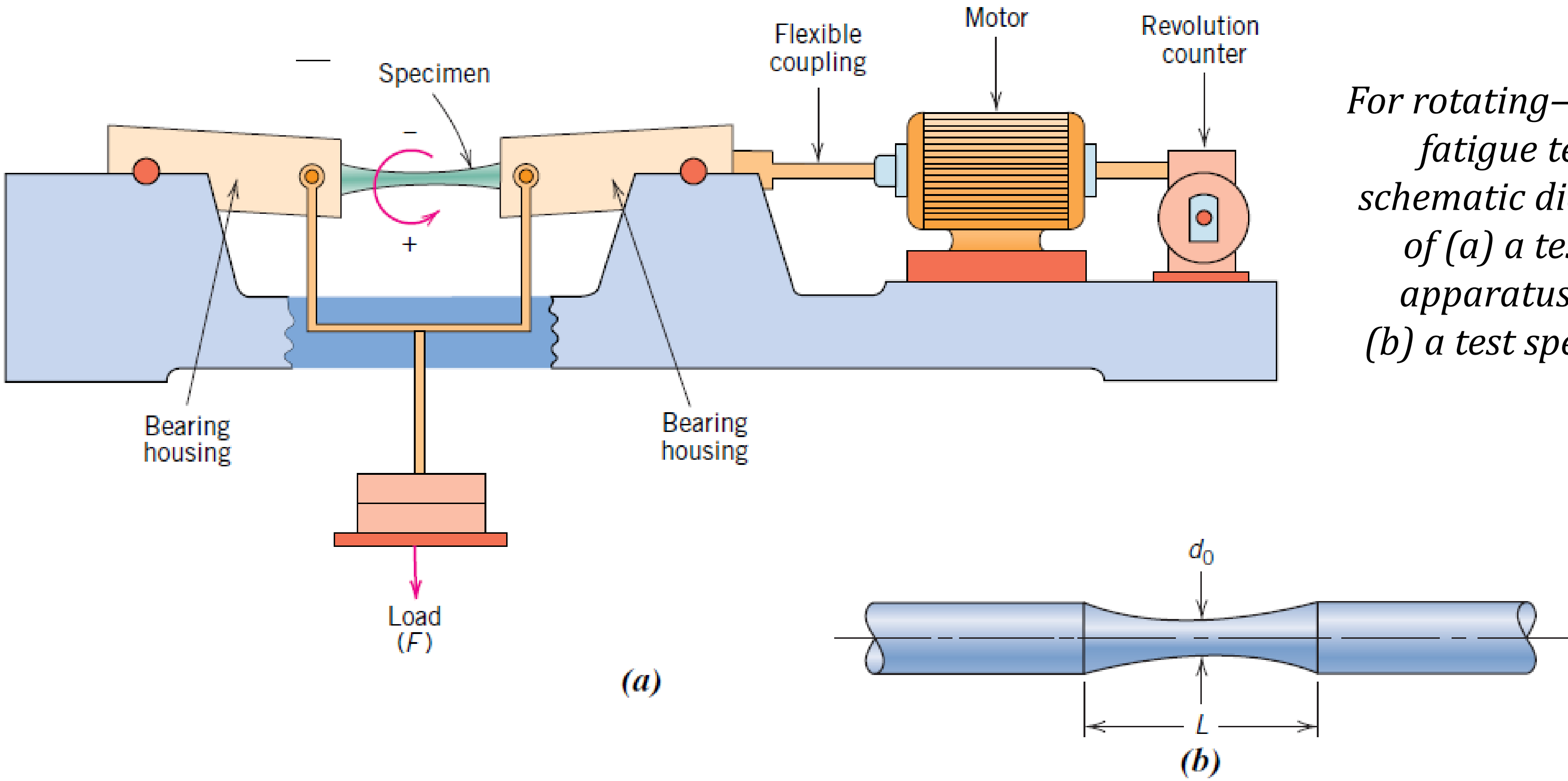
- A **test apparatus** should be **designed to duplicate** as nearly as possible the **service** stress **conditions** (**stress level, time frequency, stress pattern, etc**.).

- The **most common type** of test conducted in a laboratory setting employs a **rotating–bending beam:** **alternating** **tension** and **compression stresses** of **equal** magnitude are imposed on the specimen as it is **simultaneously bent** and **rotated**.

- In this case, the **stress cycle** is **reversed**—that is, **R=-1**.

- **Schematic** diagrams of the apparatus and test specimen commonly used for this type of fatigue testing are shown in the **next figure:**

6.8. The S–N Curve



For rotating–bending fatigue tests, schematic diagrams of (a) a testing apparatus, and (b) a test specimen.

- From Figure (a), **during rotation**, the **lower surface** of the specimen is subjected to a **tensile** (i.e., **positive**) **stress**, whereas the **upper surface** experiences **compression** (i.e., **negative**) **stress**.

https://www.youtube.com/watch?v=8riQ9Zt5UWg

6.8. The S–N Curve

- Furthermore, **anticipated in-service conditions may** call for conducting simulated laboratory fatigue tests that use either **uniaxial tension**–**compression** or **torsional** stress cycling **instead of rotating–bending**.

- 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) (Figures of stress cycle in the last section).

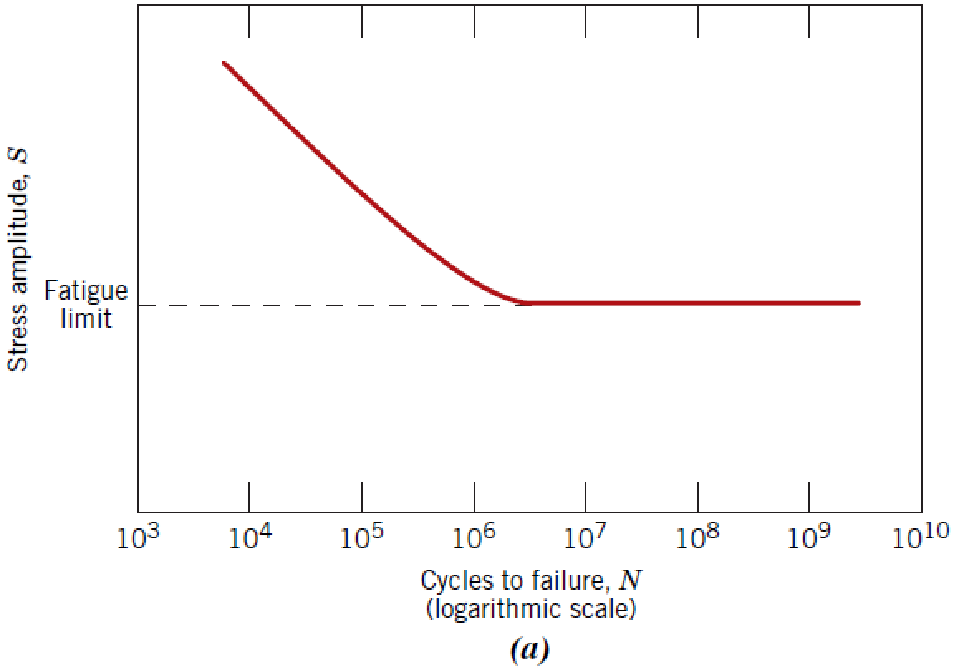
6.8. The S–N Curve

Fatigue Limit

- **Two distinct types of S–N behavior** are observed and are represented schematically.

- 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 **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**.



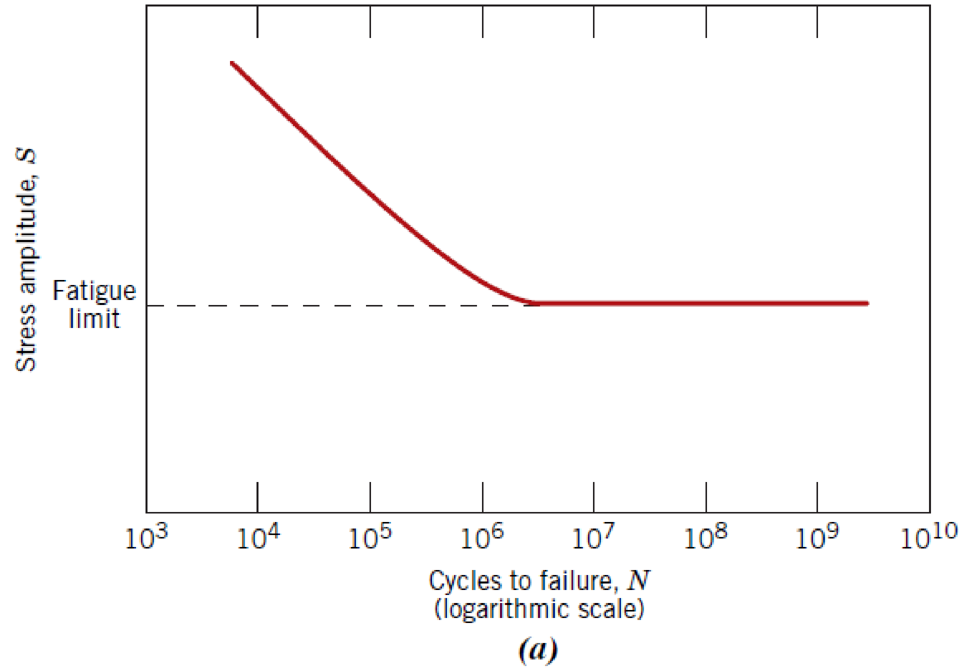
Stress amplitude (S) versus logarithm of the number of cycles to fatigue failure (N) for (a) a material that displays a fatigue limit

6.8. The S–N Curve

Fatigue Limit

- 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**.



Stress amplitude (S) versus logarithm of the number of cycles to fatigue failure (N) for (a) a material that displays a fatigue limit

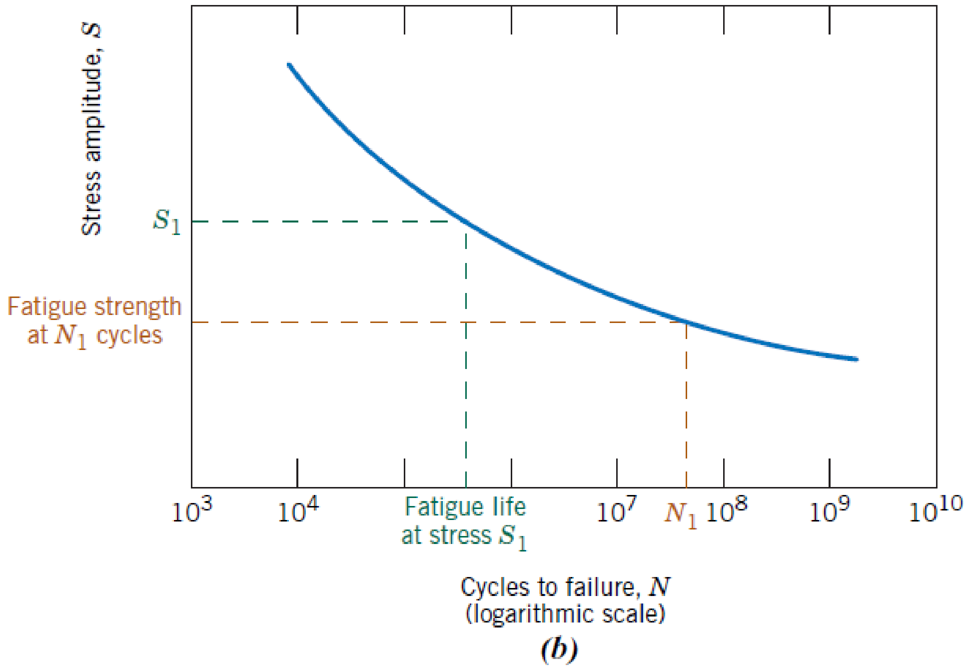
Fatigue Strength

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

- 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**.

- The determination of fatigue strength is demonstrated in the figure.



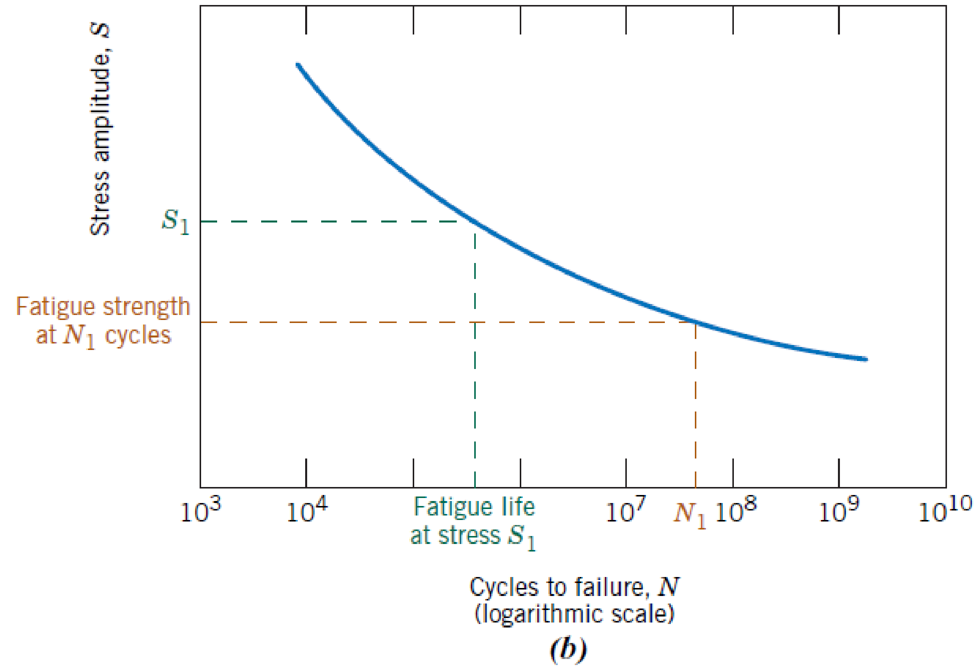
(b) a material that does not display a fatigue limit.

6.8. The S–N Curve

Fatigue Life

- **Another important parameter** that characterizes a material's **fatigue behavior** is **fatigue life N_f**.

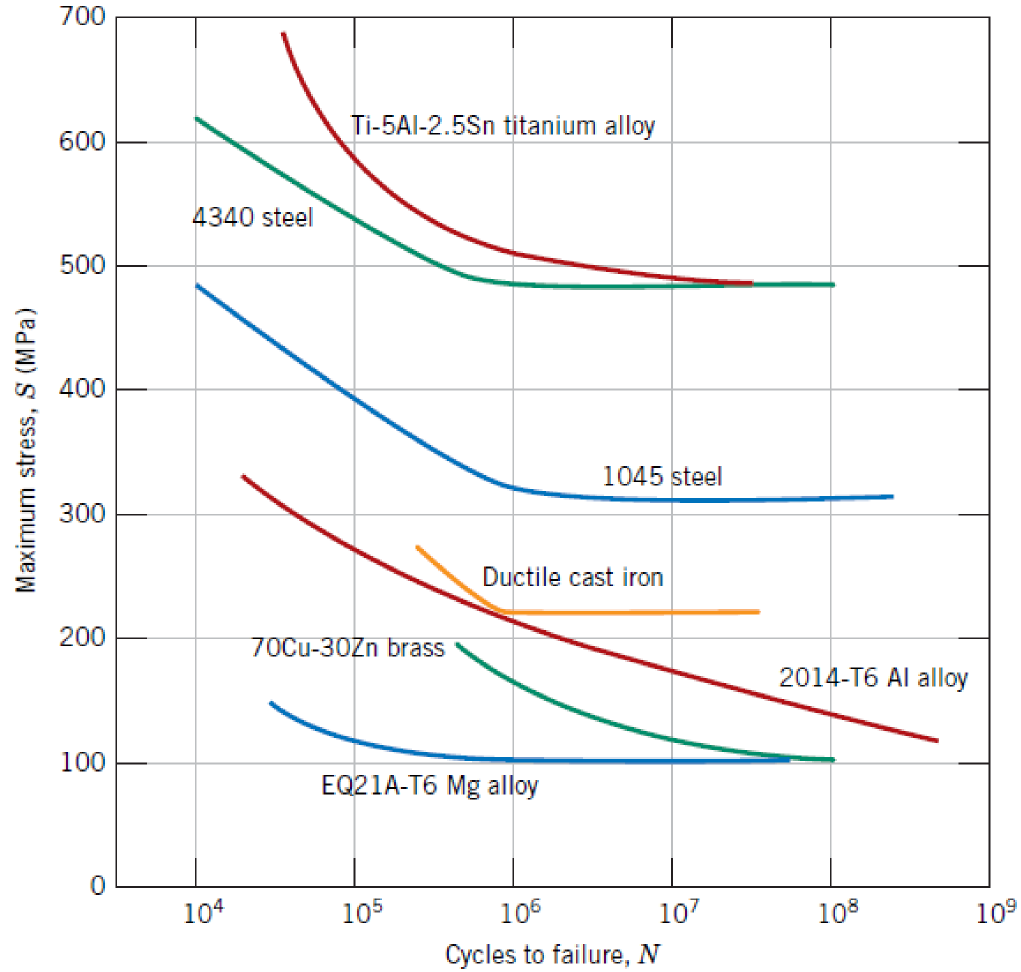
- It is the **number of cycles** to **cause failure at a specified stress level**, as taken from the S–N plot.



(b) a material that does not display a fatigue limit.

6.8. The S–N Curve

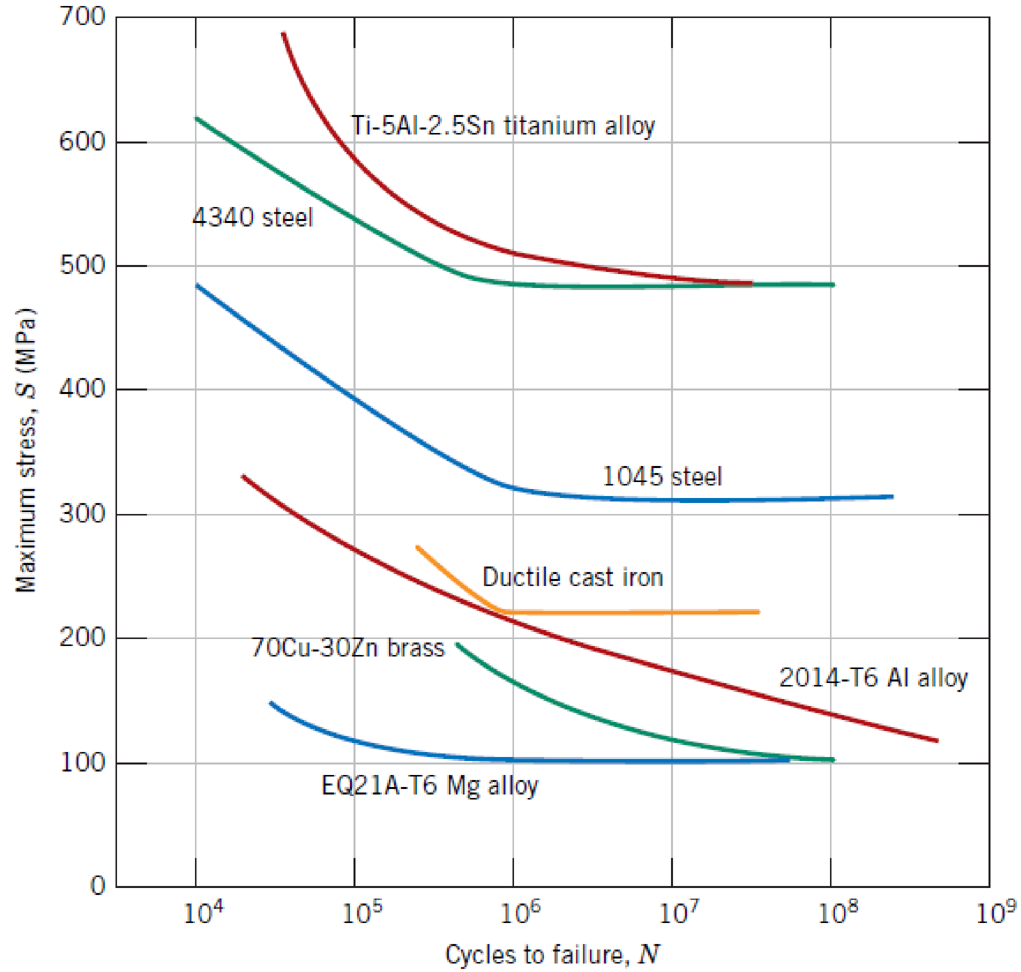
- Fatigue S–N curves for **several metal alloys** are shown in the figure.
- Curves for the **titanium**, **magnesium**, and **steel** alloys as well as for **cast iron** display **fatigue limits**;
- Curves for the **brass** and **aluminum** alloys **do not have such limits**.
- **Unfortunately**, there always exists **considerable scatter** in fatigue **data**—that is, a **variation** in the **measured N value** for a **number** of **specimens tested** at the **same stress level**.



Maximum stress (S) versus logarithm of the number of cycles to fatigue failure (N) for seven metal alloys. Curves were generated using rotating bending and reversed-cycle tests.

6.8. The S–N Curve

- **This variation** may lead to **significant design uncertainties** when fatigue life and/or fatigue limit (or strength) are being considered.
- **The scatter** in results is a **consequence of** the **fatigue sensitivity** to a number of test and material **parameters** that are **impossible to control** precisely.
- These parameters include specimen **fabrication** and **surface preparation**, **metallurgical variables**, specimen **alignment** in the apparatus, **mean stress**, and test **frequency**.

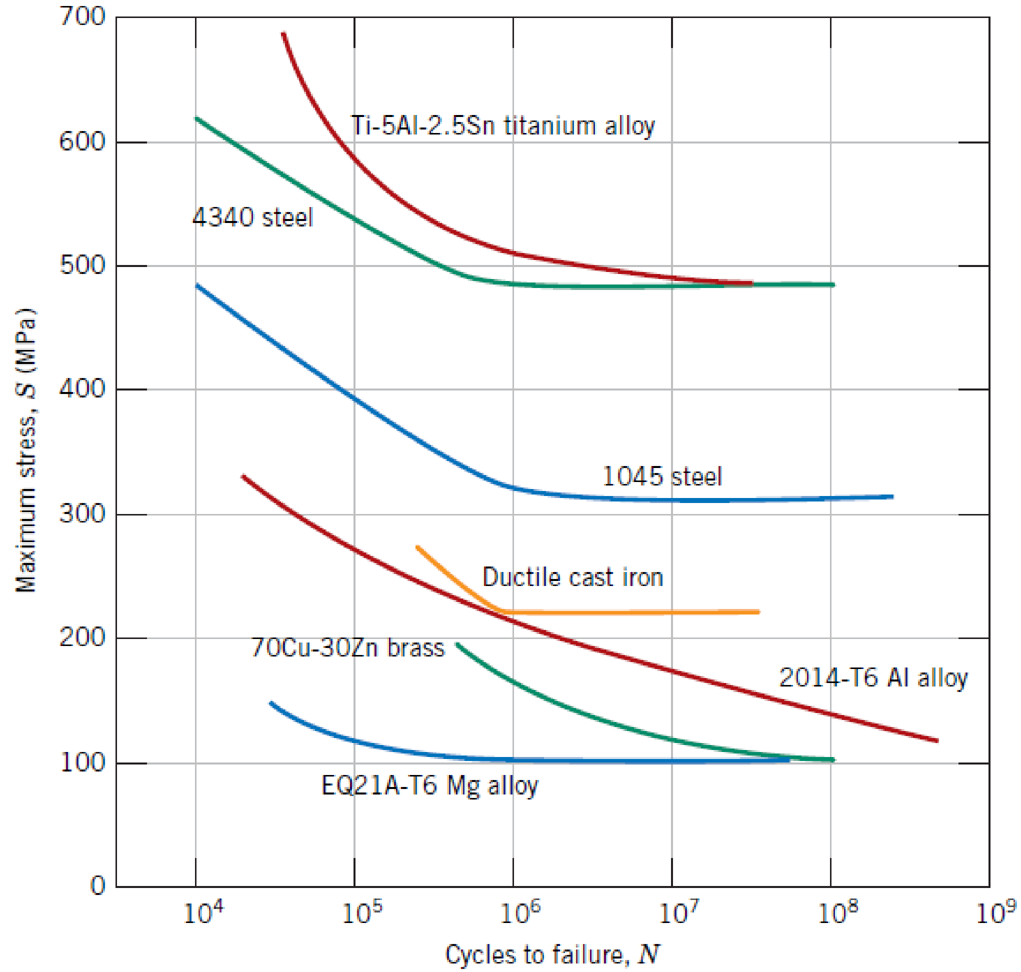


Maximum stress (S) versus logarithm of the number of cycles to fatigue failure (N) for seven metal alloys. Curves were generated using rotating bending and reversed-cycle tests.

6.8. The S–N Curve

- Fatigue S–N curves shown in the figure 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).

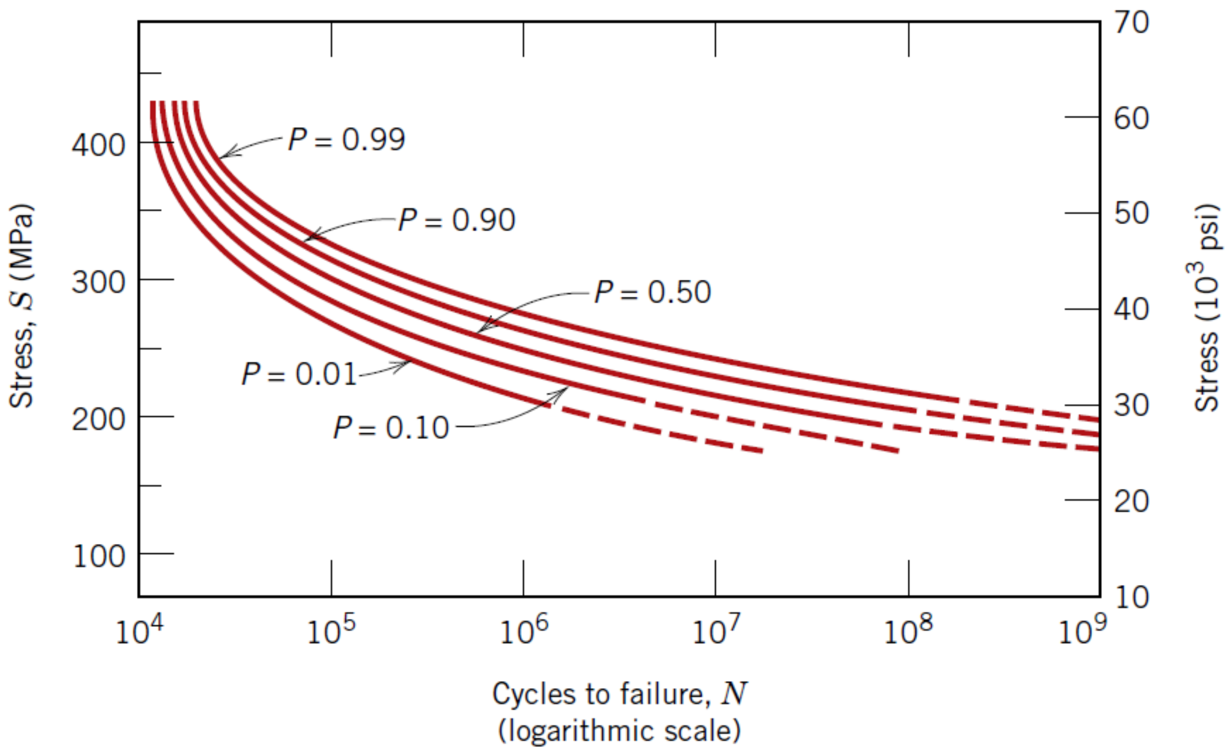


Maximum stress (S) versus logarithm of the number of cycles to fatigue failure (N) for seven metal alloys. Curves were generated using rotating bending and reversed-cycle tests.

6.8. The S–N Curve

- **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 in the figure. **The P value** associated with each curve represents the **probability of failure**.



Fatigue S–N probability of failure curves for a 7075-T6 aluminum alloy; P denotes the probability of failure.

6.8. The S–N Curve

- **For example**, at a stress of **200 MPa** we would expect **1%** of the **specimens** to **fail at about 10^6 cycles**, **50%** to **fail** at **about $2x10^7$ cycles**, and so on.

- Remember that S–N **curves** represented in the literature are **normally average values**, unless noted otherwise.

- The **fatigue behaviors** represented in "**Stress amplitude**" figure may be **classified** into **two domains**.

1. **One** is associated with **relatively high loads** that produce **not only elastic** strain but also **some plastic strain during** each **cycle**.

- Consequently, **fatigue lives** are **relatively short**; this domain is termed **low-cycle fatigue** and occurs at **less than** about **10^4 to 10^5 cycles**.

2. **For lower stress levels** wherein deformations are **totally elastic**, **longer lives result**. This is called **high-cycle fatigue** because relatively **large numbers** of **cycles** are required to produce fatigue failure.

- High-cycle fatigue is associated with fatigue lives **greater than about 10^4 to 10^5 cycles**.