MATERIALS SCIENCE FOR ENGINEERS – ME232AT

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Material behaviour: Thermal properties: thermal conductivity, thermoelectric effects, heat capacity, thermal expansion coefficient, thermal shock, thermocouple. Electrical Properties: dielectric behaviours and temperature dependence of the dielectric constant, insulating materials, ferroelectricity, piezoelectricity, super conductor. Optical properties: luminescence, optical fibers, Mechanical Properties: Stress-strain diagram, elastic deformation, plastic deformation, hardness, viscoelastic deformation, impact energy, fracture toughness, fatigue.

THERMAL CONDUCTIVITY

The rate at which heat passes through a specified material, expressed as the amount of heat that flows per unit time through a unit area with a temperature gradient of one degree per unit distance.

$$k = \frac{Q\Delta x}{A(T_2 - T_1)}$$
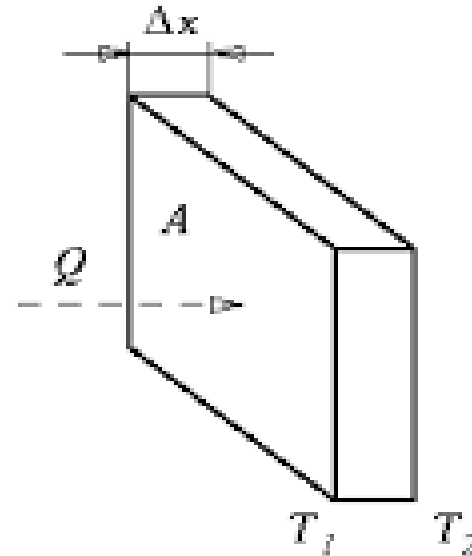
The opposite face is maintained at a temperature difference of 1 degree

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The **specific heat** **is the amount of heat per unit mass required to raise the temperature by one degree Celsius**. The relationship between heat and temperature change is usually expressed in the form shown below where c is the **specific heat**.

$$C = \frac{Q}{m \times \Delta T}$$

Coefficient of Thermal Expansion (CTE)

The **coefficient of thermal expansion** is **defined** as the fractional increase in the _length_ per unit rise in temperature.

$$\alpha = \Delta L / (L0 * \Delta T)$$

Where,
α is the coefficient of linear thermal expansion per degree Celsius.
ΔL is the change in length of test specimen due to heating or to cooling.
L0 is the original length of specimen at room temperature.

The volumetric coefficient of thermal expansion is the ratio of the change in volume to the change in temperature, while pressure is kept constant:

$$\alpha_V = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)$$

Where,
 V is the initial volume of the solid,
ΔV is the change in volume.
αV volume expansion coefficient
ΔT is the temperature difference

Thermoelectric effects refer to the generation of an electric voltage or current in a material when there is a temperature gradient across it. There are three thermoelectric effects: Seebeck effect, the Peltier effect, and the Thomson effect
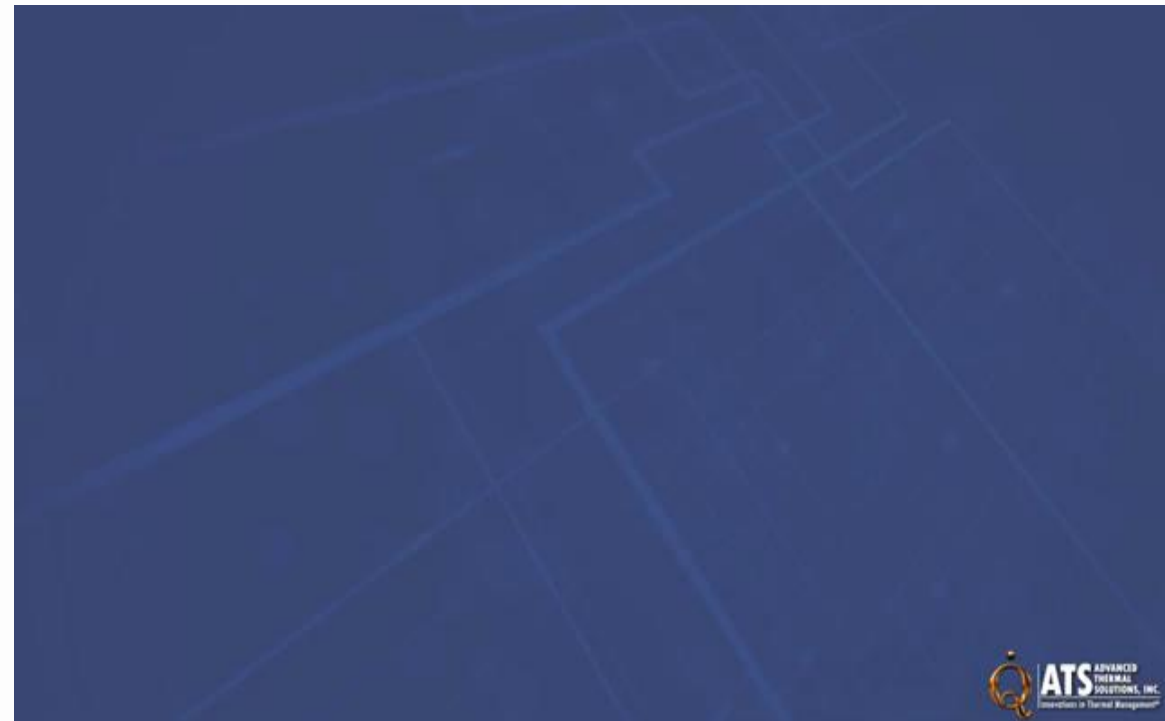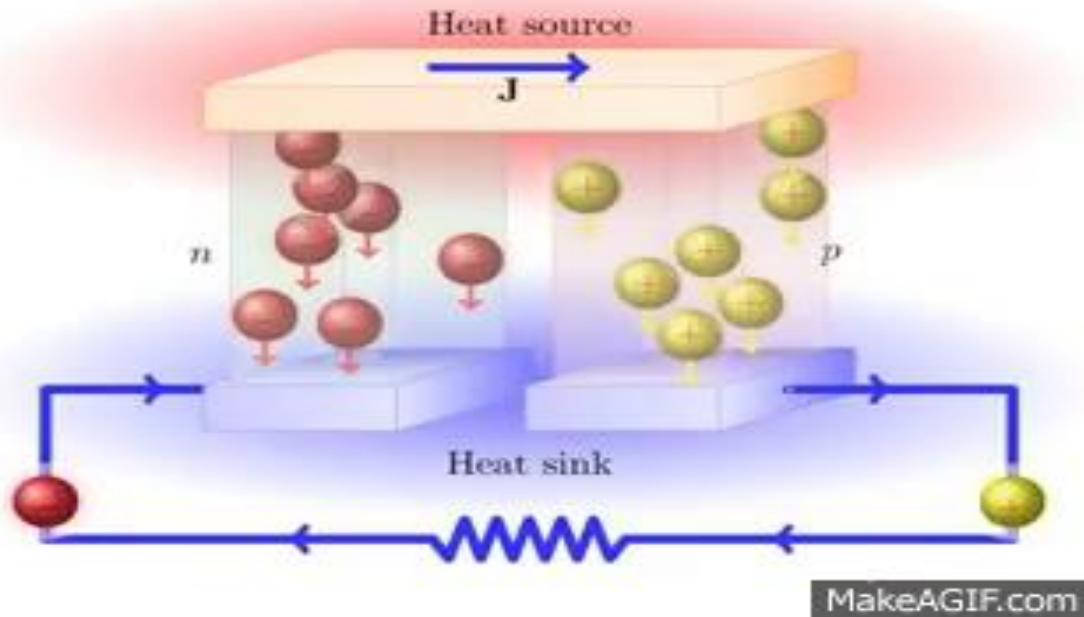
The Seebeck effect is the phenomenon where a temperature difference between two different materials or junctions in a circuit leads to the generation of an electric voltage as shown in Fig. 2.2. This effect is the foundation of thermocouples, which are widely used for temperature measurements.

Thermocouples consist of two dissimilar conductive materials joined at one end, and when the temperature at the junctions differs, they produce a voltage proportional to the temperature difference.
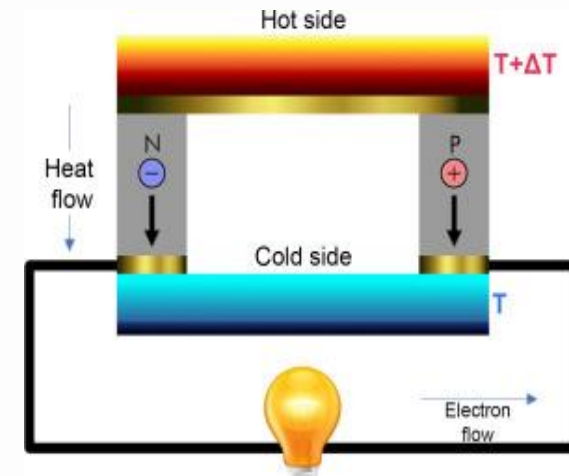

Fig.2.2 Seebeck Effects Principle

- **Explanation:** When a circuit is formed by joining two different materials and a temperature gradient is applied, electrons diffuse from the hot side to the cold side, creating a voltage across the material.
- **Equation:** The Seebeck coefficient (S) represents the extent of this effect and is given by the relationship: **V=S·ΔT,** where V is the voltage, S is the Seebeck coefficient, and ΔT is the temperature difference.

The Peltier effect is the reverse of the Seebeck effect. It occurs when an electric current is passed through a junction of two dissimilar materials, resulting in a transfer of heat across the junction as shown in Fig. 2.3.

This effect is utilized in thermoelectric cooling devices, like thermoelectric coolers (TECs) or Peltier coolers, commonly found in applications such as refrigeration, CPU cooling, and portable refrigerators.

Fig.2.3 Peltier Effects Principle
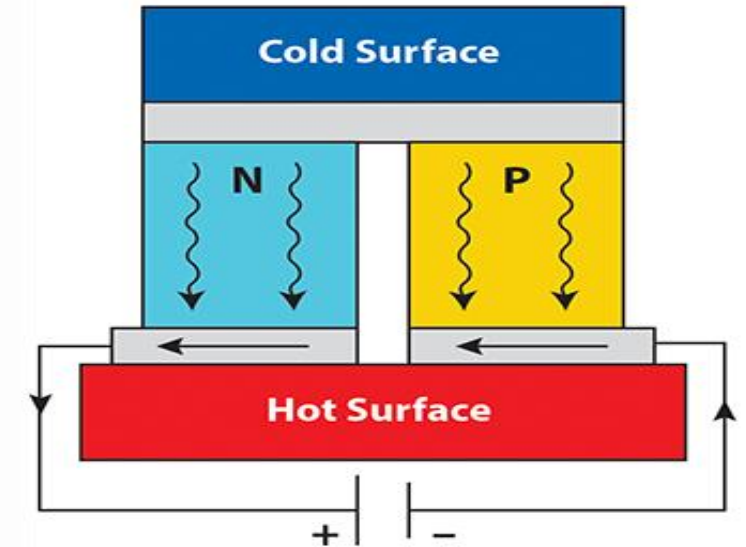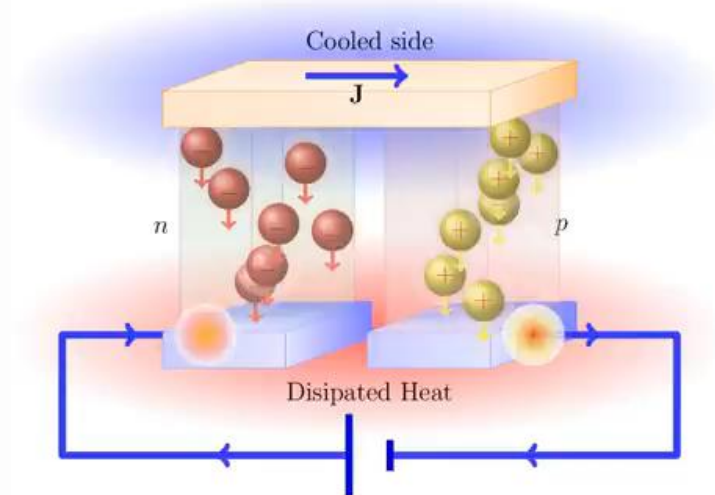

Equation: Similar to the Seebeck effect, the Peltier coefficient (π) represents the magnitude of heat transfer and is given by: $Q=π·I·ΔT,$

where Q is the heat transfer, π is the Peltier coefficient, I is the current, and ΔT is the temperature difference.

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Figure 2.37 (a) Positive Thomson effect
(b) Negative Thomson effect

3. Thomson Effect:

• **Definition:** The Thomson effect describes the phenomenon where a temperature gradient along a conductor results in the absorption or release of heat.

• **Explanation:** Unlike the Seebeck effect, where a voltage is generated, the Thomson effect involves a change in temperature along the length of the conductor itself, leading to a heat exchange.

• **Equation:** The Thomson coefficient (Θ) characterizes this effect and is defined as:
$Q=-\Theta \cdot I \cdot \Delta T$,
where Q is the heat absorbed or released,
Θ is the Thomson coefficient,
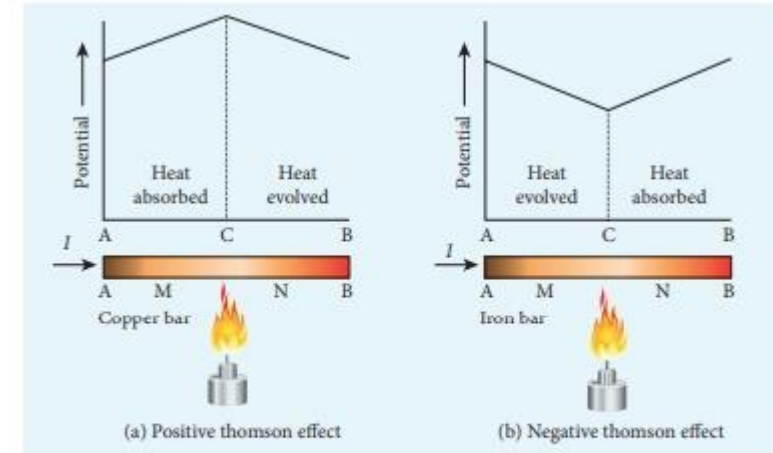I is the current, and
ΔT is the temperature gradient.

If current is passed through a copper bar AB which is heated at the middle point C, the point C will be at higher potential. This indicates that the heat is absorbed along AC and evolved along CB of the conductor as shown in Figure 2.37(a). Thus heat is transferred due to the current flow in the direction of the current. It is called positive Thomson effect. Similar effect is observed in metals like silver, zinc, and cadmium.

When the copper bar is replaced by an iron bar, heat is evolved along CA and absorbed along BC. Thus heat is transferred due to the current flow in the direction opposite to the direction of current. It is called negative Thomson effect as shown in the Figure 2.37(b). Similar effect is observed in metals like platinum, nickel, cobalt, and mercury.

Thermal Shock:

•**Definition:** Thermal shock refers to the stress and damage caused in a material or a device when it experiences a sudden and extreme change in temperature.

•**Explanation:** When a material is exposed to rapid temperature changes, especially when transitioning from high to low temperatures or vice versa, uneven expansion and contraction can occur. This can lead to the development of cracks, fractures, or other structural damage in the material.

•**Causes:** Thermal shock can result from factors such as sudden exposure to high heat, rapid cooling, or alternating between extreme temperature conditions.

•**Examples:** Glass breaking when hot liquid is poured into it, or metal parts experiencing stress during rapid quenching in manufacturing processes.

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Thermocouple:

•**Definition:** A thermocouple is a temperature sensor that consists of two different metal wires joined at one end. It generates a voltage proportional to the temperature difference between the two ends.

•**Working Principle:** The operation of a thermocouple is based on the Seebeck effect. When the two different metals are exposed to a temperature gradient, it induces a voltage that can be measured to determine the temperature.

•**Materials:** Common thermocouple materials include combinations like Type K (chromel/alumel), Type J (iron/constantan), and Type T (copper/constantan).

•**Applications:**
- **Temperature Measurement:** Thermocouples are widely used for measuring temperatures in various industries, such as manufacturing, food processing, and HVAC systems.
- **Thermoelectric Devices:** Thermocouples are also crucial components in thermoelectric devices like thermoelectric generators and coolers.

•**Advantages:**
- Reliable and rugged.
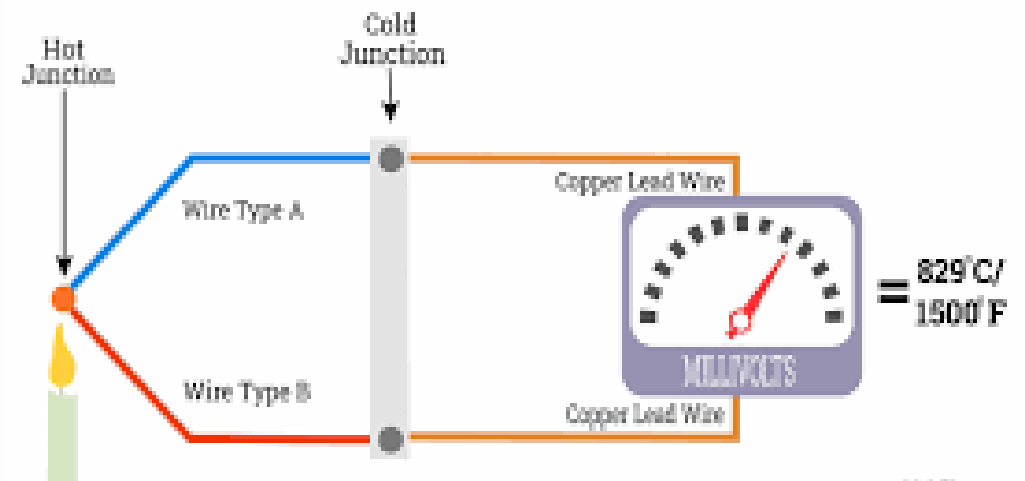- Wide temperature measurement range.
- Fast response time.

Fig. 2.7 Schematic diagram of thermocouple mechanism

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Dielectric materials: A dielectric material is an insulating material that can be polarized when an electric field is applied to it. **or**

They **do not conduct electric current easily**, but they can be **polarized in the presence of an electric field**. When subjected to an external electric field, **the atoms or molecules within a dielectric material undergo polarization**, causing the **material to become electrically charged**. This property is fundamental to the behaviour of dielectric materials in various electrical and electronic applications.

Dielectric Behaviour:

Dielectric behaviours refer to the **responses and characteristics** exhibited by dielectric materials when subjected to an electric field. Understanding these behaviours is crucial in various applications, ranging from electronic components to insulation materials. Here are key aspects of dielectric behaviours:

1. Dielectric Constant (ε):

The dielectric constant, often denoted by ε (epsilon), is a crucial property of dielectric materials. It quantifies the **ability of a substance to store electrical energy in an electric field**. Essentially, it is a measure of how well a material can be polarized under the influence of an external electric field.

2. Polarization Mechanisms:

Dielectric materials exhibit polarization through various mechanisms:

•**Electronic Polarization:** Movement of electrons in response to an external electric field.

•**Ionic Polarization:** Movement of ions within the material.

•**Orientation Polarization:** Alignment of permanent dipoles within the material.

•**Space Charge Polarization:** Accumulation of charges at interfaces or defects.

3. Dielectric Strength:

Dielectric strength is the ability of a material to withstand electric stress without breaking down or experiencing electrical failure. It is a key parameter in designing and using insulating materials, particularly in applications such as electrical insulation and high-voltage systems.

Definition: Dielectric strength is defined as the **maximum electric field a dielectric material can endure without electrical breakdown**. It is often measured in units of volts per unit thickness (V/m or kV/mm).

Factors Influencing Dielectric Strength:

1. **Material Composition:** Different materials have varying dielectric strengths. For example, gases generally have lower dielectric strengths compared to solids.

2. **Purity of the Material:** Impurities or defects within the material can weaken its dielectric strength.

3. **Temperature:** Dielectric strength can be influenced by temperature. In some cases, it may decrease with increasing temperature due to thermal effects on the material.

4. **Thickness:** Generally, thicker materials have higher dielectric strength. This is an important consideration in the design of insulating layers.

5. **Rate of Voltage Application:** The dielectric strength can depend on the rate at which the electric field is applied. Rapid changes in voltage may affect breakdown characteristics.

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**4. Dielectric Hysteresis:** is the **delayed response of polarization in a dielectric material to changes in the applied electric field** Dielectric hysteresis refers to a phenomenon observed in certain dielectric materials where the **polarization of the material lags behind changes in the applied electric field**. This lag or delay in response is similar to the hysteresis observed in magnetic materials and is characterized by a loop in the polarization-electric field curve.

Hysteresis Loop:
1. The relationship between polarization and electric field strength can be graphically represented by a hysteresis loop.
2. The loop shows the polarization of the material as the electric field is varied in magnitude and direction.

Energy Loss:
1. The area enclosed by the hysteresis loop represents the energy loss in the material due to the hysteresis effect.
2. This energy loss is usually converted into heat within the dielectric material.
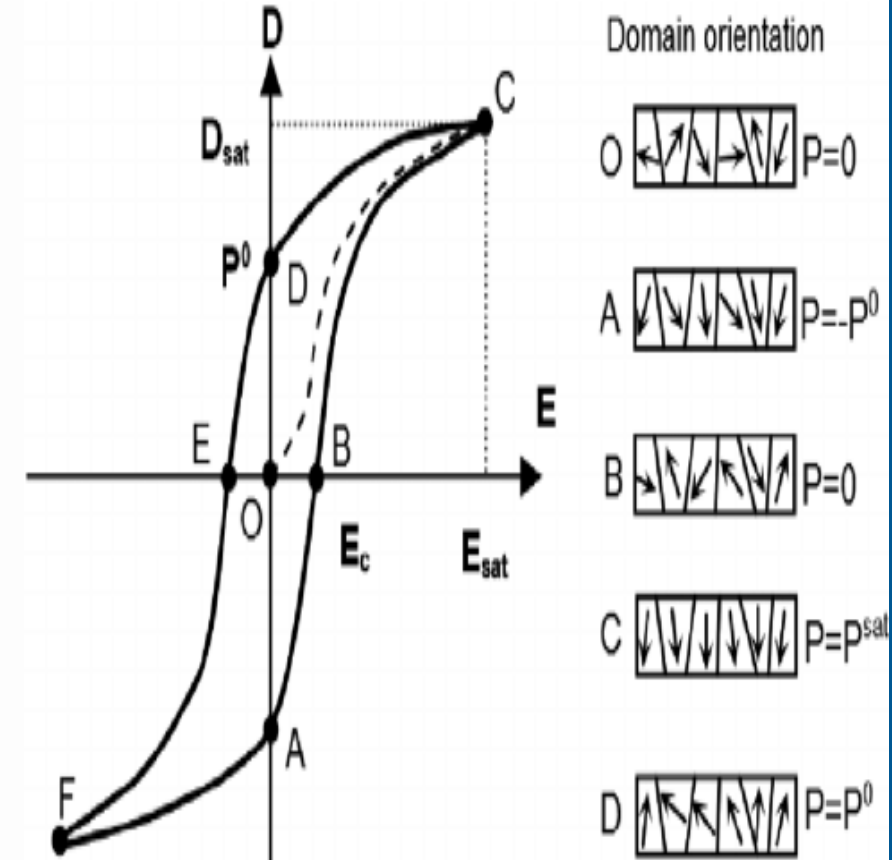
Causes:
1. **Rotational Motion of Dipoles:** In materials with permanent dipoles, hysteresis can be caused by the rotational motion of these dipoles as they attempt to align with the changing electric field.
2. **Deformation of Crystal Lattice:** In ferroelectric materials, hysteresis is often associated with the deformation of the crystal lattice.

Applications:
1. **Memory Devices:** Materials exhibiting dielectric hysteresis are sometimes used in memory devices. The hysteresis loop can represent different states of polarization, allowing for the storage of information.
2. **Actuators:** Certain piezoelectric materials with hysteresis can be used in actuators, where the delayed response is utilized for specific mechanical applications.

Ferroelectric Materials:
1. Ferroelectric materials are a common example of substances that exhibit dielectric hysteresis.
2. These materials have a spontaneous polarization that can be reversed by an external electric field.

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5. Breakdown Voltage: Breakdown voltage, also known as dielectric breakdown voltage or electrical breakdown voltage, is a critical parameter in electrical engineering. It refers to the **minimum voltage at which an insulating material, typically a dielectric, fails and allows electrical current to pass through**. The breakdown voltage is a crucial consideration in the design and operation of electrical systems, ensuring the reliability and safety of components.

1.Dielectric Breakdown: Breakdown occurs when the **electric field applied** to the dielectric material becomes **strong enough to overcome the insulating properties** of the material. The breakdown can lead to the formation of a conductive path through the dielectric, potentially causing damage to the material and the surrounding components.

- **Factors Influencing Breakdown Voltage:**
- **Material Properties:** Different dielectric materials have different breakdown voltages. For instance, air has a lower breakdown voltage compared to solid insulating materials.
- **Material Purity:** The presence of impurities or defects in the material can lower its breakdown voltage.
- **Temperature:** Breakdown voltage may be influenced by temperature. Generally, higher temperatures can decrease breakdown voltage.

- **Importance in Electrical Systems:**
- Breakdown voltage is a critical factor in determining the insulation strength of materials used in electrical systems.
- It ensures that insulating materials can withstand the electric fields present in various components, such as transformers, capacitors, and cables.

- **Types of Breakdown:**
- **Partial Discharge:** A localized breakdown that does not bridge the entire insulation, often resulting in cumulative damage over time.
- **Complete Breakdown:** The dielectric completely loses its insulating properties, allowing continuous current flow.

Temperature dependence of the dielectric constant: It describes how the dielectric constant of a material changes with temperature. The temperature dependence of the dielectric constant varies depending on the type of material. Here are some general trends:

1. **Dielectric Constant Increases with Temperature:** In some materials, especially *ferroelectric* materials [**Lead titanate**($PbTiO_3$), **Lead zirconate titanate**(PZT), Lead lanthanum zirconate titanate (PLZT)], the dielectric constant may increase as temperature rises. This behavior is often observed near phase transition temperatures, such as the Curie temperature for ferroelectrics. As the material transitions to a **different phase**, its dielectric constant may change.

2. **Dielectric Constant Decreases with Temperature:** Many *dielectric* materials exhibit a decrease in their dielectric constant as temperature increases. This is a common behavior in materials like **ceramics and polymers** (water, Silicon dioxide, mica, polystyrene. As the temperature rises, **thermal vibrations** of atoms and molecules **disrupt the alignment of dipoles** within the material, **reducing its ability to store electric charge**.

3. **Minimal Temperature Dependence**: Some dielectric materials, like certain ceramics and glasses (Polytetrafluoroethylene (PTFE), Alumina (Al2O3), water, etc), may have minimal temperature dependence over a certain range. These materials are often chosen for applications requiring stable dielectric properties across a broad temperature spectrum.

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Insulating materials

Materials have **very high electrical resistance** and are used to **prevent or control the flow of electricity** within electrical and electronic systems. Insulating materials are essential for electrical safety, as they help isolate conductive elements and prevent unintended electrical contact. key characteristics and applications of insulating materials are

- ✓ **High Electrical Resistance**: Insulating materials have a high resistance to the flow of electric current. This property ensures that minimal electrical energy is dissipated as heat within the material.
- ✓ **Electrical Insulation**: The **primary function** of insulating materials is to provide electrical insulation. They are used to separate conductive components in electrical circuits, **preventing short circuits and electrical shocks.**
- ✓ **Thermal Insulation**: Some insulating materials also exhibit good thermal insulation properties. They are used to **reduce heat transfer**, maintain temperature stability, and improve energy efficiency in various applications, including building insulation and refrigeration.

Types of Insulating Materials: There is a wide range of insulating materials, including ceramics, plastics (polyethylene, polypropylene, and PVC), rubber, glass, mica, and various composite materials. The choice of material depends on factors like electrical requirements, temperature, and environmental conditions.

Applications

✓ **Electrical Cables:** Insulating materials are used to cover and protect the conductive cores of electrical cables. Common cable insulation materials include PVC, XLPE (cross-linked polyethylene), and rubber.

✓ **Transformers and Capacitors:** Insulating materials are used as dielectric materials in transformers and capacitors to store and manage electrical energy.

✓ **Electronics:** In printed circuit boards (PCBs) and electronic devices, insulating materials are used as substrates to support and isolate conductive traces and components.

✓ **Building Insulation**: Insulating materials are used in construction to improve energy efficiency by reducing heat transfer through walls, roofs, and floors.

✓ **Safety Equipment**: Insulating materials are employed in safety equipment such as electrical gloves and insulating mats to protect individuals working with live electrical components.

Fig. 2.5 Changing Polarisation

Ferroelectricity is the **ability of the material to have a spontaneous electric polarization** as shown in Fig. 2.5. This polarization can be reversed by the application of an external electric field in the opposite direction.

Key characteristics of ferroelectric materials include:

•**Spontaneous Polarization:** Ferroelectric materials possess a spontaneous electric polarization that arises when the material's electric dipoles align in a specific direction. This polarization can be reversed when the direction of the applied electric field is changed.

•**Hysteresis:** Ferroelectric materials exhibit hysteresis behaviour in their polarization-electric field curves. This means that **even after the applied electric field is removed, the polarization persists until an opposite electric field is applied to reverse it.**

•**Phase Transition:** Ferroelectricity is often associated with phase transitions, particularly at a critical temperature called the Curie temperature. Above this temperature, the material may lose its ferroelectric properties and transition to a paraelectric phase.
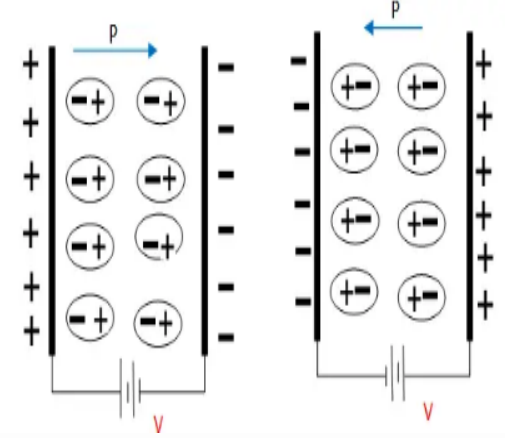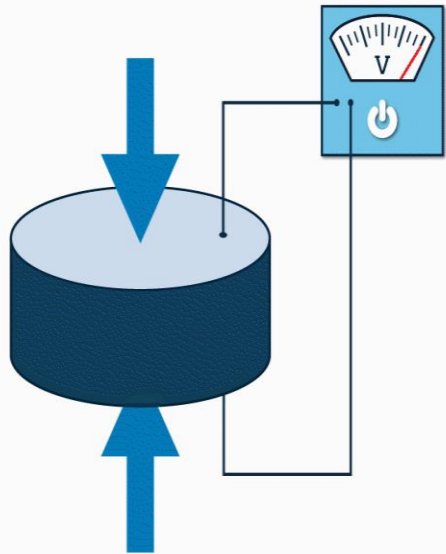
Applications:

Ferroelectric materials find use in a wide range of applications, including capacitors, piezoelectric devices (sensors and actuators), non-volatile memory (ferroelectric RAM), and sensors for thermal imaging and sound.

Piezoelectricity Mechanism

- Vibration sensors
- Actuators
- Home security
- Gas Igniters
- Ultrasonic cleaners
- Piezo Motors
- Remote controls
- Shock sensors
- Nebulizers

- Piezoelectric materials produce an electrical field when subject to a mechanical strain. Conversely, if an electrical field is applied to them, the material is stressed.

- Thus they can be used to generate low levels of power from simple mechanical motions or to deform surfaces in response to electrical signals.

An excellent example of this is the application of smart materials in ***snow skis***. Piezoelectric elements adjust the stiffness of the skis in response to conditions on the slope by damping shock and optimizing performance throughout a run.

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•**Direct Piezoelectric Effect**: When mechanical stress is applied to a piezoelectric material, it causes a displacement of electric charges within the material, resulting in the generation of an electric voltage. This effect is utilized in piezoelectric sensors, actuators, and transducers.

•**Inverse Piezoelectric Effect:** When an electric field is applied to a piezoelectric material, it induces mechanical strain or deformation in the material. This effect is exploited in piezoelectric actuators, such as those used in inkjet printers, ultrasonic devices, and precision positioning systems.

•**Applications:** Piezoelectric materials have a wide range of applications, including pressure sensors (in touchscreens and accelerometers), ultrasound transducers, energy harvesting devices (generating electricity from mechanical vibrations), and even musical instruments like electric guitars.

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Go, change the world

Superconductivity is a fascinating phenomenon in physics, characterized by the **complete absence of electrical resistance** and the expulsion of magnetic fields from the interior of a material. Here are the basic concepts and properties associated with superconductors:

1. Zero Electrical Resistance: Superconductors exhibit **zero electrical resistance** when they are cooled below a critical temperature (Tc). Below this critical temperature, superconductors **can carry an electric current indefinitely** without any loss of energy due to resistance.

2. Critical Temperature (Tc): The critical temperature is the **temperature below which a material becomes superconducting**. Different materials have different critical temperatures. Some superconductors require extremely low temperatures (near absolute zero), while others have higher critical temperatures, making them more practical for certain applications.

3. Type I and Type II Superconductors:

• **Type I Superconductors:** These materials **exhibit a sharp transition** to superconductivity and **completely expel magnetic fields** below the critical temperature. They are typically elemental superconductors like **lead and mercury**.

• **Type II Superconductors:** These materials can **tolerate some penetration** of magnetic fields even in the superconducting state. They are often compounds and alloys, such as **niobium-tin and yttrium-barium-copper oxide**.

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○ Optical property of a material is defined as its interaction with electro-magnetic radiation in the visible.

○ Materials are classified on the basis of their interaction with visible light into three categories :

- Materials that are capable of transmitting light with relatively little absorption and reflection are called **transparent materials** i.e. we can see through them.

- **Translucent materials** are those through which light is transmitted diffusely i.e. objects are not clearly distinguishable when viewed through.

- Those materials that are impervious to the transmission of visible light are termed as **opaque materials**. These materials absorb all the energy from the light photons.

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> **Refraction**: when light photons are transmitted through a material, they causes polarization of the electrons and in-turn the speed of light is reduced and the beam of light changes direction.

$$n = \frac{c_0}{c}$$

$$n = \frac{\sin\theta_i}{\sin\theta_r}$$
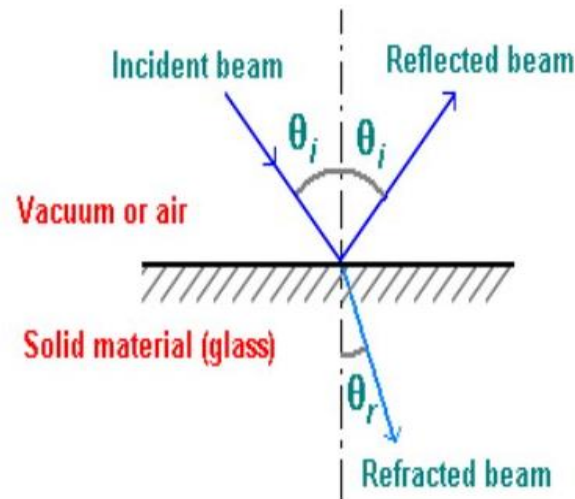
> Snell's law of light refraction:

$$\frac{n}{n'} = \frac{\sin\theta'}{\sin\theta}$$

Reflection

> Reflectivity is defined as fraction of light reflected at an interface.

$$R = \frac{I_R}{I_0}$$

> If the material is in other material with refractive index n_i

$$R = \left(\frac{n - n_i}{n + n_i}\right)^2$$

> Materials with a high index of refraction have a higher reflectivity than materials with a low index. Because the index of refraction varies with the wavelength of the photons, so does the reflectivity.

> In metals, the reflectivity is typically on the order of 0.90-0.95, whereas for glasses it is close to 0.05. The high reflectivity of metals is one reason that they are opaque. High reflectivity is desired in many applications including mirrors, coatings on glasses, etc.

- **Luminescence :** It is the process where a material **absorbs energy and then immediately emits visible or near-visible radiation**. It consists of electron excitation and then dropping down to lower energy states.

- If the emission of radiation occurs within 10^{-8} sec after excitation, the luminescence is called *fluorescence, and* if it takes longer than 10^{-8} sec, it is known as *phosphorescence.*

- Ordinarily pure materials do not display this phenomenon. Special materials called *phosphors* have the capability of absorbing high-energy radiation and spontaneously emitting lower-energy radiation. Ex.: some sulfides, oxides, tungstates, and few organic materials.

- **Based on source for electron excitation**, luminescence is three types: photo-luminescence, cathode-luminescence, and electro-luminescence.

- *Photo-luminescence: occurs in fluorescent lamps.*

- *Cathode-luminescence*
  - is produced by an **energized cathode** which generates a beam of high-energy bombarding electrons. Ex: Applications of this include electron microscope; cathode-ray oscilloscope; color television screens.

- *Electro-luminescence :*
  - occurs in devices with **p-n rectifying junctions** which are stimulated by an externally applied voltage.
  - When a forward biased voltage is applied across the device, electrons and holes recombine at the junction and emit photons in the visible range (mono-chromatic light i.e. singe color). These diodes are called *light emitting diodes* (LEDs).

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- **Laser** is an acronym for *light amplification by stimulated emission of radiation.* It is in fact special application of luminescence.

- Unlike most radiation processes, such as luminescence, which produce incoherent light, the **light produced by laser emission is coherent**.

- This is based on the fact that in certain materials, electrons excited by a stimulus produce photons which in turn excite additional photons of identical wavelength.

- Unlike ordinary light, which scatters in all directions, laser light is **monochromatic** (one wavelength or color), **directional, and coherent**, meaning all the light waves are in phase. This makes lasers very powerful and precise tools with a wide range of applications.

- Lasers are useful in many **applications** such as welding, metal cutting, heat treatment, surgery, mapping, reading compact disks, etc. Ex.: Ruby, single crystal of Al2O3

How Lasers Work

○ **Energy Absorption**: Atoms or molecules in a material (called the **gain medium**) are excited by an external energy source, usually light (optical pumping) or an electrical current. This energy elevates electrons to higher energy levels (excited states).

○ **Spontaneous Emission**: When an excited electron returns to a lower energy state, it emits a photon (a particle of light). This process happens randomly, and the emitted photon has a specific energy (or wavelength).

○ **Stimulated Emission**: If an electron is already excited and a photon with the same energy as the electron's energy gap passes by, it can stimulate the electron to drop to a lower energy state, releasing a second photon identical to the first. These two photons are in phase and travel in the same direction, amplifying the light.

○ **Optical Feedback**: In a laser, mirrors are placed at each end of the gain medium. One of the mirrors is fully reflective, and the other is partially reflective. As light bounces back and forth between the mirrors, it stimulates more emission, creating a cascade of coherent photons. Some of the light escapes through the partially reflective mirror, forming the laser beam.

- **Applications of Lasers**

- **Communications:** Lasers are used in fiber-optic communication, transmitting data over long distances with high speed and minimal signal loss.

- **Medicine:** Lasers are used in surgeries (e.g., LASIK eye surgery), dental procedures, and cancer treatments to precisely cut or destroy tissue with minimal damage to surrounding areas.

- **Manufacturing:** Industrial lasers are used for cutting, welding, engraving, and drilling materials like metal, plastic, and glass.

- **Military:** Lasers are used in targeting systems, rangefinders, and missile defence systems.

- **Entertainment:** Lasers are used in light shows, CD/DVD players, and projection systems.

- **Scientific Research:** Lasers are essential tools in various scientific experiments, including spectroscopy, particle trapping (optical tweezers), and holography.

- **Advantages of Lasers**

  - Precision in targeting and cutting

  - Ability to focus light energy over long distances

  - High efficiency in data transmission

  - Non-contact interaction with materials

Disadvantages of Lasers

- High cost, especially for industrial and medical-grade lasers
- Safety concerns, as high-powered lasers can cause eye and skin damage
- Complex cooling and maintenance requirements in some high-power lasers

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○ **Thermal emission :** When a material is heated, electrons are excited to higher energy levels, particularly in the outer energy levels where the electrons are less strongly bound to the nucleus.

○ These **excited electrons**, upon dropping back to the ground state, **release photons** in process what is called *thermal emission*.

○ During thermal emission a continuous spectrum of radiation is emitted with a minimum wavelength and the intensity distribution is dependent on the temperature.

- **Bombardment of semiconductors by photons**, with energy equal to greater than the band gap, may result in creation of electron-hole pairs that can be used to generate current. This process is called *photo conductivity*.

- **Absorption of Photons:** The material absorbs photons with energy greater than or equal to the bandgap energy of the material.

- **Creation of Electron-Hole Pairs:** The absorbed energy excites electrons from the valence band to the conduction band, leaving behind holes (positive charge carriers) in the valence band. These free electrons and holes act as charge carriers.

- **Increased Conductivity:** The presence of these charge carriers allows the material to conduct electricity more easily when a voltage is applied across it. The more light that hits the material, the more charge carriers are generated, and the higher the conductivity.

- This phenomenon is utilized in photographic light meters. Cadmium sulfide (CdS) is commonly used for the detection of visible light, as in light meters.

- Photo-conductivity is also the underlying principle of the photo-voltaic cell, known to common man as *solar cell,* used for conversion of solar energy into electricity.

- **Applications of Photoconductivity:** **Photodetectors:** Photoconductive materials are used in light sensors to detect and measure light intensity. These are employed in cameras, optical communication devices, and scientific instruments. **Photoresistors (LDRs):** These are resistors whose resistance decreases with increased light intensity. They are used in light meters, streetlights (for automatic on/off control), and alarm systems**. Solar Cells:** In photovoltaic cells, photoconductivity is used to convert light energy directly into electrical energy by generating electron-hole pairs in a semiconductor material. **Photocopy Machines**: Photoconductivity is used in photocopying (xerography). A photoconductive drum is selectively charged, and light is used to form the image on the drum by creating regions of different conductivity. **Optoelectronic Devices:** In devices like light-emitting diodes (LEDs), lasers, and phototransistors, photoconductivity plays a role in detecting or generating light.

- **Advantages of Photoconductivity:** Simple operation and low-cost materials for applications like LDRs, Fast response to changes in light intensity, Non-contact measurement and control, useful in sensors and automation systems

- **Disadvantages of Photoconductivity**: Limited response time due to carrier recombination, Sensitivity can vary with temperature and material degradation over time Limited range of light wavelengths based on the material's bandgap

○ **Optical fibers** have revolutionized the communication industry.

○ It primarily **consists of core, cladding and coating**. The core transmits the signals, while the cladding constrains the light beam to the core; outer coating protects the core and cladding from the external environment.

○ Typically both the core and cladding are made of special types of glass with carefully controlled indices of refraction.

○ **There are two primary types of optical fibers:**

○ Single-Mode Fibers (SMF): These have a small core (around 8-10 micrometers in diameter) and allow only one mode of light to propagate. They are used for long-distance communication and high bandwidth because they minimize signal dispersion.

○ Multi-Mode Fibers (MMF): These have a larger core (50-62.5 micrometers) and can support multiple modes of light. They are typically used for shorter-distance communication because signal distortion is more pronounced over long distances.

- **Working Principle:** Optical fibers work on the principle of total internal reflection, where light entering the core at a certain angle (above the critical angle) is reflected back into the core instead of refracting out into the cladding. This allows light to travel through the fiber with minimal loss.

- **Applications of Optical Fibers**

- **Telecommunications:** Optical fibers are widely used in internet and telephone networks because they can transmit data at very high speeds over long distances with little signal degradation.

- **Medical:** In endoscopy, optical fibers help transmit light and images from inside the body, enabling non-invasive medical procedures.

- **Sensors**: Optical fibers are used in sensor technology to detect changes in temperature, pressure, and strain in various industries.

- **Illumination:** Fiber optics are used in lighting displays and decorations.

- **Military and Aerospace:** Optical fibers are also used for secure communication and in harsh environments where traditional wires may not function properly.

- **Advantages of Optical Fibers**

- High bandwidth and data transmission capacity

- Low signal loss and attenuation over long distances

- Immunity to electromagnetic interference

- Lightweight and flexible

- Secure, as they are difficult to tap without detection

- **Disadvantages of Optical Fibers**

- High installation cost compared to traditional copper wires

- Fragility, as glass fibers can be more easily damaged or broken
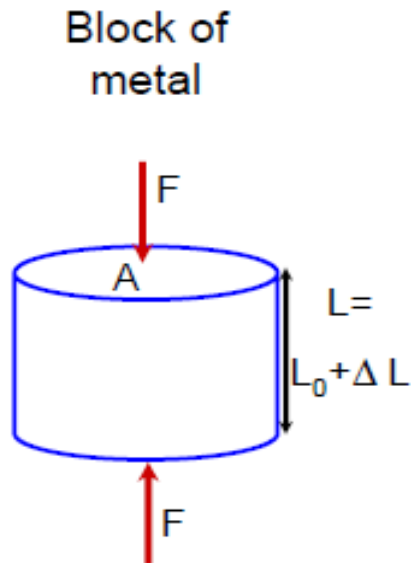
- More difficult to splice or join compared to copper cables

Block of metal

Stress (σ)
- defining F is not enough (F and A can vary)
- Stress σ stays constant

$$\sigma = \frac{F}{A}$$

- Units

Force / area = N / m^2 = Pa

usually in MPa or Gpa

Strain (ε) – result of stress
- For tension and compression: change in length of a sample divided by the **original** length of sample

$$\varepsilon = \frac{\Delta L}{L}$$

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Not deformed

Pure shear

Torsion
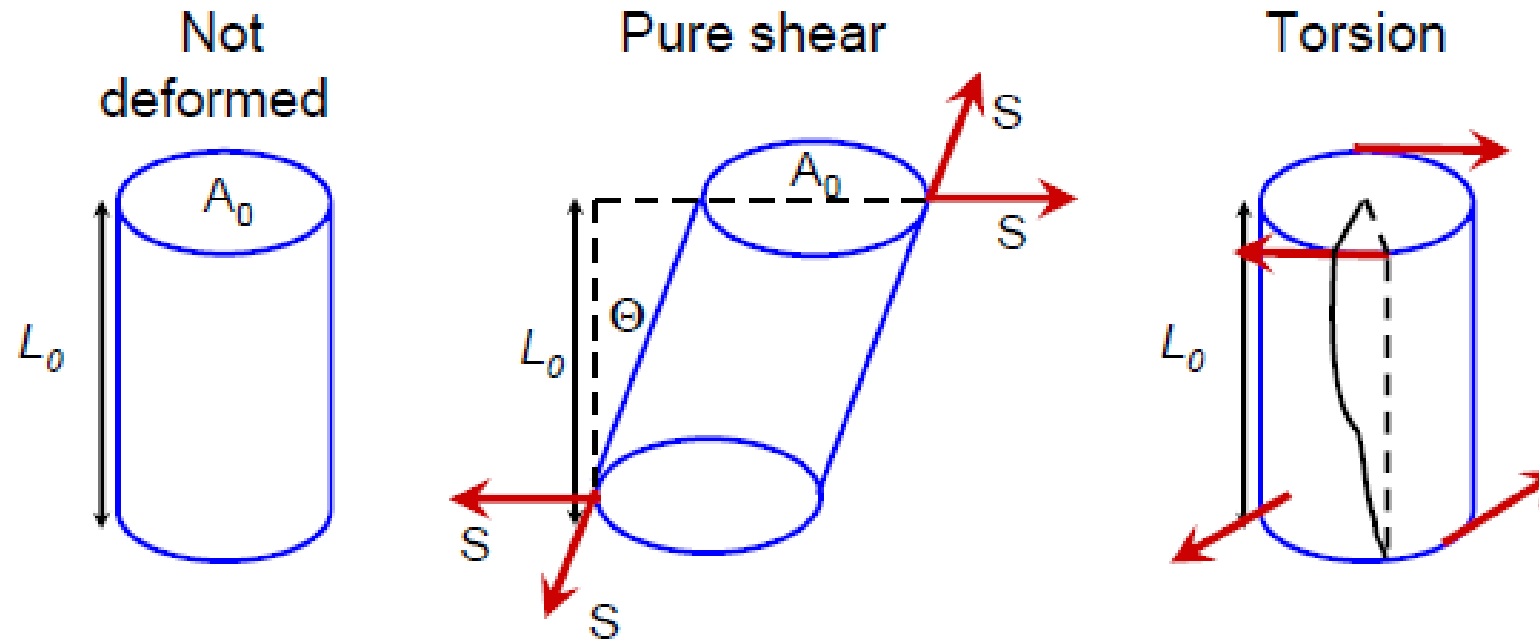
Note: the forces are applied in this way, so that there is no net torque
If the forces are applied **along** the faces of the material, they are called shear forces

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Result of a uniaxial tensile test

Change from linear to non linear
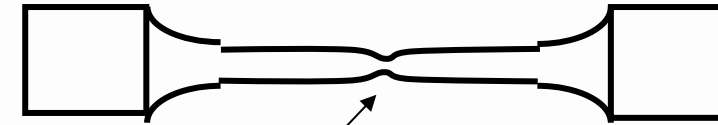
necking

σe (Engineering stress) = P/A0

Ultimate tensile strength

σ_{UTS}

Yield point

True stress- strain curve

σT (True stress) = P/Ai

Ai – instantaneous area

Yield stress σ_y

Failure stress σf

break

Area = Toughness

Strain is a measure of ductility

STIFFNESS

Slope = Young's modulus (Y)

DUCTILITY

ε_f (strain to fracture)

STRENGTH

Strain Hardening

elastic

plastic

εy

εu

εf

e (engineering strain)

ε(True strain)

41
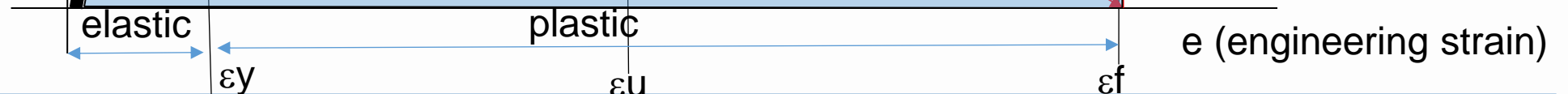
Stiffness	Resistance to *elastic* deformation	Young's modulus (E)
Strength	Resistance to *plastic* deformation	Yield stress (σy)
Toughness	Resistance to *fracture*	Energy absorbed before fracture (G)
ductility	Ability to deform plastically	Strain at fracture (εf)

Proof stress- stress corresponding to 0.2% strain (0.002 strain)

Resilience- Area under the elastic region – Ability to absorb energy when a material is elastically deformed and then to return to original state upon load removal
Example –cantilever beam or spring

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The degree to which a structure deforms or strains depends on the magnitude of an imposed stress. For most metals that are stressed in tension and at relatively low levels, stress and strain are proportional to each other through the relationship

$$\sigma = E\epsilon$$

This is known as Hooke's law, and the constant of proportionality *E (GPa or psi)* is the **modulus of elasticity,** or ***Young's modulus. For most typical metals the magnitude*** of this modulus ranges between 45 GPa, for magnesium, and 407 Gpa, for tungsten.

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Ductility is another important mechanical property. It is a measure of the degree of plastic deformation that has been sustained at fracture. A material that experiences very little or no plastic deformation upon fracture is termed *brittle.* Ductility may be expressed quantitatively as either *percent elongation or percent reduction in area. The percent elongation %EL is the percentage of plastic strain at fracture.*

$$\%\,EL = \left(\frac{l_f - l_0}{l_0}\right) \times 100$$

where l_f is the fracture length and l_0 is the original gauge length as above.

In as much as a significant proportion of the plastic deformation at fracture is confined to the neck region, the magnitude of %EL will depend on specimen gauge length.

The shorter l_0 the greater is the fraction of total elongation from the neck and, consequently, the higher the value of %EL. Therefore, l_0 should be specified when percent elongation values are cited; it is commonly 50 mm (2 in.).

Percent reduction in area %RA is defined as

$$\%\,RA = \left(\frac{A_0 - A_f}{A_0}\right) \times 100$$

44

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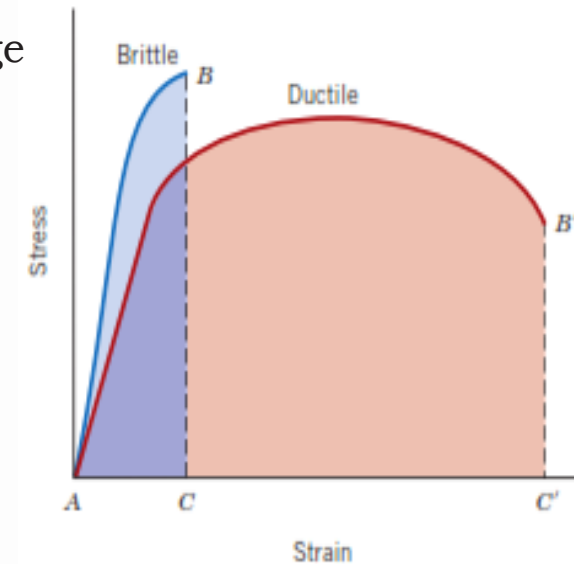
Resilience is the capacity of a material to absorb energy when it is deformed elastically and then, upon unloading, to have this energy recovered. The associated property is the *modulus of resilience, U_r* which is the strain energy per unit volume required to stress a material from an unloaded state up to the point of yielding.

Computationally, the modulus of resilience for a specimen subjected to a uniaxial tension test is just the area under the engineering stress–strain curve taken to yielding

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Toughness is a mechanical term that is used in several contexts; loosely speaking**,** it is a measure of the **ability of a material to absorb energy up to fracture**. Specimen geometry as well as the manner of load application are important in toughness determinations. For dynamic (high strain rate) loading conditions and when a notch (or point of stress concentration) is present, *notch toughness is assessed by* using an *impact test.*

Furthermore, fracture toughness is a property indicative of a material's resistance to fracture when a crack is present For the static (low strain rate) situation, toughness may be ascertained from the results of a tensile stress–strain test. **It is the area under the curve up to the point of fracture**.

The units for toughness are the same as for resilience (i.e**., energy per unit volume** of material). For a material to be tough, it must display both strength and ductility; often, ductile materials are tougher than brittle ones. Hence, even though the brittle material has higher yield and tensile strengths, it has a lower toughness than the ductile one, by virtue of lack of ductility.

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Most structures are designed to ensure that only elastic deformation will result when a stress is applied. A structure or component that has plastically deformed, or experienced a permanent change in shape, may not be capable of functioning as intended.

It is therefore desirable to know the stress level at which plastic deformation begins, or where the phenomenon of **yielding occurs.** For metals that experience this gradual elastic–plastic transition, the point of yielding may be determined as the initial departure from linearity of the stress–strain curve; this is sometimes called the **proportional limit.** In such cases the position of this point may not be determined precisely. As a consequence, a convention has been established wherein a straight line is constructed parallel to the elastic portion of the stress–strain curve at some specified strain offset, usually 0.002.

The stress corresponding to the intersection of this line and the stress–strain curve as it bends over in the plastic region is defined as the **yield strength**. *Of course, the units of yield strength are MPa or psi.*

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For those materials having a nonlinear elastic region, use of the strain offset method is not possible, and the usual practice is to define the yield strength as the stress required to produce some amount of strain (e.g.,).

Some steels and other materials exhibit the tensile stress–strain behavior. ***The elastic–plastic transition is very well defined and occurs* abruptly in what is termed a *yield point phenomenon**. At the upper yield point, plastic* deformation is initiated with an actual decrease in stress. Continued deformation fluctuates slightly about some constant stress value, termed the lower yield point; stress subsequently rises with increasing strain. For metals that display this effect, the yield strength is taken as the average stress that is associated with the lower yield point, since it is well defined and relatively insensitive to the testing procedure. it is not necessary to employ the strain offset method for these materials.

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After yielding, the stress necessary to continue plastic deformation in metals increases to a maximum, *and then decreases to the eventual* fracture, point *F. The* **tensile strength** ***TS (MPa or psi) is the stress at the maximum*** on the engineering stress–strain curve. This corresponds to the maximum stress that can be sustained by a structure in tension; if this stress is applied and maintained, fracture will result. All deformation up to this point is uniform throughout the narrow region of the tensile specimen. However, at this maximum stress, a small constriction or neck begins to form at some point, and all subsequent deformation is confined at this neck. This phenomenon is termed "necking," and fracture ultimately occurs at the neck. The fracture strength corresponds to the stress at fracture.

Tensile strengths may vary anywhere from 50 MPa (7000 psi) for an aluminum to as high as 3000 MPa (450,000 psi) for the high-strength steels. Ordinarily, when the strength of a metal is cited for design purposes, the yield strength is used. This is because by the time a stress corresponding to the tensile strength has been applied, often a structure has experienced so much plastic deformation that it is useless. Furthermore, fracture strengths are not normally specified for engineering design purposes.

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Hardness, is a measure of a material's resistance to localized plastic deformation (e.g., a small dent or a scratch)

Table 6.5 Hardness-Testing Techniques
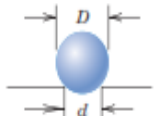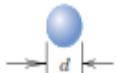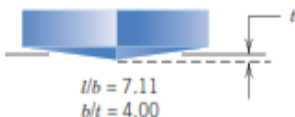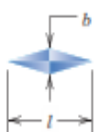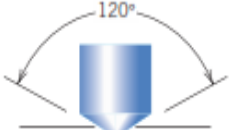
Test	Indenter	Shape of Indentation Side View	Shape of Indentation Top View	Load	Formula for Hardness Number[a]
Brinell	10-mm sphere of steel or tungsten carbide	D, d	d	P	$HB = \dfrac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid	$136°$	d_1, d_1	P	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid	$l/b = 7.11$ $b/t = 4.00$	b, l	P	$HK = 14.2P/l^2$
Rockwell and Superficial Rockwell	Diamond cone; $\frac{1}{16}, \frac{1}{8}, \frac{1}{4}, \frac{1}{2}$ in. diameter steel spheres	$120°$		60 kg, 100 kg, 150 kg } Rockwell; 15 kg, 30 kg, 45 kg } Superficial Rockwell	

Table 6.6a Rockwell Hardness Scales

Scale Symbol	Indenter	Major Load (kg)
A	Diamond	60
B	$\frac{1}{16}$-in. ball	100
C	Diamond	150
D	Diamond	100
E	$\frac{1}{8}$-in. ball	100
F	$\frac{1}{16}$-in. ball	60
G	$\frac{1}{16}$-in. ball	150
H	$\frac{1}{8}$-in. ball	60
K	$\frac{1}{8}$-in. ball	150

The Rockwell tests constitute the most common method used to measure hardness because they are so simple to perform and require no special skills. Several different scales may be utilized from possible combinations of various indenters and different loads, which permit the testing of virtually all metal alloys (as well as some polymers). Indenters include spherical and hardened steel balls having diameters of 1/16, 1/8, 1/4 and 1/2 in. (1.588, 3.175, 6.350, and 12.70 mm), and a conical diamond (Brale) indenter, which is used for the hardest materials.

For Rockwell, the minor load is 10 kg, whereas major loads are 60, 100, and 150 kg. Each scale is represented by a letter of the alphabet; several are listed with the corresponding indenter and load in Tables 6.5 and 6.6a.For superficial tests, 3 kg is the minor load; 15, 30, and 45 kg are the possible major load values. These scales are identified by a 15, 30, or 45 (according to load), followed by N, T, W, X, or Y, depending on indenter.

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In Brinell tests, as in Rockwell measurements, a hard, spherical indenter is forced into the surface of the metal to be tested. The diameter of the hardened steel (or tungsten carbide) indenter is 10.00 mm (0.394 in.). Standard loads range between 500 and 3000 kg in 500-kg increments; during a test, the load is maintained constant for a specified time (between 10 and 30 s). Harder materials require greater applied loads.

The Brinell hardness number, HB, is a function of both the magnitude of the load and the diameter of the resulting indentation. This diameter is measured with a special low-power microscope, utilizing a scale that is etched on the eyepiece. The measured diameter is then converted to the appropriate HB number using a chart; only one scale is employed with this technique.

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Two other hardness-testing techniques are Knoop (pronounced) and Vickers (sometimes also called diamond pyramid). For each test a very small diamond indenter having pyramidal geometry is forced into the surface of the specimen. Applied loads are much smaller than for Rockwell and Brinell, ranging between 1 and 1000 g. The resulting impression is observed under a microscope and measured; this measurement is then converted into a hardness number. Careful specimen surface preparation (grinding and polishing) may be necessary to ensure a well-defined indentation that may be accurately measured.

The Knoop and Vickers hardness numbers are designated by HK and HV, respectively, and hardness scales for both techniques are approximately equivalent. Knoop and Vickers are referred to as micro indentation-testing methods on the basis of indenter size. Both are well suited for measuring the hardness of small, selected specimen regions; furthermore, Knoop is used for testing brittle materials such as ceramics.

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Correlation Between Hardness and Tensile Strength

Both tensile strength and hardness are indicators of a metal's resistance to plastic deformation. Consequently, they are roughly proportional, as shown in Figure 6.19, for tensile strength as a function of the HB for cast iron, steel, and brass. The same proportionality relationship does not hold for all metals, as Figure 6.19 indicates. As a rule of thumb for most steels, the HB and the tensile strength are related according to
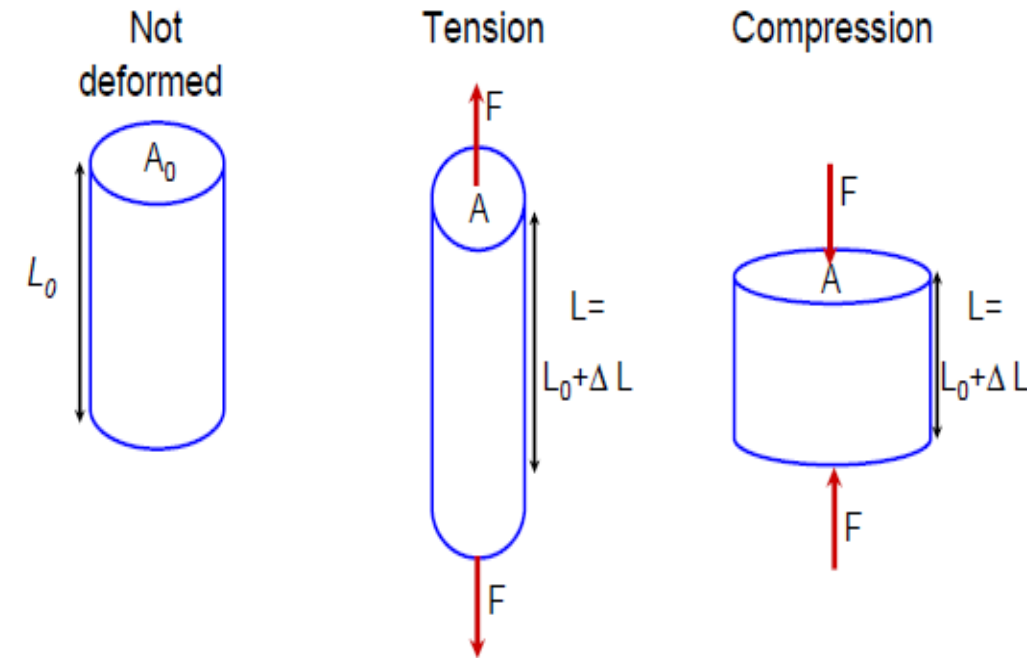
$$TS(\text{MPa}) = 3.45 \times HB \qquad (6.20a)$$

$$TS(\text{psi}) = 500 \times HB \qquad (6.20b)$$
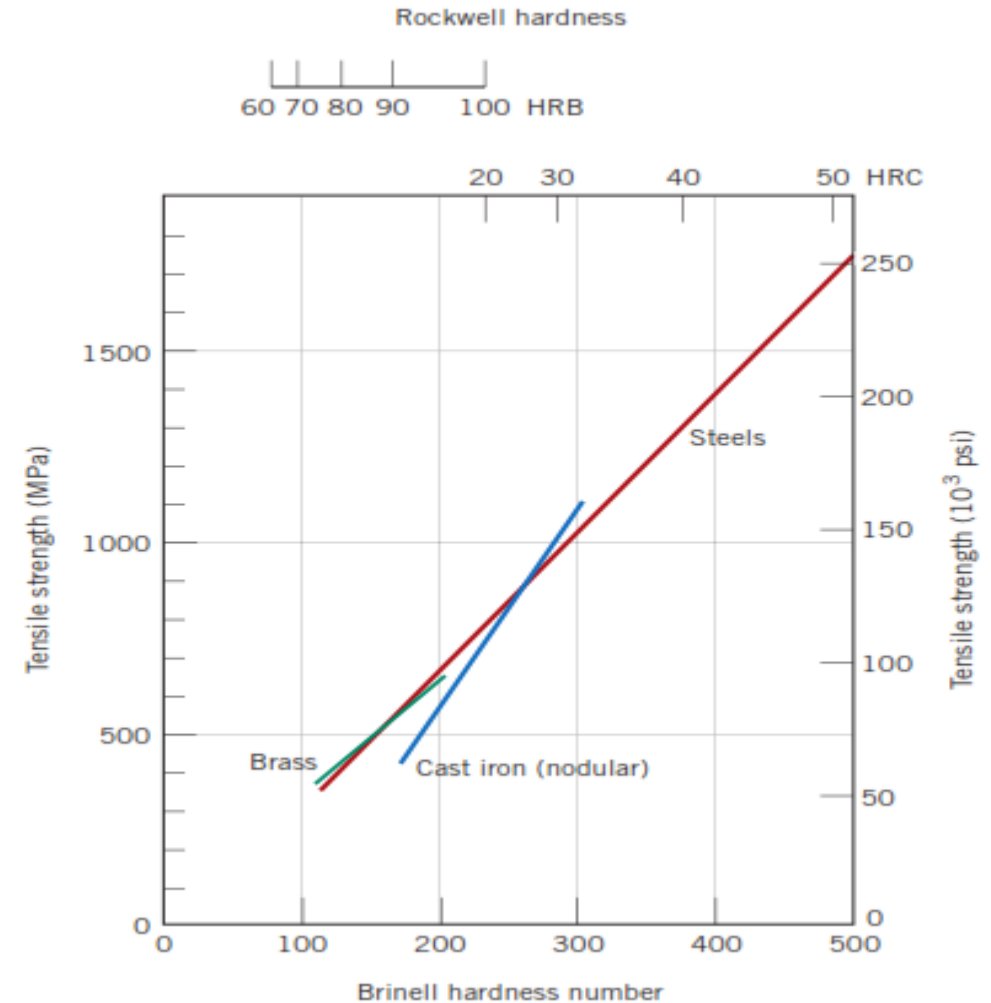
- ***Change in dimensions or form of matter under the action of applied forces.*** (external forces or physical and physic chemical processes-temperature gradient)

- Metal piece is subjected to a uniaxial force ⇒ deformation occurs

• When force is removed:

- metal returns to its original dimensions ⇒ **elastic** deformation (atoms return to their *original position*)

- metal deformed to an extent that it cannot fully recover its original dimensions ⇒ **plastic** deformation (shape of the material changes, atoms are *permanently displaced* from their positions)

- Plastic deformation many times intentionally done (Stamping of automobile part, extrusion of telephone wires, forging of crankshafts)

Load can be applied to the material by applying axial forces:

Not deformed

Tension

Compression

A_0

L_0

F

A

$L = L_0 + \Delta L$

F

F

A

$L = L_0 + \Delta L$

F

ΔL can be measured as a function of the applied force; area A_0 changes in response

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Two prominent mechanisms of plastic deformation, namely **slip and twinning .**

•**Slip** is the prominent mechanism of plastic deformation in metals. It involves **sliding of blocks of crystal** over one other along definite crystallographic planes, called **slip planes**.

•it is analogous to a deck of cards when it is pushed from one end. Slip occurs when shear stress applied exceeds a critical value.

During slip each atom usually moves same integral number of atomic distances along the slip plane producing a step, but the **orientation of the crystal remains the same.**

•Generally **slip plane is the plane of greatest atomic density**, and the **slip direction is the close packed direction** within the slip plane.

For a given set of **slip systems,** slip occurs on that system where the shear stress is maximum
 (at 45 degree to the applied tensile load direction)

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A rod of a single crystal **Zn (hcp)** stressed beyond its elastic limit:
- slipbands: slip of metal atoms on specific crystallographic planes (*slip planes*)
- slip is **predominately** along the *basal planes*

A rod of a single crystal **Cu (fcc)** during plastic deformation:
- slip lines: 50-500 atoms apart
- slipbands: separated by ~>10,000 atomic planes

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Table-6.1: *Slip systems for different crystal structures.*

Crystal	Occurrence	Slip planes	Slip directions
FCC		{111}	<110>
BCC	More common	{110}	<111>
	Less common	{112},{123}	
HCP	More common	Basal plane	Close packed
	Less common	Prismatic & Pyramidal planes	directions
NaCl		{110}	<110>

Slip in polycrystalline material involves ***generation, movement and (re-)arrangement*** of dislocations. Because of dislocation motion on different planes in various directions, they may interact as well. This interaction can cause dislocation ***immobile or mobile at higher stresses.*** During deformation, mechanical integrity and coherency are maintained along the grain boundaries; that is, the grain boundaries are constrained, to some degree, in the shape it may assume by its neighbouring grains. Once the yielding has occurred, continued plastic deformation is possible only if enough slip systems are simultaneously operative so as to accommodate grain shape changes while maintaining grain boundary integrity.

- Polycrystals stronger than single crystals – grain boundaries are barriers to dislocation motion.

- Slip planes & directions change from one grain to another.

- Resolved shear stress (t_R) will vary from one grain to another.

- The grain with the largest Resolved shear stress yields first.

- Other (less favorably oriented) grains yield later.

S

300 mm
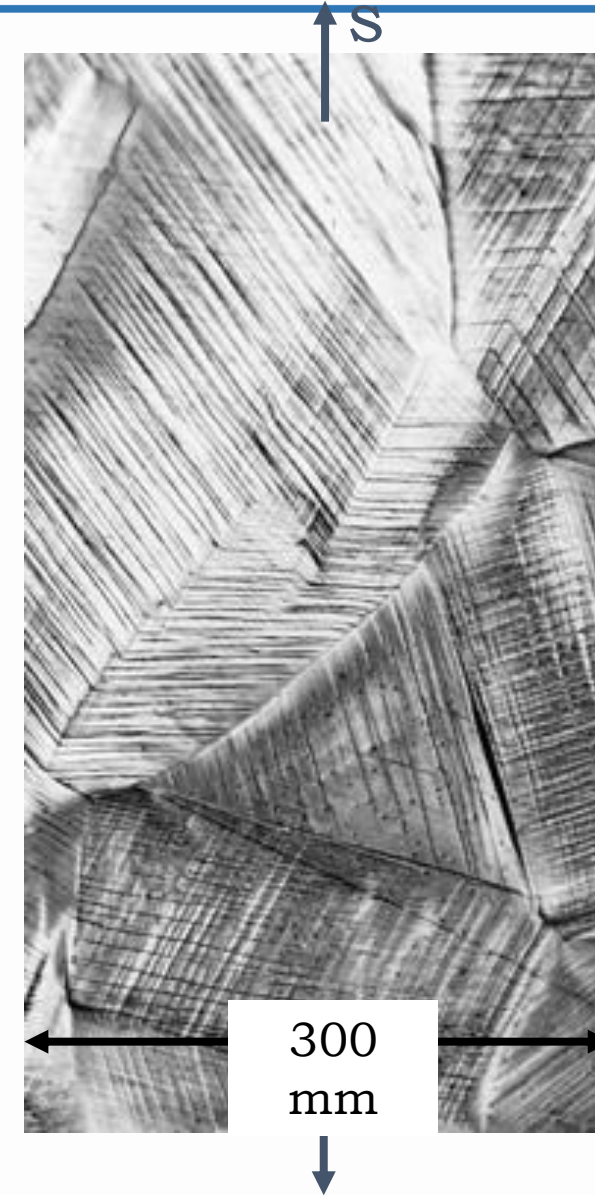
Adapted from Fig. 7.10, *Callister & Rethwisch 8e.* (Fig. 7.10 is courtesy of C. Brady, National Bureau of Standards [now the National Institute of Standards and Technology, Gaithersburg, MD].)

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Twinning : Portion of crystal takes up an orientation that is related to the orientation of the rest of the untwined lattice in a definite, symmetrical way.

The twinned portion of the crystal is a mirror image of the parent crystal.

•The plane of symmetry is called twinning plane.

•The important role of twinning in plastic deformation is that it causes changes in plane orientation so that further slip can occur.
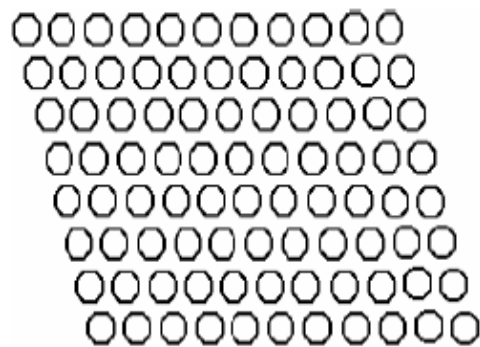
Undeformed Crystal   After Slip   After Twinning
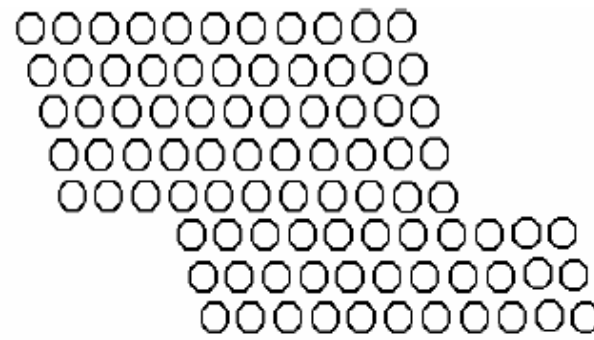
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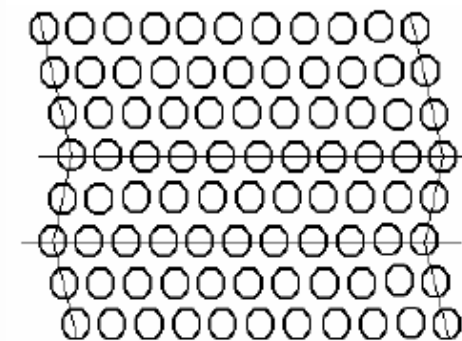
Twinning generally occurs when slip is restricted, because the stress necessary for twinning is usually higher than that for slip. Thus, some HCP metals with limited number of slip systems may preferably twin. Also, BCC metals twin at low temperatures because slip is difficult. Of course, twinning and slip may occur sequentially or even concurrently in some cases.

Table-6.2: *Twin systems for different crystal structures.*

Crystal	Example	Twin plane	Twin direction
FCC	Ag, Au, Cu	(111)	[112]
BCC	α-Fe, Ta	(112)	[111]
HCP	Zn, Cd, Mg, Ti	(10̄12)	[̄1011]

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Table-6.3: *Comparison of mechanism of plastic deformation.*

	during/in slip	**during/in twinning**
Crystal orientation	Same above and below the slip plane	Differ across the twin plane
Size (in terms of inter-atomic distance)	Multiples	Fractions
Occurs on	Widely spread planes	Every plane of region involved
Time required	Milli seconds	Micro seconds
Occurrence	On many slip systems simultaneously	On a particular plane for each crystal

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Another important plastic deformation mechanism (low T)
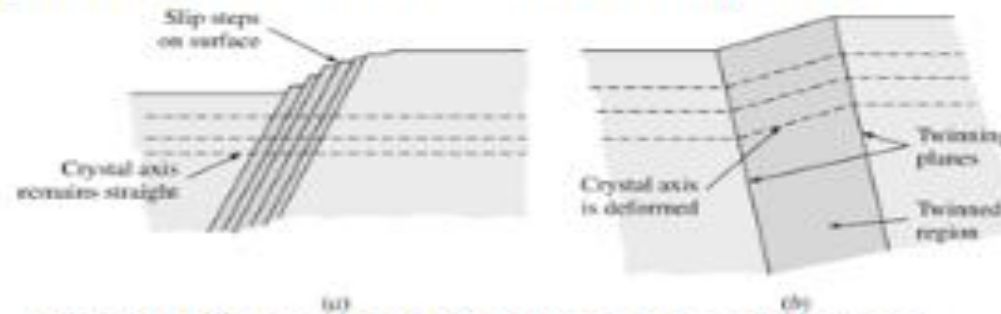
Schematic diagram of surfaces of a deformed metal after (a) slip and (b) twinning
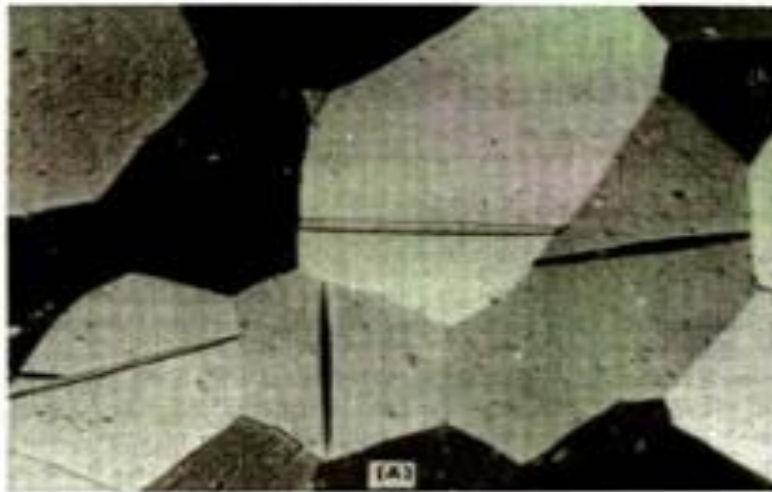
Fig. 6.22. Deformation twins in zirconium.

from G. Gottstein
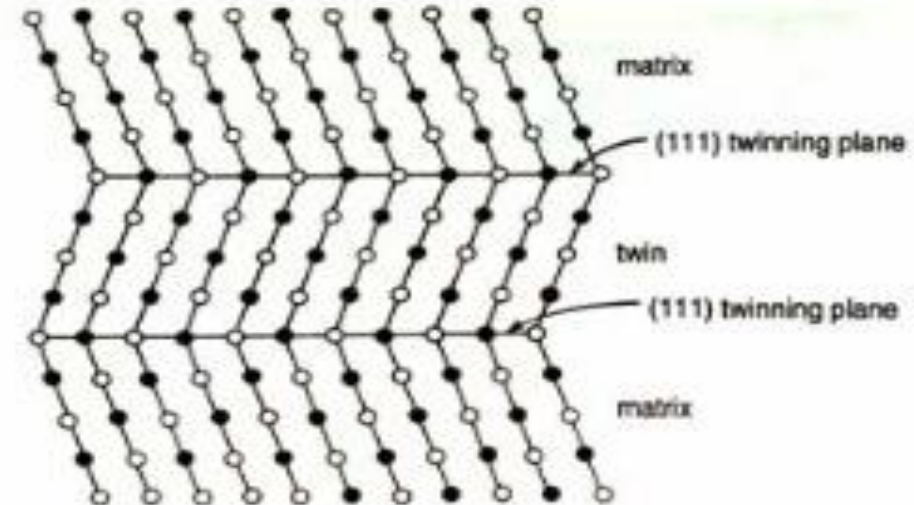
Fig. 6.23. Atomic configuration in matrix and twin of a fcc lattice.

Chapter 6

24

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Comparison between Slip and Twinning

The differences between slip and twinning are as follows:

1) **Deformed surface:** Slip forms a series of steps (seen as lines in microscope) on the surface, whereas twinning forms a well-defined region of deformed crystal on the surface (seen as a band under microscope), as shown in **Fig. 2-22.**
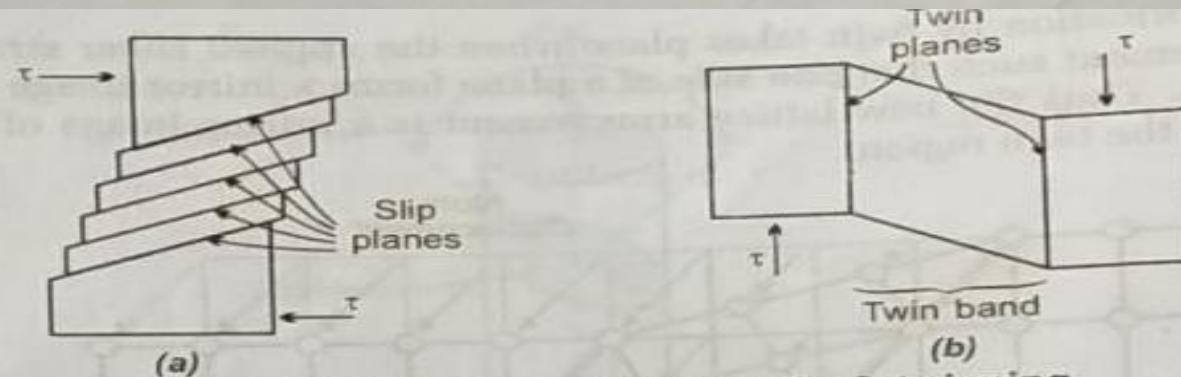
Fig. 2-22. Difference between slip & twinning

2) **Crystallographic orientation:** The crystallographic orientation does not change after the slip, while the orientation changes after twinning with the formation of a mirror image along the twin plane.

3) **Atomic displacement:** Slip takes place in distinct atomic spacing multiplies, but in the case of twinning the atomic displacement is less than the inter-atomic distance. Moreover, the atomic displacement in twinning varies from a twin plane, but is proportional to the distance from the twin plane.

4) **Overall deformation:** The volume of metal undergoing twinning is very small; hence the overall plastic deformation by twinning is very small as compared to that caused by slip dislocation.

5) **Stress for deformation:** Twinning requires a higher value of shear stress to cause deformation than the slip.

6) **Crystal structures:** Mechanical twinning is common in HCP and BCC structured metals, and takes place under shock or impact loading. Slip is most common in FCC structures and takes place at lower values of loading like in metal forming by rolling, drawing, etc.

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Summary

•Introduced stress, strain and modulus of elasticity

$$\sigma = \frac{F}{A}$$

$$\varepsilon = \frac{\Delta L}{L}$$

$$E = \frac{\sigma(stress)}{\varepsilon(strain)}$$

• Plastic deformations of single crystal metals

- In the single crystal metal - slip mechanism: dislocations move through the metal crystals like wave fronts, allowing metallic atoms to slide over each other under *low shear stress*

- Slip process begins within the crystal when the shear stress on the slip plane in slip direction reaches **critical resolved shear stress** τ_c

 - *Schmid's law:*

$$\tau_r = \frac{F \cos \lambda \cos \phi}{A_o} = \frac{F}{A_o} \cos \lambda \cos \phi = \sigma \cos \lambda \cos \phi$$

• Plastic deformations in polycrystalline metals

- Strength and grain size are related by *Hall-Pelch equation:*

$$\sigma_y = \sigma_o + \frac{k}{\sqrt{d}}$$

• Nanocrystalline materials

Chapter 6

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Viscoelastic Deformation: Viscoelasticity is the property of materials that exhibit **both viscous (flow-like) and elastic** (spring-like) characteristics when subjected to deformation.

1.Behavior: When a material is subjected to a constant load or stress, it exhibits *time-dependent deformation*. This means that the **material deforms over time**, and *the rate of deformation depends on the duration of the applied stress.*

2.Applications: Many polymeric materials, such as rubber and certain plastics, show viscoelastic behavior. Understanding viscoelastic properties is crucial in applications like **damping materials, gaskets,** and certain components in mechanical systems.

An **amorphous polymer may behave like a glass at low temperatures, a rubbery solid at intermediate temperatures and a viscous liquid as the temperature is further raised.**

For relatively small deformations, the mechanical behavior at low temperatures may be elastic; that is, in conformity to Hooke's law, At the highest temperatures, viscous or liquidlike behavior prevails.

For intermediate temperatures the polymer is a rubbery solid that exhibits the combined mechanical characteristics of these two extremes; the condition is termed **viscoelasticity.**
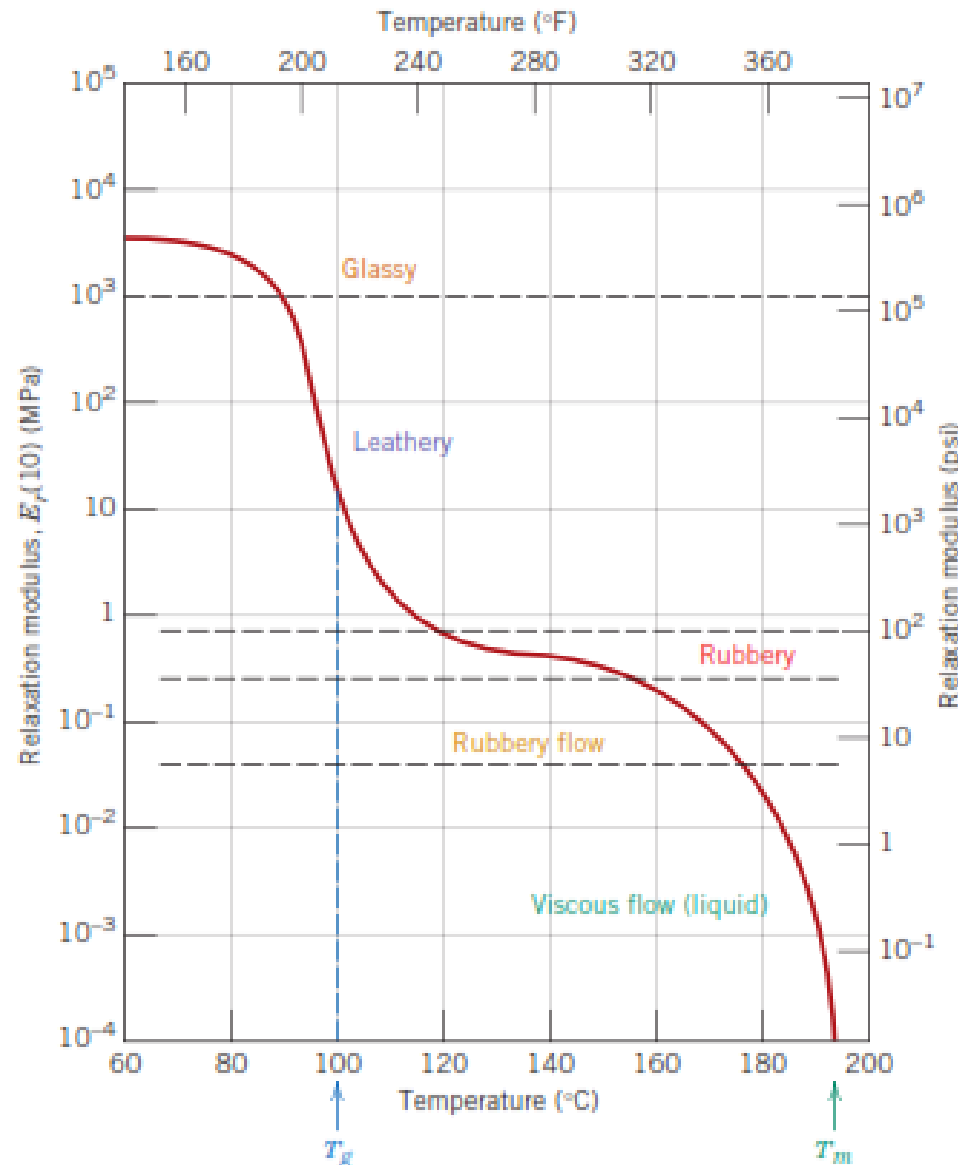
Figure 15.7 Logarithm of the relaxation modulus versus temperature for amorphous polystyrene, showing the five different regions of viscoelastic behavior. (From A. V. Tobolsky, *Properties and Structures of Polymers.* Copyright © 1960 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

Elastic deformation is instantaneous, which means that total deformation (or strain) occurs the instant the stress is applied or released (i.e., the strain is independent of time). In addition, upon release of the external stress, the deformation is **totally recovered**— the specimen assumes its original dimensions. This behavior is represented in Figure **15.5b** *as strain versus time for the instantaneous load–time* curve, shown in Figure 15.5a.

For the intermediate viscoelastic behavior, the imposition of a stress in the manner of Figure 15.5a results in an instantaneous elastic strain, which is followed by **a viscous, time-dependent strain,** a form of anelasticity, this behavior is illustrated in Figure 15.5c.

By way of contrast, for totally viscous behavior, deformation or strain is not instantaneous; that is, in response to an applied stress, **deformation is delayed** or **dependent on time**. Also, this deformation is **not reversible** or completely recovered after the stress is released. This phenomenon is demonstrated in Figure 15.5d.

Figure 15.5 (a) Load versus time, where load is applied instantaneously at time t_a and released at t_r. For the load–time cycle in (a), the strain-versus-time responses are for totally elastic (b), viscoelastic (c), and viscous (d) behaviors.

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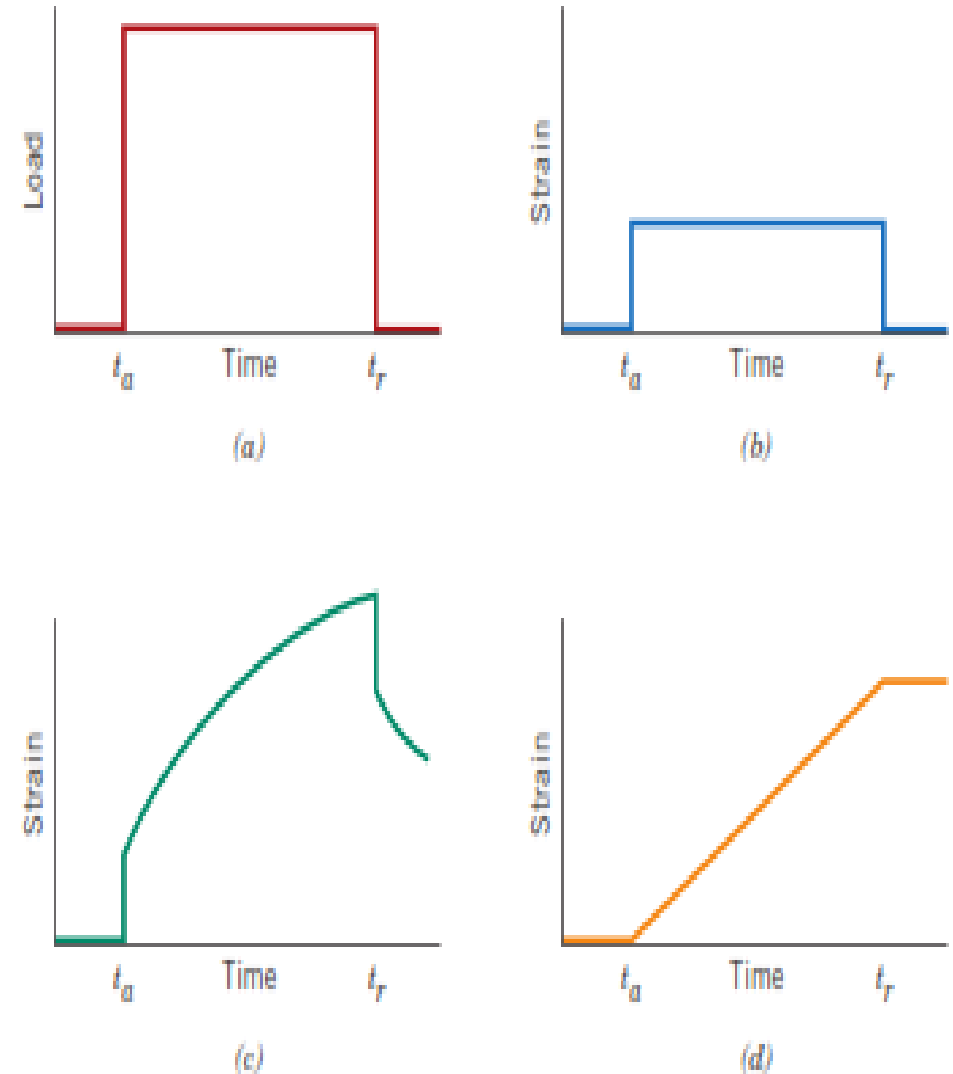
A familiar example of these viscoelastic extremes is found in a silicone polymer that is sold as a novelty and known by some as "silly putty." When rolled into a ball and dropped onto a horizontal surface, it bounces elastically—the rate of deformation during the bounce is very rapid. On the other hand, if pulled in tension with a gradually increasing applied stress, the material elongates or flows like a highly viscous liquid. For this and other viscoelastic materials, the rate of strain determines whether the deformation is elastic or viscous.

1.Definition: Impact energy is the amount of energy dissipated or absorbed by a material when it experiences a sudden force or impact.

2.Behavior: Materials respond differently to impact loading based on their composition and structural characteristics. Brittle materials may fracture upon impact, while ductile materials may deform before failure.

3.Applications: Impact energy is an important consideration in designing materials for applications where they may experience sudden and intense forces, such as in the automotive industry (crashworthiness), construction (impact resistance), or sports equipment.

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)
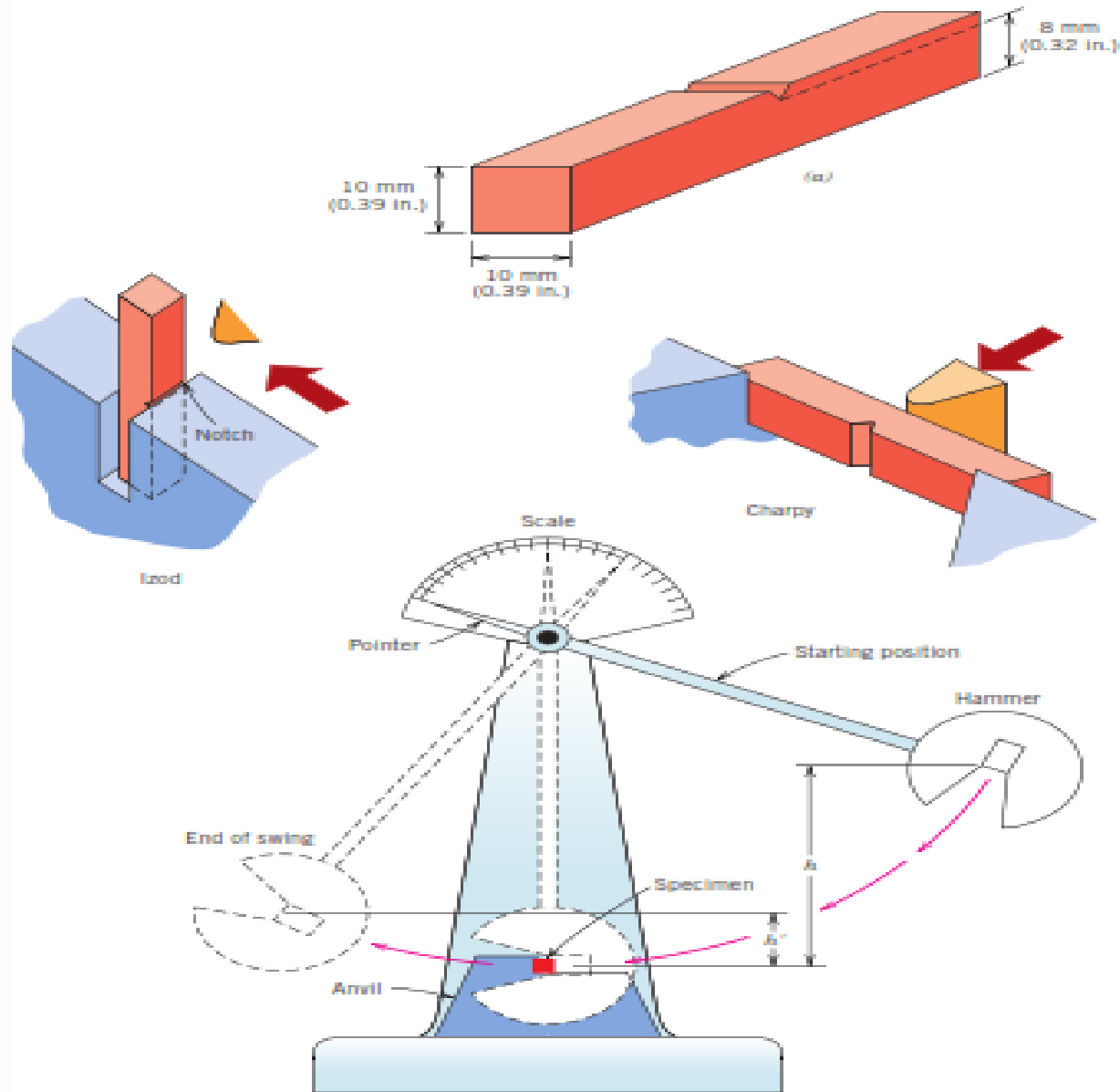
(*a*) *Specimen used* for Charpy and Izod impact tests. (*b*) *A* schematic drawing of an impact testing apparatus. The hammer is released from fixed height h and strikes the specimen; the energy expended in fracture is reflected in the

difference between h and the swing height $h_¿$.

Specimen placements for both Charpy and Izod

tests are also shown.

1.Definition: Fracture toughness is a **measure of a material's resistance to crack propagation or fracture.** It quantifies the ability of a material to withstand the growth of a pre-existing crack.

2.Behavior: Materials with high fracture toughness can resist crack propagation and are less prone to sudden failure. It is particularly important in materials engineering to ensure the reliability and safety of structures and components.

3.Applications: Fracture toughness is a critical parameter in designing materials for applications where the presence of flaws or cracks is inevitable, such as in structural components, aerospace materials, and biomaterials.

Fracture Toughness

Furthermore, using fracture mechanical principles, an expression has been developed that relates this critical stress for crack propagation (σ_c) and crack length (a) as

$$K_c = Y\sigma_c\sqrt{\pi a} \qquad (8.4)$$

In this expression K_c is the **fracture toughness**, a property that is a measure of a material's resistance to brittle fracture when a crack is present. Worth noting is that K_c has the unusual units of MPa$\sqrt{m}$ or psi$\sqrt{in}$. (alternatively, ksi$\sqrt{in}$.). Further-more, Y is a dimensionless parameter or function that depends on both crack and specimen sizes and geometries, as well as the manner of load application.

Fracture: separation of a body into pieces due to stress, at temperatures below the melting point.

Steps in fracture: crack formation

  crack propagation

Depending on the ability of material to undergo plastic deformation before the fracture two fracture modes can be defined - **ductile or brittle**

- **Ductile fracture** - most metals (not too cold):

  Extensive plastic deformation ahead of crack

  Crack is "stable": *resists further extension unless applied stress is increased*

- **Brittle fracture** - ceramics, ice, cold metals:

  Relatively little plastic deformation

  Crack is "unstable": *propagates rapidly without increase in applied stress*

Ductile fracture is preferred in most applications

Ductile materials - extensive plastic deformation and energy absorption ("toughness") before fracture

Brittle materials - little plastic deformation and low energy absorption before fracture

Brittle vs. Ductile Fracture

A   B   C
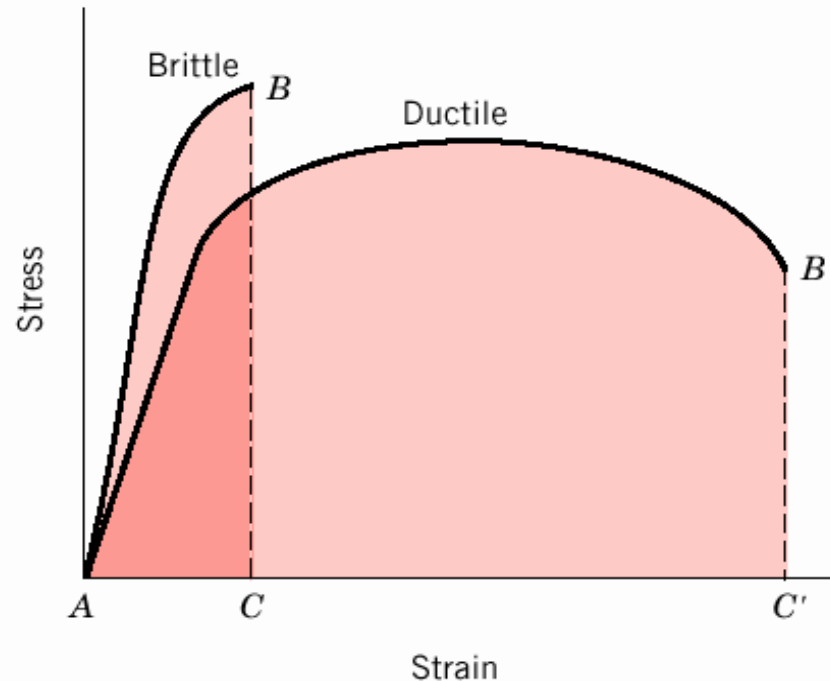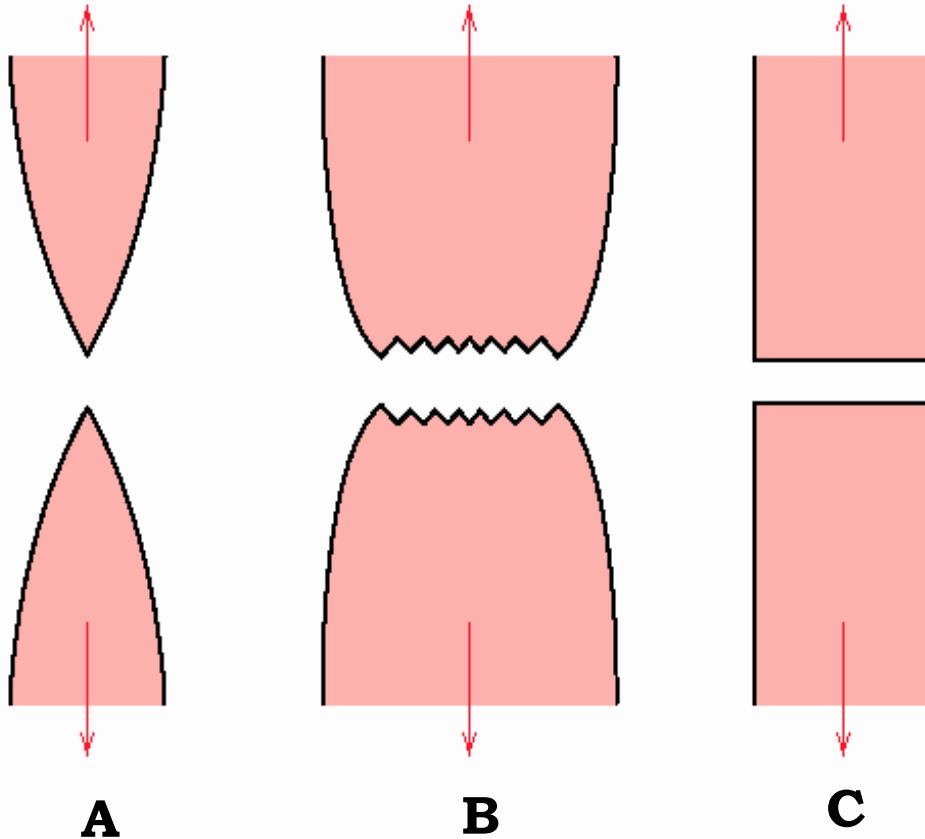
A. **Very ductile**, soft metals (e.g. Pb, Au) at room temperature, other metals, polymers, glasses at high temperature.

B. **Moderately ductile fracture**, typical for ductile metals

C. **Brittle fracture,** cold metals, ceramics.

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Crack grows 90° to applied stress

(Cup-and-cone fracture in Al
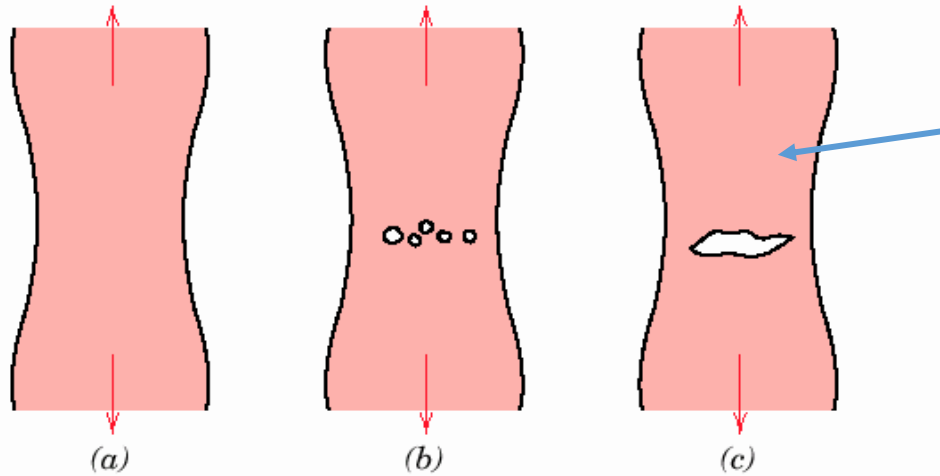
45° - maximum shear stress
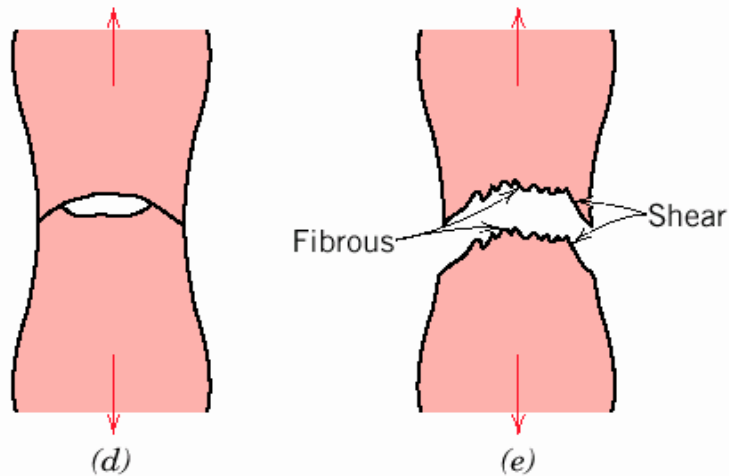
Cup-and-cone fracture

(a) Necking
(b) Formation of micro voids
(c) Coalescence of micro voids to form a crack
(d) Crack propagation by shear deformation
(e) Fracture

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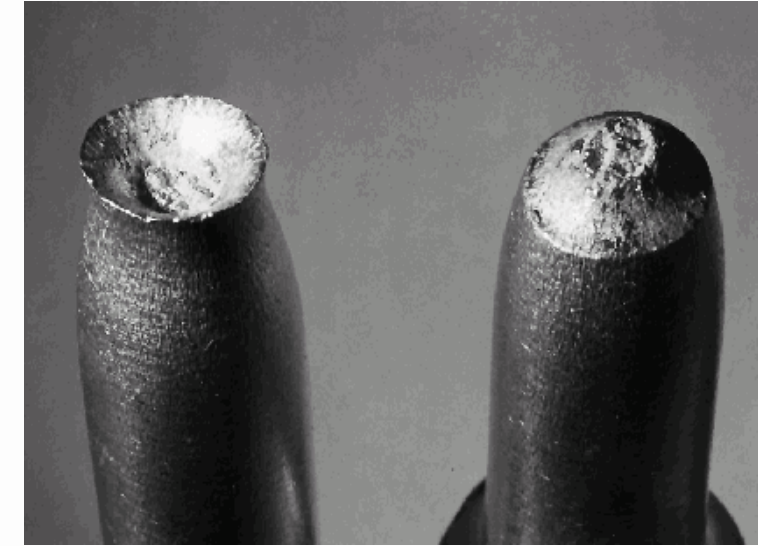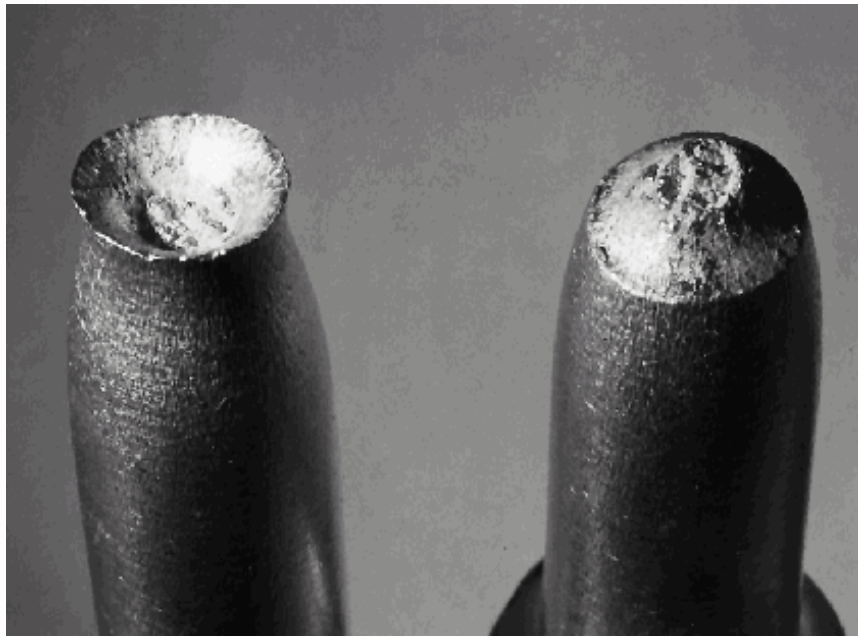
(Cup-and-cone fracture in Al)
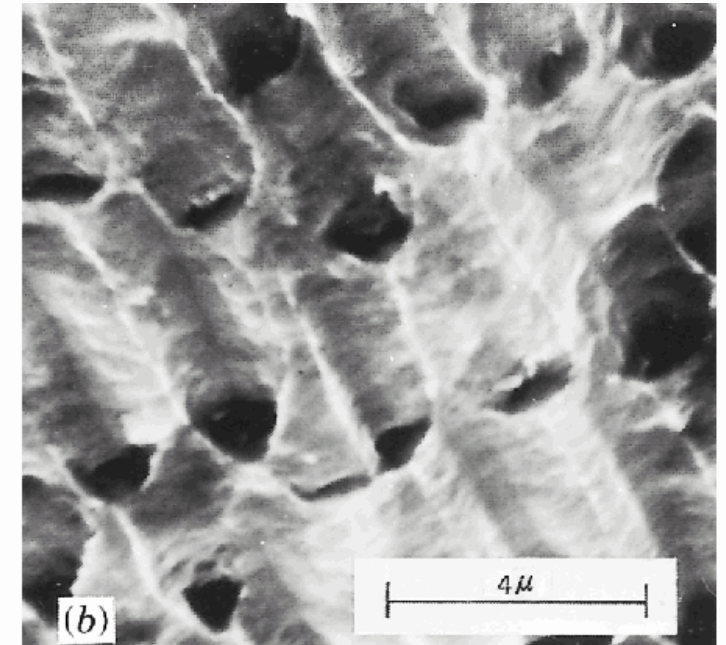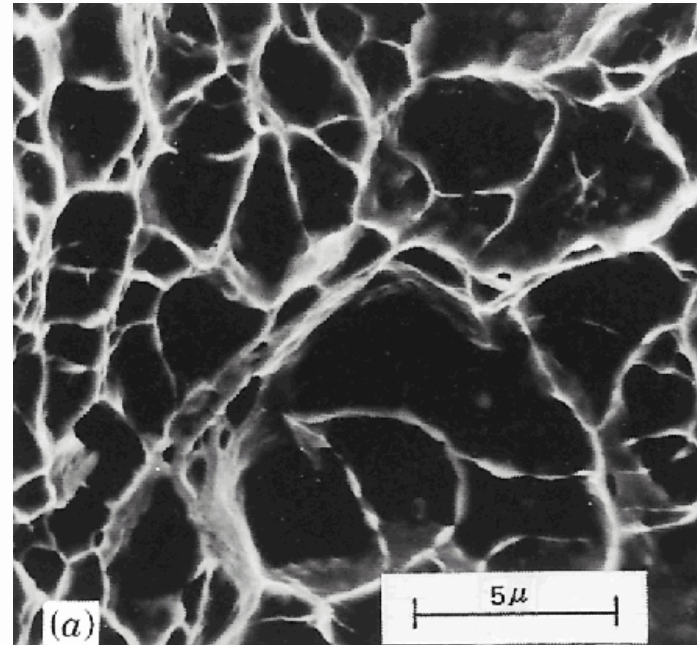
Scanning Electron Microscopy: *Fractographic* studies at high resolution. Spherical "dimples" correspond to micro voids that initiate crack formation
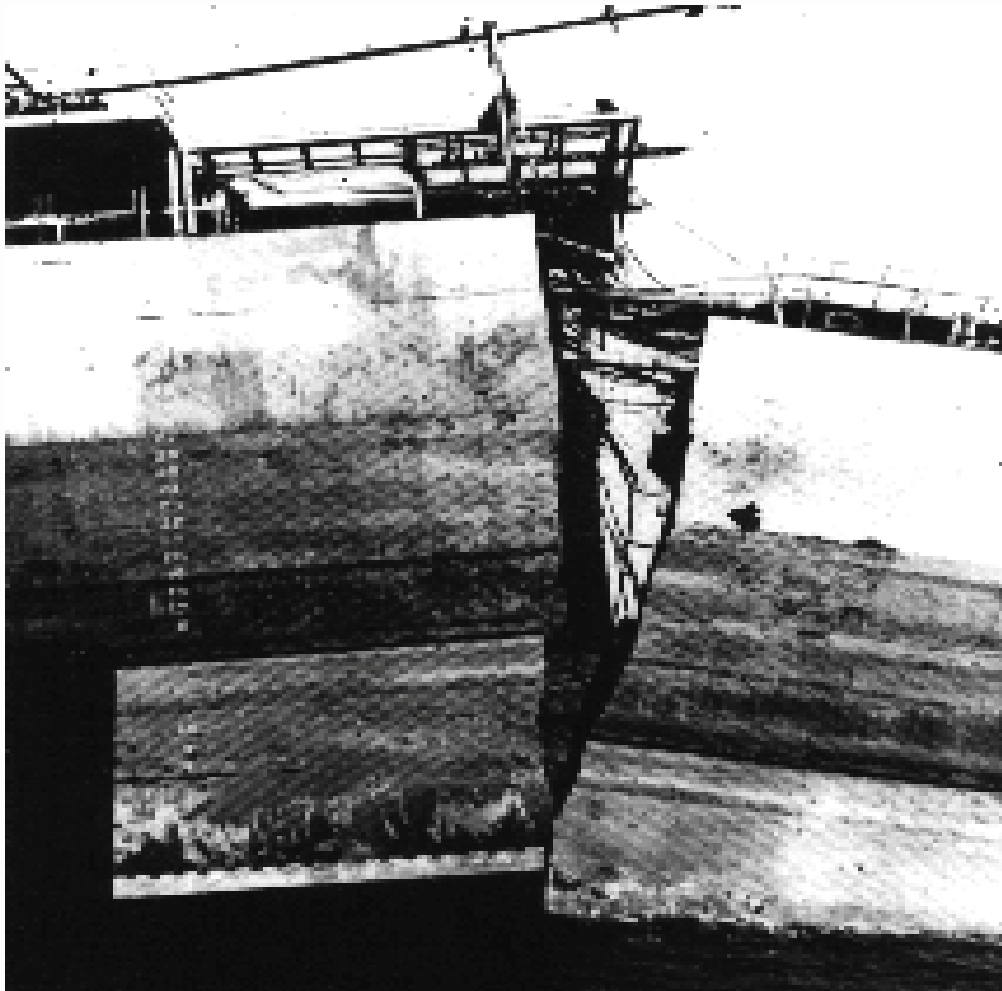
Low temperatures can severely embrittle steels. The **Liberty ships**, produced in great numbers during the WWII were the first all-welded ships. A significant number of ships failed by catastrophic fracture. Fatigue cracks nucleated at the corners of square hatches and propagated rapidly by brittle fracture.

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- No appreciable plastic deformation
- Crack propagation is very fast
- Crack propagates nearly perpendicular to the direction of the applied stress

- Crack often propagates by cleavage - breaking of atomic bonds along specific crystallographic planes (cleavage planes).
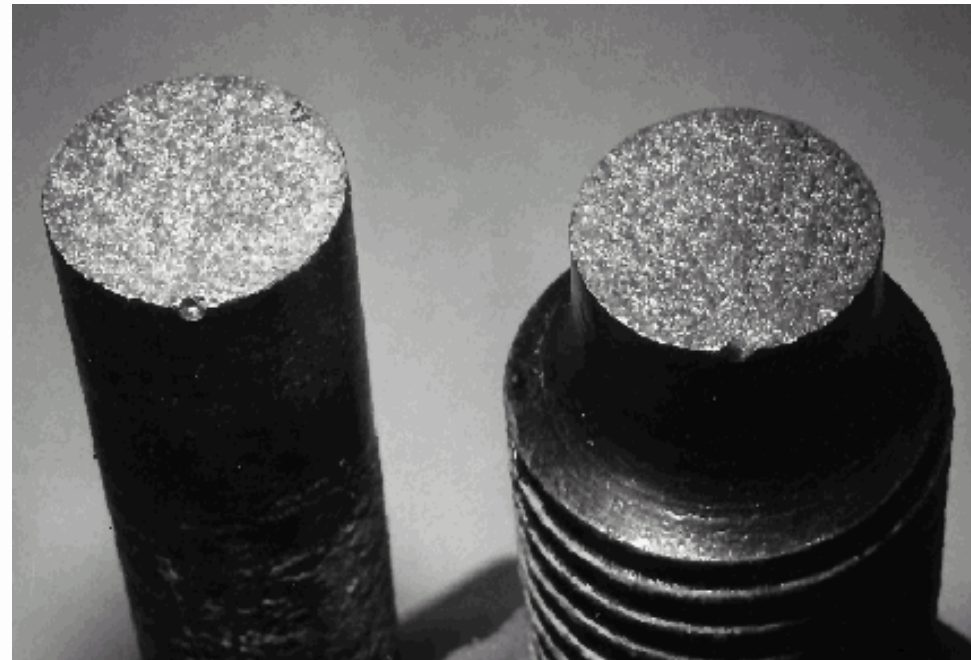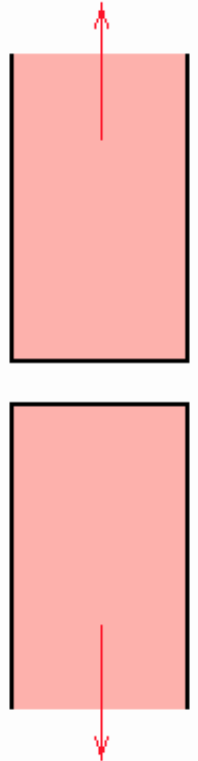
Brittle fracture in a mild steel

A. Trans granular fracture: Fracture cracks pass through grains. Fracture surface have faceted texture because of different orientation of cleavage planes in grains.
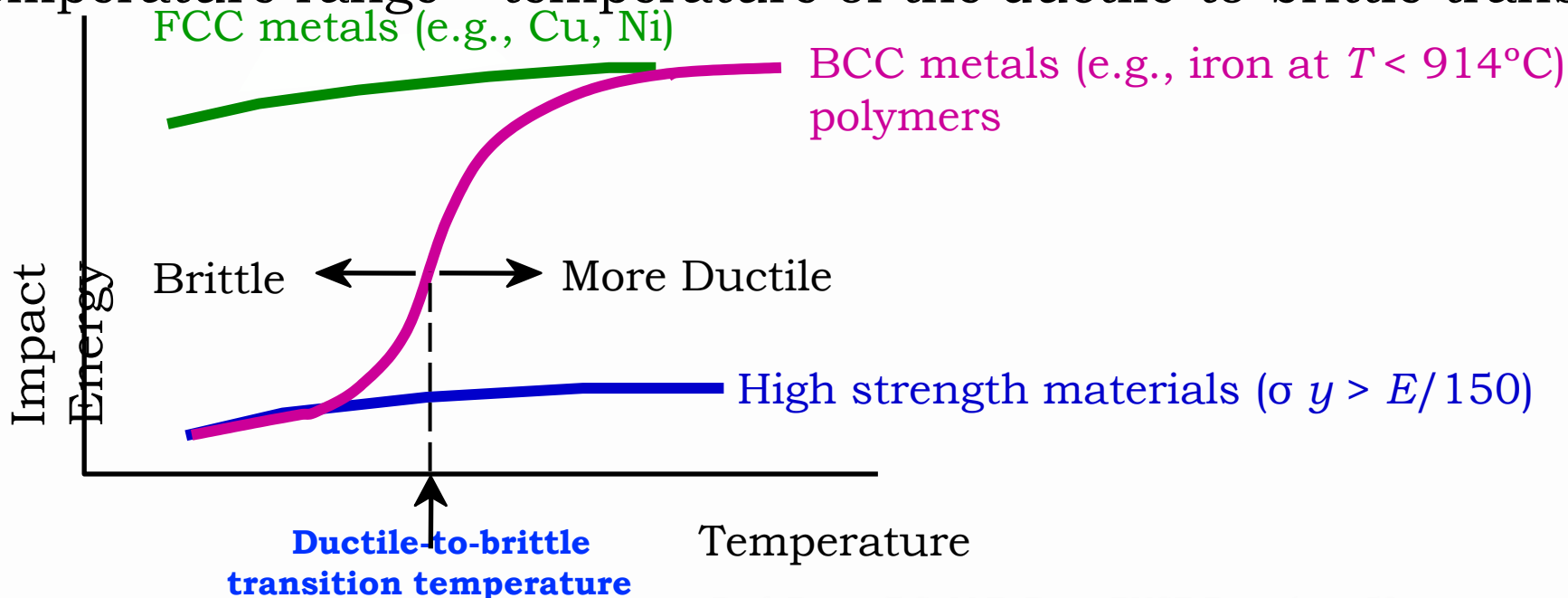
B. Intergranular fracture: Fracture crack propagation is along grain boundaries (grain boundaries   are weakened or embrittled by impurities segregation etc.)
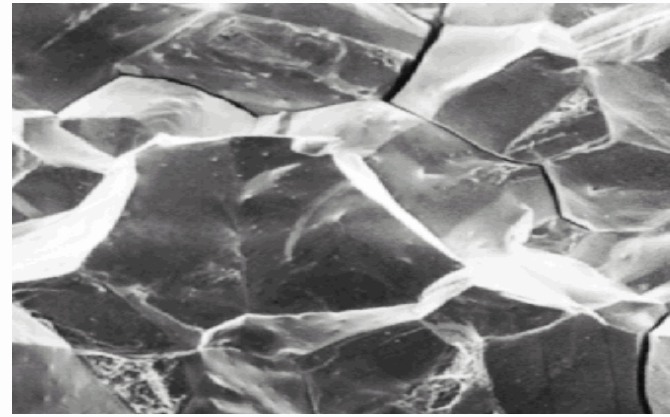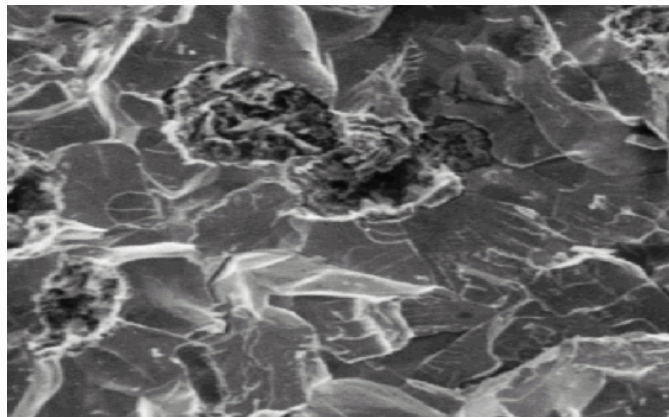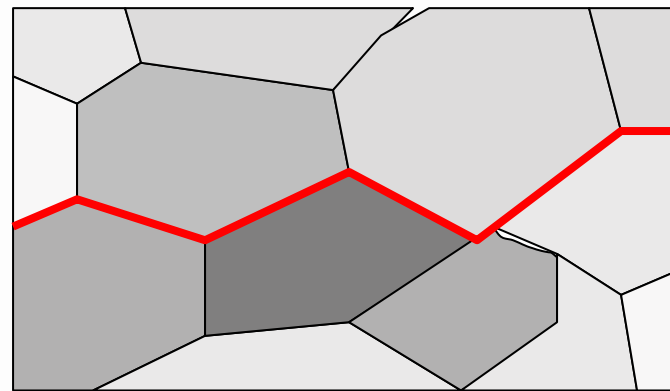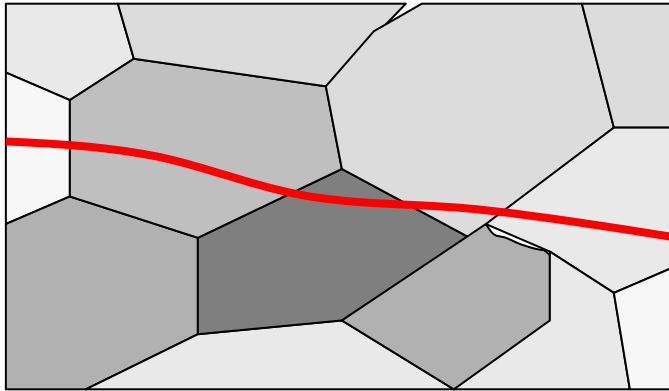
As temperature decreases a ductile material can become brittle - ductile-to-brittle transition

Alloying usually increases the ductile-to-brittle transition temperature. FCC metals remain ductile down to very low temperatures. For ceramics, this type of transition occurs at much higher temperatures than for metals.

The ductile-to-brittle transition can be measured by **impact testing**: the impact energy needed for fracture drops suddenly over a relatively narrow temperature range – temperature of the ductile-to-brittle transition.

FCC metals (e.g., Cu, Ni)

BCC metals (e.g., iron at $T < 914°C$) polymers

Brittle ← → More Ductile

High strength materials ($\sigma_y > E/150$)

Impact Energy

Ductile-to-brittle transition temperature

Temperature

Under fluctuating / cyclic stresses, failure can occur at loads considerably lower than tensile or yield strengths of material under a static load: **Fatigue**

Estimated to cause 90% of all failures of metallic structures (bridges, aircraft, machine components, etc.)

Fatigue failure is brittle-like (relatively little plastic deformation) - even in normally ductile materials.Thus sudden and catastrophic!

Applied stresses causing fatigue may be axial (tension or compression), flexural (bending) or torsional (twisting).

Fatigue failure proceeds in three distinct stages: crack *initiation* in the areas of stress concentration (near stress raisers), *incremental crack propagation, final catastrophic failure.*

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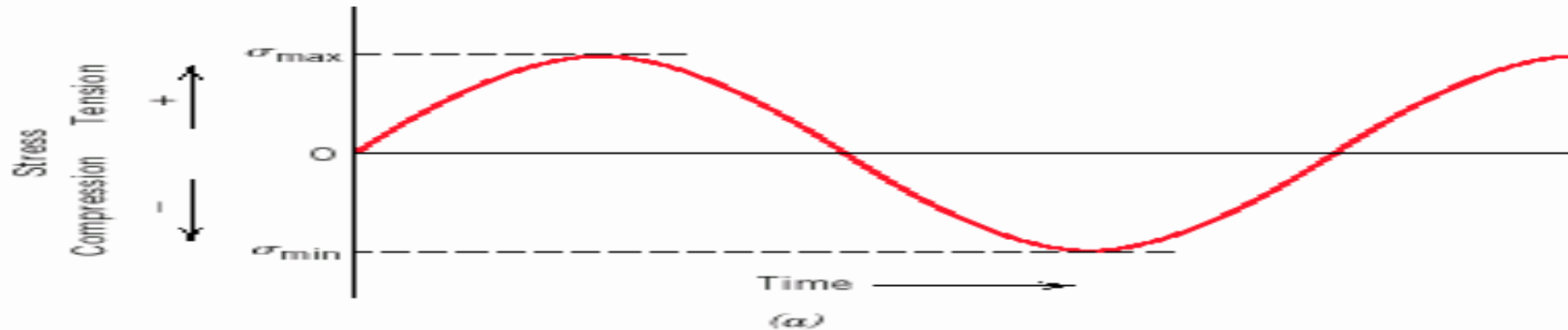
Fatigue properties of a material (S-N curves) are tested in **rotating-bending**
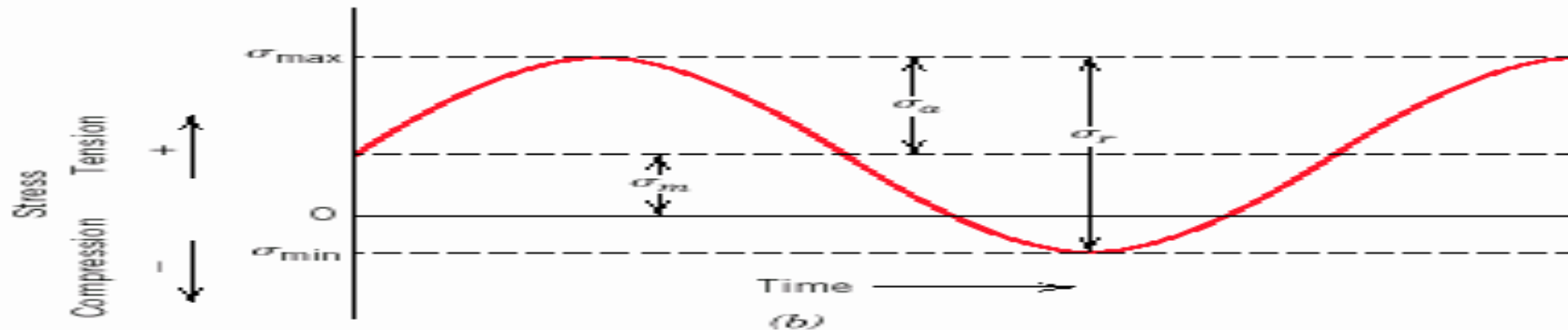
tests in fatigue testing apparatus:
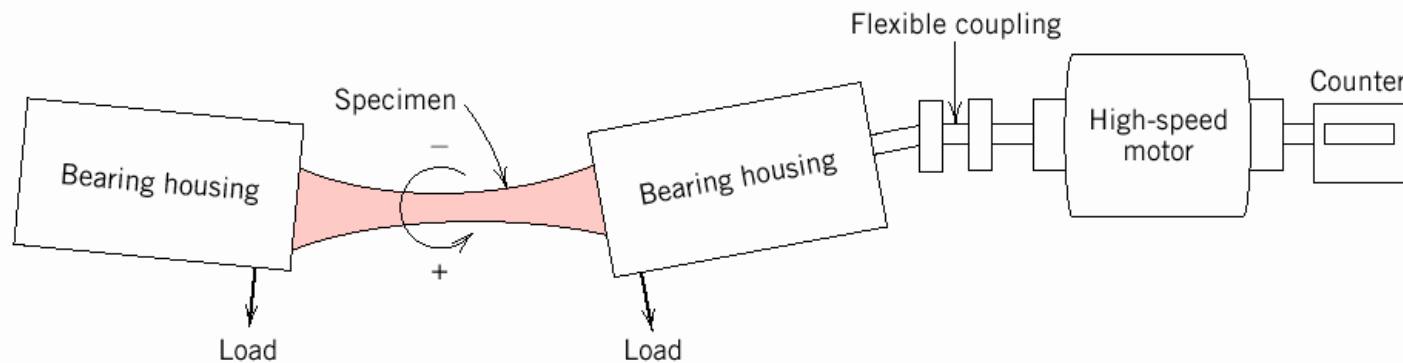
Result is commonly plotted as S (stress) vs. N (number of cycles to failure)

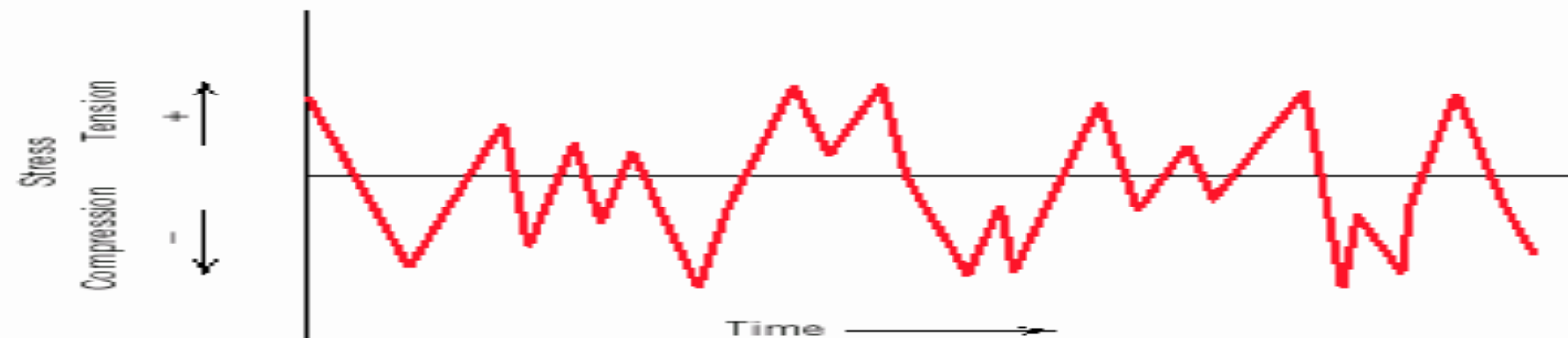**Low cycle fatigue:** high loads, plastic and elastic deformation
High cycle fatigue: low loads, elastic deformation ($N > 10_5$)

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Periodic and symmetrical about zero stress

Periodic and asymmetrical about zero stress

Random stress fluctuations

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Cyclic stresses are characterized by maximum, minimum and mean stress, the range of stress, the stress amplitude, and the stress ratio

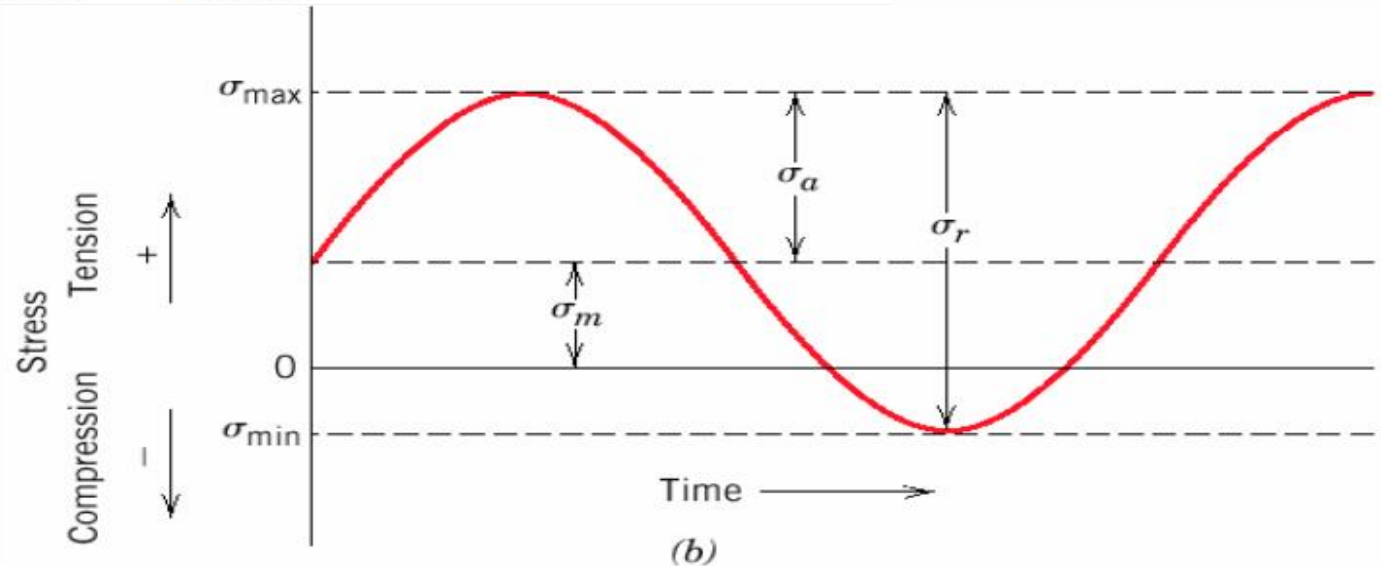Mean stress: $\sigma_m = (\sigma_{max} + \sigma_{min}) / 2$

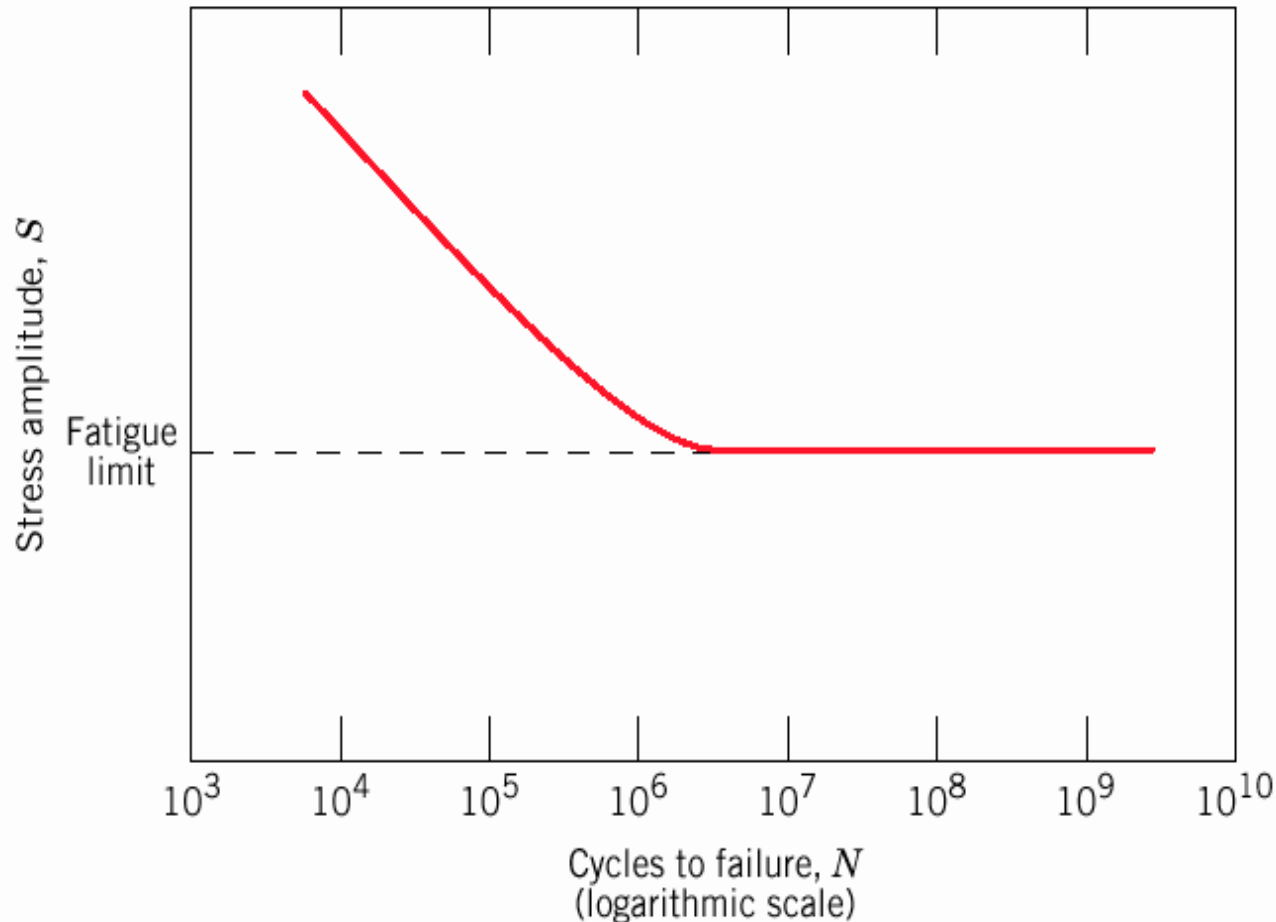Range of stress: $\sigma_r = (\sigma_{max} - \sigma_{min})$

Stress amplitude: $\sigma_a = \sigma_r/2 = (\sigma_{max} - \sigma_{min}) / 2$

Stress ratio: $R = \sigma_{min} / \sigma_{max}$

(b)

Remember the convention that tensile stresses are positive, compressive stresses are negative

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Fatigue limit (endurance limit) occurs for some materials (e.g. some Fe and Ti alloys). In this case, the S—N curve becomes horizontal at large N. The *fatigue limit is a maximum stress amplitude below which the material never fails, no matter how large the number of cycles is.*
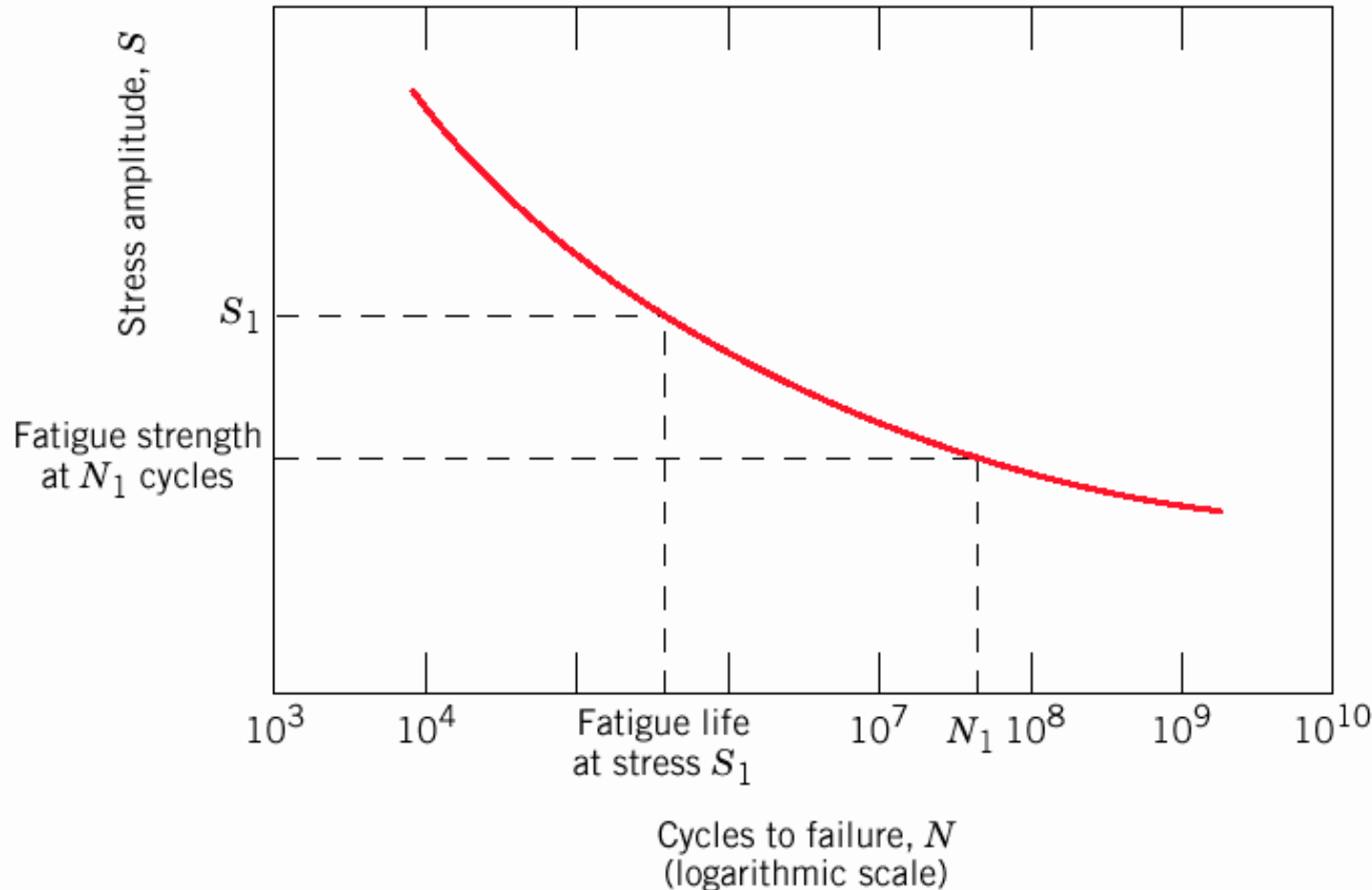
In most alloys, S decreases continuously with N. In this cases the fatigue properties are described by

Fatigue strength: *stress at which fracture occurs after a specified number of cycles (e.g. 10^7)*

Fatigue life: *Number of cycles to fail at a specified stress level*

Three stages of fatigue failure:
1. crack initiation in the areas of stress concentration (near stress raisers)
2. incremental crack propagation
3. final rapid crack propagation after crack reaches critical size

The total number of cycles to failure is the sum of cycles at the first and the second stages:

$$N_f = N_i + N_p$$

N_f : Number of cycles to failure
N_i : Number of cycles for crack initiation
N_p : Number of cycles for crack propagation

High cycle fatigue (low loads): N_i is relatively high. With increasing stress level, N_i decreases and N_p dominates

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Crack initiation at the sites of stress concentration (microcracks, scratches, indents, interior corners, dislocation slip steps, etc.). Quality of surface is important.

Crack propagation

Stage I: initial slow propagation along crystal planes with high resolved shear stress. Involves just a few grains, and has flat fracture surface

Stage II: faster propagation perpendicular to the applied stress. Crack grows by repetitive blunting and sharpening process at crack tip. Rough fracture surface.

Crack eventually reaches critical dimension and propagates very rapidly
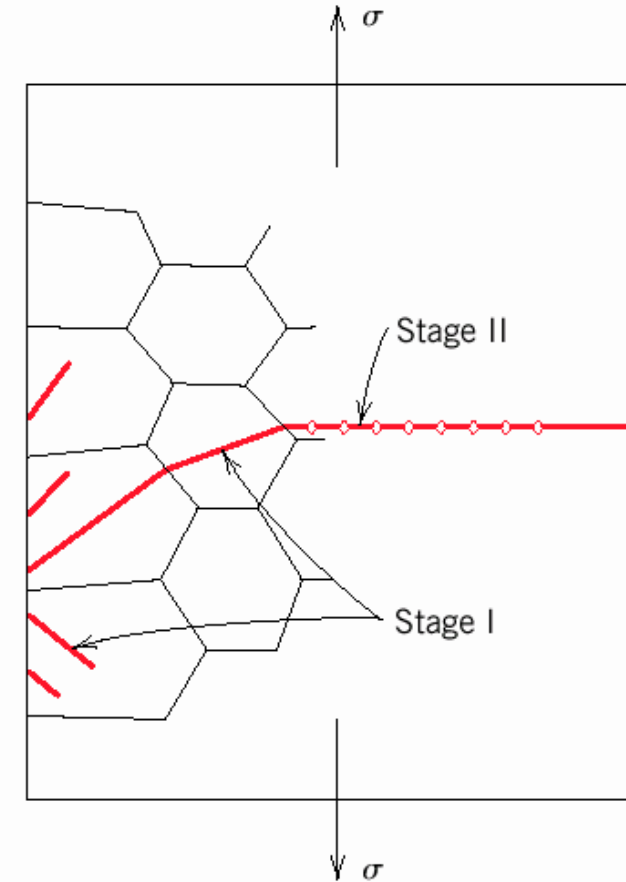
- Magnitude of stress (mean, amplitude...)
  - **Mean stress:** Increasing the mean stress level

    leads to a decrease in fatigue life

Figure 8.25 Demonstration of how design can reduce stress amplification. (*a*) Poor design: sharp corner. (*b*) Good design: fatigue lifetime improved by incorporating rounded fillet into a rotating shaft at the point where there is a change in diameter.

- Quality of the surface (scratches, sharp transitions).

- Design factors- Any notch or geometrical discontinuity can *act as a stress raiser and fatigue crack initiation site;* these design features include **grooves, holes, keyways, threads**, and so on. The sharper the discontinuity (i.e., the smaller the radius of curvature), the more severe the stress concentration. The probability of fatigue failure may be reduced by avoiding (when possible) these structural irregularities, or by making design modifications whereby sudden contour changes leading to sharp corners are eliminated—for example, calling for rounded fillets with large radii of curvature at the point where there is a change in diameter for a rotating shaft.

- Surface Treatments - During machining operations, small scratches and grooves are invariably introduced into the workpiece surface by cutting tool action. These surface markings can limit the fatigue life.
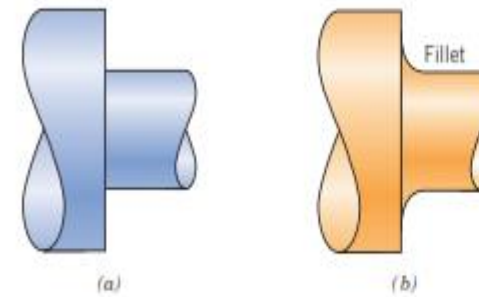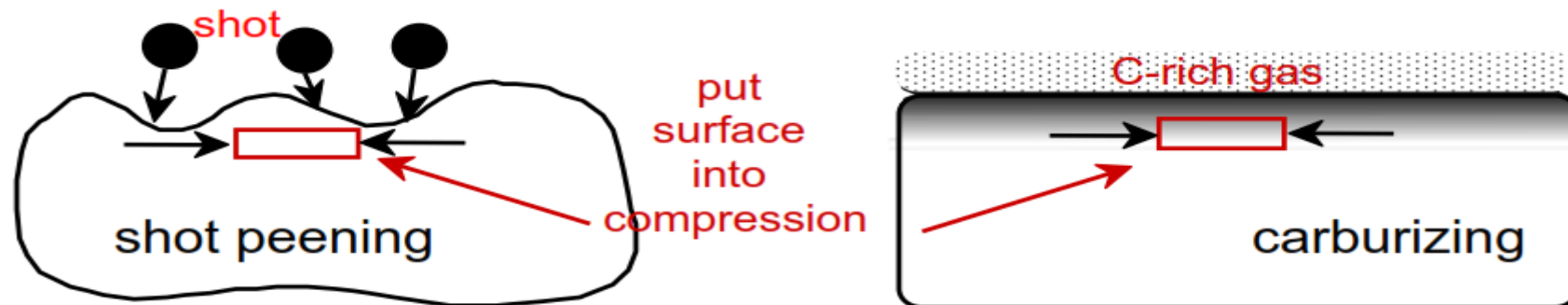
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Solutions:

- Polishing (removes machining flaws etc.)
- Introducing compressive stresses (compensate for applied tensile stresses) into thin surface layer by "Shot Peening"- firing small shot into surface to be treated. High-tech solution - ion implantation, laser peening.
- Case Hardening - create C- or N- rich outer layer in steels by atomic diffusion from the surface. Makes harder outer layer and also introduces compressive stresses
- Optimizing geometry - avoid internal corners, notches etc.

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- **Thermal Fatigue. Thermal cycling causes expansion** and contraction, hence thermal stress, if component is restrained.

Solutions:
eliminate restraint by design
use materials with low thermal expansion coefficients

- **Corrosion fatigue. Chemical reactions induce pits** which act as stress raisers. Corrosion also enhances crack propagation.

Solutions:
decrease corrosiveness of medium, if possible
add protective surface coating
add residual compressive stresses

Thank You