Materials in Mechanical Design

Materials taken from Chapter 2 of Mott, Machine Elements in Mechanical Design, 2003

Materials in Mechanical Design

- The designer must specify the required materials for each part of a mechanical device.
  - Physical properties
  - Mechanical properties
  - Match the properties to the expectations placed on them

Classes of Material

- Metals and their alloys
- Elastomers
- Plastics
- Woods
- Composites
- Ceramics and glasses

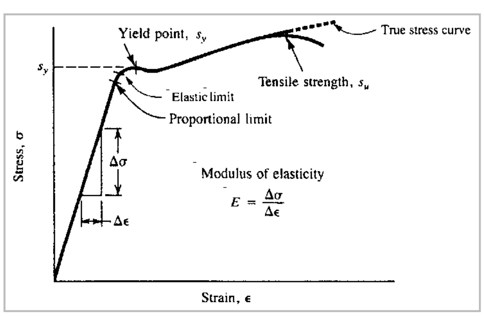
Properties of Metals

- Tensile tests determine strength, elastic, and ductility properties for metals, plastics, and other types of materials.
- A round or flat bar of the material is clamped between jaws and pulled slowly until it breaks in tension.
- The data from these tensile tests are shown on stress-strain diagrams.

Tensile strength

- The peak of the stress-strain curve is considered the ultimate tensile strength (su).
  - (AKA: ultimate strength, tensile strength)
- Measures the highest apparent stress on a test bar of the material

Stress-Strain Diagram for Steel



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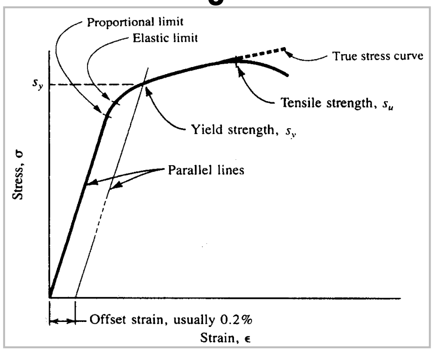
Stress-Strain Diagram for Aluminum



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Yield Strength

- Yield Strength (s_y): The portion of the stress-strain diagram where there is a large increase in strain with little or no increase in stress.
- Proportional Limit: The point on the stress-strain curve where the straight line deviates.
- Elastic Limit: The point at which a material experiences some amount of plastic strain and thus will not return to its original shape after release of the load.

Modulus of Elasticity in Tension

- For part of the stress-strain diagram that is straight, stress is proportional to strain.
- There, the value of E, the modulus of elasticity, is the constant of proportionality.

- $E = \frac{\text{stress}}{\text{strain}} = \frac{\sigma}{\varepsilon}$

Ductility and Percent Elongation

- Ductility: The degree to which a material will deform before ultimate fracture.
  - Antonym = brittleness
- When ductile materials are used in machine members, impending failure is detected easily, so sudden failure is unlikely.
- Percent Elongation: The usual measure of ductility.
  - Percent Elongation = $\frac{L_f - L_o}{L_o}$ * 100%

Shear Strength

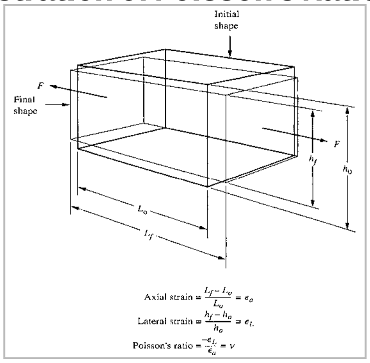
- Both the yield strength and the ultimate strength in shear are important properties of materials.

- $s_{ys} = s_y / 2 = 0.50\ s_y$ = yield strength in shear
- $s_{us} = 0.75\ s_u$ = ultimate strength in shear

Poisson's Ratio

- During a tensile strain, the cross-sectional dimensions perpendicular to the direction of the tensile strain shorten.
- Poisson's ratio (v): The ratio of the shortening strain to the tensile strain.

Illustration of Poisson's Ratio



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Modulus of Elasticity in Shear

- The Modulus of Elasticity in Shear (G): The ratio of shearing stress to shearing strain.
- This property indicates a material's stiffness under shear loading (the resistance to shear deformation).
- $G = \frac{E}{2(1 + v)}$

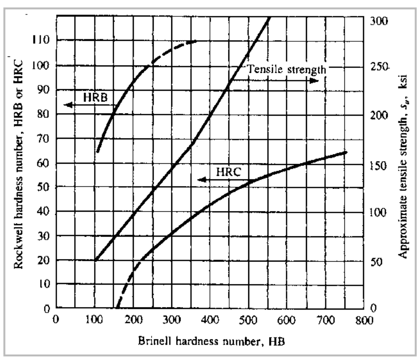
Hardness

- The resistance of a material to indention by a penetrator is an indication of its hardness.
- Of the several methods to measure hardness, the Brinell hardness tester and the Rockwell hardness tester are most frequently used for machine elements.
- For steels, the Brinell hardness tester employs a hardened steel ball with a 1/16-in diameter under a load of 100-kg force for softer metals (Rockwell B, R_B, or HRB).

Hardness con't

- For harder metals, the Rockwell C scale is used. A load of 150-kg force is placed on a diamond penetrator (R_C or HRC).
- The Brinell and Rockwell methods are based on different parameters and lead to quite different numbers. However, one correlation is the nearly linear relationship between the Brinell hardness number and the tensile strength of the steel.
  - 0.50 (HB) = approximate tensile strength (ksi)

Hardness Conversions



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Comparisons of Hardness Scales

TABLE 2–1 Comparison of hardness scales with tensile strength

Material and condition	Hardness			Tensile strength	
	HB	HRB	HRC	ksi	MPa
1020 annealed	121	70		60	414
1040 hot-rolled	144	79		72	496
4140 annealed	197	93	13	95	655
4140 OQT 1000	341	109	37	168	1160
4140 OQT 700	461		49	231	1590

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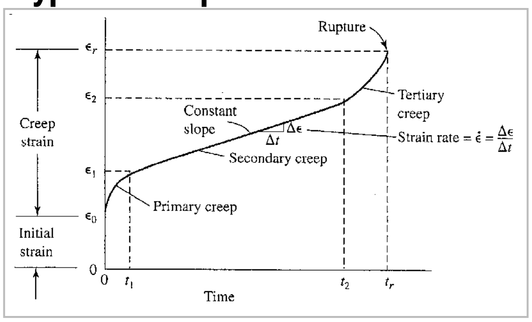
Creep

- When materials are subjected to high loads continuously, they may experience progressive elongation over time (creep).
  - Ex: metals operating at high temperatures
- Check for creep when the operating temperature of a loaded metal member exceeds approximately 0.3 (T_m)
  - T_m is the melting temperature expressed as an absolute temperature.

Typical Creep Behavior



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Coefficient of Thermal Expansion

- Coefficient of Thermal Expansion: a measure of the change in length of a material subjected to a change in temperature.

$$\alpha = \frac{\text{change in length}}{L_o(\Delta T)} = \frac{\text{strain}}{(\Delta T)} = \frac{\epsilon}{(\Delta T)}$$

where L_o = original length
ΔT = change in temperature

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Carbon and Alloy Steel

- Steel is the most widely used material for machine elements because of high strength, high stiffness, durability, and relative ease of fabrication.
- <u>Steel</u>: an alloy of iron, carbon, manganese, and one or more other significant elements.
  - Carbon has a very strong effect on the strength, hardness, and ductility of any steel alloy.
- The other elements affect hardenability, toughness, corrosion resistance, machinability, and strength retention at high temperatures.

Carbon and Alloy Steel con't***

- The primary alloying elements in the various alloy steels are sulfur, phosphorus, silicon, nickel, chromium, molybdenum, and vanadium.

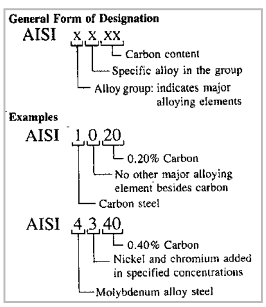

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TABLE 2–3 Alloy groups in the AISI numbering system

10xx	Plain carbon steel: No significant alloying element except carbon and manganese; less than 1.0% manganese. Also called *nonresulfurized*.
11xx	Free-cutting steel: Resulfurized. Sulfur content (typically 0.10%) improves machinability.
12xx	Free-cutting steel: Resulfurized and rephosphorized. Presence of increased sulfur and phosphorus improves machinability and surface finish.
12Lxx	Free-cutting steel: Lead added to 12xx steel further improves machinability.
13xx	Manganese steel: Nonresulfurized. Presence of approximately 1.75% manganese increases hardenability.
15xx	Carbon steel: Nonresulfurized; greater than 1.0% manganese.
23xx	Nickel steel: Nominally 3.5% nickel.
25xx	Nickel steel: Nominally 5.0% nickel.
31xx	Nickel-chromium steel: Nominally 1.25% Ni; 0.65% Cr.
33xx	Nickel-chromium steel: Nominally 3.5% Ni; 1.5% Cr.
40xx	Molybdenum steel: 0.25% Mo.
41xx	Chromium-molybdenum steel: 0.95% Cr; 0.2% Mo.
43xx	Nickel-chromium-molybdenum steel: 1.8% Ni; 0.5% or 0.8% Cr; 0.25% Mo.
44xx	Molybdenum steel: 0.5% Mo.
46xx	Nickel-molybdenum steel: 1.8% Ni; 0.25% Mo.
48xx	Nickel-molybdenum steel: 3.5% Ni; 0.25% Mo.
5xxx	Chromium steel: 0.4% Cr.
51xx	Chromium steel: Nominally 0.8% Cr.
51100	Chromium steel: Nominally 1.0% Cr; bearing steel, 1.0% C.
52100	Chromium steel: Nominally 1.45% Cr; bearing steel, 1.0% C.
61xx	Chromium-vanadium steel: 0.50%–1.10% Cr; 0.15% V.
86xx	Nickel-chromium-molybdenum steel: 0.55% Ni; 0.5% Cr; 0.20% Mo.
87xx	Nickel-chromium-molybdenum steel: 0.55% Ni; 0.5% Cr; 0.25% Mo.
92xx	Silicon steel: 2.0% silicon.
93xx	Nickel-chromium-molybdenum steel: 3.25% Ni; 1.2% Cr; 0.12% Mo.

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Alloy Groups***

- Sulfur, phosphorus, and lead improve the machinability of steels.
  - These grades are used for screw machine parts requiring high production rates where the resulting parts are not subjected to high stresses or wear conditions.
- Nickel improves the toughness, hardenability, and corrosion resistance of steel.
- Chromium improves hardenability, wear and abrasion resistance, and strength at elevated temperatures.
- Molybdenum improves hardenability and high-temperature strength.

TABLE 2–4 Uses of some steels

UNS number	AISI number	Applications
G10150	1015	Formed sheet-metal parts; machined parts (may be carburized)
G10300	1030	General-purpose, bar-shaped parts, levers, links, keys
G10400	1040	Shafts, gears
G10800	1080	Springs; agricultural equipment parts subjected to abrasion (rake teeth, disks, plowshares, mower teeth)
G11120	1112	Screw machine parts
G12144	12L14	Parts requiring good machinability
G41400	4140	Gears, shafts, forgings
G43400	4340	Gears, shafts, parts requiring good through-hardening
G46400	4640	Gears, shafts, cams
G51500	5150	Heavy-duty shafts, springs, gears
G51601	51B60	Shafts, springs, gears with improved hardenability
G52986	E52100	Bearing races, balls, rollers (bearing steel)
G61500	6150	Gears, forgings, shafts, springs
G86500	8650	Gears, shafts
G92600	9260	Springs

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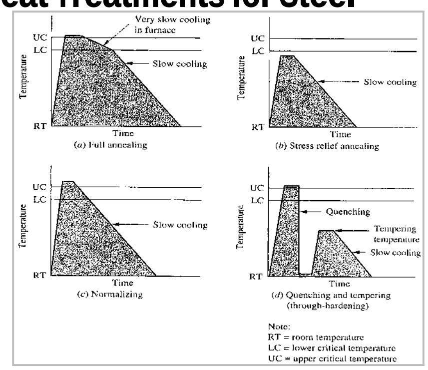
Conditions for Steels and Heat Treatment

- The way the steels are produced determines the final properties of steels.
- Carbon steel bar and sheet forms are usually delivered in the as-rolled condition (rolled at an elevated temperature to ease the rolling process).
- Cold-drawn bar and wire have the highest strength of the worked forms and good surface finishes.

Heat Treating

- Heat treating: Any process in which steel is subjected to elevated temperatures to modify its properties.
- Some of the processes available are annealing, normalizing, through-hardening (quench and temper), and case hardening.

Heat Treatments for Steel



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Annealing

- Full annealing: Heating the steel above the upper critical temperature and holding it until the composition is uniform.
- It creates a soft, low-strength form of the material with no significant internal stresses.
  - Parts are cold-formed or machined in the annealed condition.

Normalizing

- Normalizing: similar to annealing, but performed at a higher temperature --- above the transformation range where austenite is formed, approximately 1600°F (870°C).
- Results in a uniform internal structure in the steel and a higher strength than annealing.
- Machinability and toughness are better than the as-rolled condition.

Through-hardening, Quenching, and Tempering

- Through-hardening: Heating the steel to above the transformation range where austenite forms and then rapidly cooling it in a quenching medium, creating martensite (the hard, strong form of steel).
- Tempering: heating the steel to a temperature of 400°F to 1300°F and then slowly cooling it in air back to room temperature.
  - Performed right after quenching
- Tensile strength and yield strength decrease with increasing tempering temperature, whereas ductility improves with an increase in the percent elongation.

Case Hardening

- Usually, the bulk of the part needs only moderate strength, although the surface must have a very high hardness.
  - Ex: gear teeth need high surface hardness to resist wear as the mating teeth come into contact several million times during the expected life of the gears
- The surface (case) of the part is given a high hardness to a depth of 0.010 to 0.040 inches (0.25-1.00 mm)
  - the interior of the part (core) is affected only slightly

Case Hardening con't

- Advantage of surface hardening: As the surface receives the required wear-resisting hardness, the core of the part remains in a more ductile form, resistant to impact and fatigue.
- The processes used most often for case hardening are flame hardening, induction hardening, carburizing, nitriding, cyaniding, and carbo-nitriding.

Stainless Steels

- Stainless Steel: an alloy with a chromium content of at least 10%.
  - characterizes the high level of corrosion resistance offered by alloys

Structural Steel

- Most structural steels are designated by American Society for Testing and Materials (ASTM) numbers.
  - Ex: ASTM A36, which has a minimum yield point of 36,000 psi (248 MPa) and is very ductile.
- Most wide-flange beams (W-shapes) are made using ASTM A992 structural steel, with a yield point of 50 to 65 ksi (345 to 448 MPa) and a minimum tensile strength of 65 ksi (448 MPa).

Tool Steels and Cast Iron

- Tool Steels: A group of steels used for cutting tools, punches, dies, shearing blades, chisels, etc.
- Cast Iron: Used for large gears, machine structures, brackets, linkage parts, and other important machine parts.
- Gray iron is available in grades having tensile strengths ranging from 20,000 to 60,000 psi. Its ultimate compressive strength is 3 to 5 times as high as the tensile strength.
  - However, it is brittle and can not be used in applications where impact loading is likely.

Powdered Metals***

- Making parts with intricate shapes by powder metallurgy (PM) can sometimes eliminate the need for extensive machining.
- Metal powders are available in many formulations whose properties approach those of the wrought form of the metal.
- The processing involves preparing a preform by compacting the powder in a die under high pressure.

Powdered Metals con't***

- Next, sinter at a high temperature to fuse the powder into a uniform mass.
- Re-pressing is sometimes done to improve properties or dimensional accuracy of the part.
- Typical parts made by the PM process are gears, gear segments, cams, eccentrics, and various machine parts having oddly shaped holes or projections.

Aluminum

- Aluminum is light-weight, with good corrosion resistance, is relatively easy to form and machine, and has a pleasing appearance.
  - widely used for structural and mechanical applications
- Its density is approximately 1/3 that of steel, but its strength is somewhat lower.

Zinc Alloys***

- Zinc is the fourth most commonly used metal in the world.
- Much of it is in the form of zinc galvanizing used as a corrosion inhibitor for steels.
- Very large quantities of zinc alloys are used in castings and for bearing materials.

Titanium

- Titanium: used for aerospace structures and components, chemical tanks and processing equipment, fluids-handling devices, and marine hardware.
- Titanium has very good corrosion resistance and a high strength-to-weight ratio.
- However, it is expensive and is difficult to machine.

Copper, Brass, and Bronze

- Copper has high electrical conductivity and good corrosion resistance.
  - used in its nearly pure form for electrical and plumbing applications
- It has little strength so it is rarely used for machine parts.
- Brass is often used in marine applications because of its resistance to corrosion in salt water.
  - In the family with copper and zinc
- Bronze is a class of alloys of copper with several different elements, like tin.
  - used in gears, bearings, and other applications where good strength and high wear resistance are desirable.

Plastics

- Plastics: A wide variety of materials formed of large molecules called polymers. The thousands of different plastics are created by combining different chemicals to form long molecular chains.
- The thermoplastic materials can be formed by heating or molding because their basic chemical structure is unchanged from its initial linear form.
- Thermosetting plastics do change during forming, resulting in a structure in which the molecules are cross-linked and form a network of interconnected molecules.

Thermoplastics ***

- Nylon: strong, wear resistant, and tough; wide range of possible properties depending on fillers and formations.
  - Used for structural parts, mechanical devices such as gears and bearings, and parts needing wear resistance.
- Polycarbonate: excellent toughness, impact resistance, and dimensional stability.
  - Used for cams, gears, housings, electrical connectors, food processing products, helmets, and pump and meter parts.

Thermoplastics con't***

- Polyvinyl chloride (PVC): good strength, weather resistance, and rigidity.
  - Used for pipe, electrical conduit, small housings, ductwork, and moldings.
- Thermoplastic polyester resin (PET): polyethylene terephthalate (PET) resin with fibers of glass and/or mineral. Very high strength and stiffness, excellent resistance to chemicals and heat, excellent dimensional stability, and good electrical properties.
  - Used for pump parts, housings, electrical parts, motor parts, auto parts, oven handles, gears, sprockets, and sporting goods.

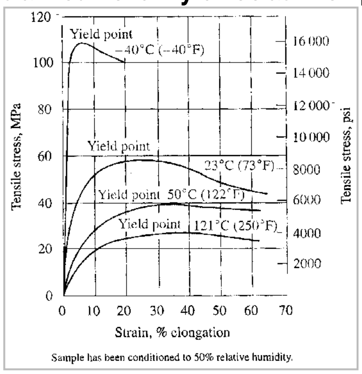
Thermosets ***

- Phenolic: high rigidity, good moldability and dimensional stability, very good electrical properties.
  - Used for load-carrying parts in electrical equipment, switchgear, terminal strips, small housings, handles for appliances and cooking utensils, gears, and structural and mechanical parts.

Plastics

- Many ways to form plastics, even within a given class.
  1. Most properties of plastics are highly sensitive to temperature.
  2. Many plastics absorb a considerable amount of moisture from the environment and exhibit dimensional changes and degradation of strength and stiffness properties as a result.
  3. Components that carry loads continuously must be designed to accommodate creep or relaxation.

Stress-Strain Curve for Nylon 66 at 4 Temperatures



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Plastics con't

4. Fatigue resistance data of a plastic must be acquired for the specific formulation used and at a representative temperature.
5. Processing methods can have large effects on the final dimensions and properties of parts made from plastics.
6. Resistance to chemicals, weather, and other environmental conditions must be checked.

Plastics con't

7. Plastics may exhibit a change in properties as they age, particularly when subjected to elevated temperatures.
8. Flammability and electrical characteristics must be considered.
9. Plastics used for food storage or processing must meet US Food and Drug Administration standards.

Composite Materials

- Composite Materials: two or more different materials that act together to product properties that are different/better than those of the individual components.
- Designers can make the properties meet the specific needs of a particular application by choosing the variables that will determine the performance of the final product.

Composite Materials con't

- Among the factors under the designer's control are:
  - Matrix resin or metal
  - Type of reinforcing fibers
  - Amount of fiber contained in the composite
  - Orientation of the fibers
  - number of individual layers used
  - Overall thickness of the material
  - Orientation of the layers relative to each other
  - Combination of 2 or more types of composites or other materials into a composite structure.

Advantages of Composites

- Designers want to make products that are safe, strong, stiff, lightweight, and highly tolerant of the environment.
  - Much better than metals, wood, and unfilled plastics
- Specific Strength: the ratio of the tensile strength of a material to its specific weight.
- Specific Modulus: the ratio of the modulus of elasticity of a material to its specific weight.

Advantages of Composites con't

1. Specific strengths for composite materials can range as high as five times those of high-strength steel alloys.
2. Specific modulus values for composite materials can be as high as 8 times those for steel, aluminum, or titanium alloys.
3. Composite materials typically perform better than steel or aluminum in application where cyclic loads can lead to the potential for fatigue failure.

Advantages of Composites con't

4. Where impact loads and vibrations are expected, composites can be specially formulated with materials that provide high toughness and a high level of damping.
5. Some composites have much higher wear resistance than metals.
6. Careful selection of the matrix and filler materials can provide superior corrosion resistance.

Advantages of Composites con't

7. Dimensional changes due to changes in temperature are typically much less for composites than for metals.
8. Designers can tailor the placement of reinforcing fibers in directions that provide the required strength and stiffness under the specific loading conditions to be encountered.
9. Composite structures can often be made in complex shapes in one piece, thus reducing the number of parts in a product and the number of fastening operations required.
10. Composite structures are typically made in their final form directly or in a near-net shape, thus reducing the number of secondary operations required.

Limitations of Composites

1. Material costs for composites are typically higher then for many alternative materials.
2. Fabrication techniques are quite different and new manufacturing equipment may be required.
3. The performance of products made from some composite production techniques is subject to a wider range of variability.
4. The operating temperature limits for composites having a polymeric matrix are typically 500^{o}F.

Limitations of Composites con't

5. Properties vary dramatically with the direction of the applied loads. Designers must account for these variations to ensure safety and satisfactory operation under all expected types of loading.
6. Many designers lack understanding of the behavior of composite materials and the details of predicting failure modes.
7. The analysis of composite structures requires detailed knowledge of more properties of the materials than would be required for metals.

Limitations of Composites con't

8. Inspection and testing of composite structures are typically more complicated and less precise than for metal structures.
9. Repair and maintenance of composite structures are serious concerns.