Engineering Design I: Methods and Skills
Topic Readings

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Chapter 7

Material Selection

We have previously discussed how to design lightweight, strong parts made from a preselected material. In this chapter we will remove that constraint, widening the design space to include material selection.

Optimal qualitative part geometry is quite often independent from material. For example, an I-beam is a good shape for resisting bending whether it is made from aluminum or steel. But as we will see, some materials are more optimal for particular geometries, loads, or desired deflections. For example, materials with a low value of $\rho \cdot E \cdot \sigma_y^{-2}$ often make for good springs.

Manufacturing and cost considerations are usually important when selecting a material, but we will put off detailed discussion of manufacturing processes and cost estimation until later. In this chapter, we will treat each part as if it were manufactured using typical prototyping processes such as conventional machining or three-dimensional printing.

Material properties other than strength, modulus and density may be important for a given application. For example, parts might need high corrosion resistance, low thermal expansion, or even particular aesthetics. Such requirements can typically be treated as constraints on the selection process for a given design problem.

In this chapter, we will assume that you have already had an introduction to basic concepts of material properties and behavior, which will be only briefly reviewed. The remainder of the text will focus on design through material selection.

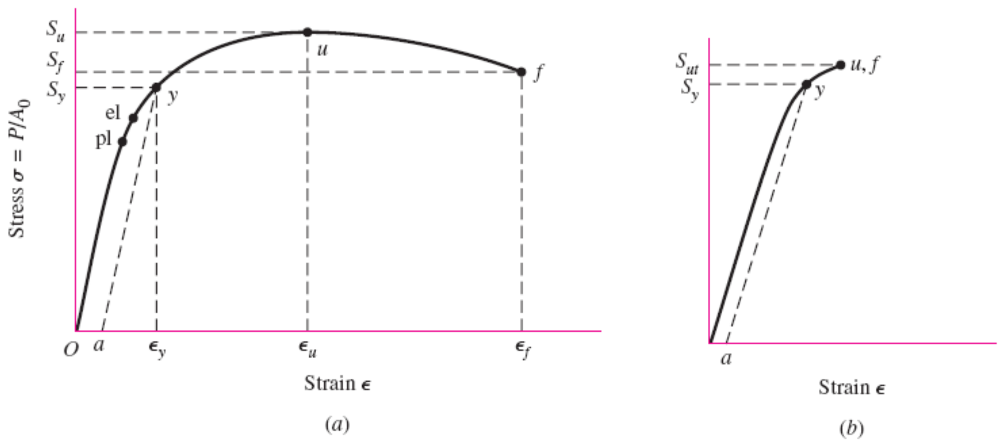


Figure 7.1: Engineering stress-strain diagram obtained using a standard tensile test. (a) ductile material; (b) brittle material. Points are defined as: *pl*, the proportional limit; *el*, the elastic limit; *y*, the offset-yield as defined by offset strain *a*; *u*, point of maximum or ultimate stress; and *f*, fracture.

7.1 Review of Material Properties

Standardized tests are used to obtain a variety of properties that characterize material behavior:

Elastic modulus, E, also known as Young's modulus, describes the stress-strain behavior under approximately linear, elastic deformations. This behavior is shown in Figure 7.1, in the region between O and pl, modeled by Hooke's Law as:

$$\sigma = E\varepsilon$$

where σ is stress and ε is strain. Elastic modulus is important for understanding how mechanical parts deform under moderate loads.

Yield Strength, S_y, or σ_y, is the stress at which the material begins to plastically deform. This is typically defined as the stress at which there is a departure of 0.2% in ε from the linear elastic behavior described above (point y in Figure 7.1). Yield strength is useful for predicting whether a part will become permanently deformed under typical use, which is usually undesirable.

Ultimate Strength, S_u or S_{ut} is the maximum stress reached before fracture, typically following some plastic deformation (point u in Figure 7.1). Ultimate strength is useful for predicting whether fracture will occur under high loads.

Ductility refers to the amount of plastic deformation that occurs before fracture. Materials with a strain at fracture (point f in Figure 7.1) of more than 5% are typically referred to as 'ductile', while those with a lower value of ε_f are referred to as 'brittle' and may exhibit very little plastic deformation before fracture. Ductility is useful for understanding behavior past yield and the effects that stress concentrations may have on overall component strength.

Toughness is the amount of work per unit volume that must be done on a material to cause fracture. This involves both ultimate stress and strain. More precisely:

$$u_T = \int_0^{\varepsilon_f} \sigma d\varepsilon$$

or the area under the stress-strain curve. Toughness is useful for understanding how much punishment a material will take before breaking.

Resilience is similar to toughness, but includes only elastic behavior, i.e. below yield. Since this region is linear, $u_R = S_y^2/2E$. Resilience is useful for understanding how much energy a part can absorb without permanently deforming.

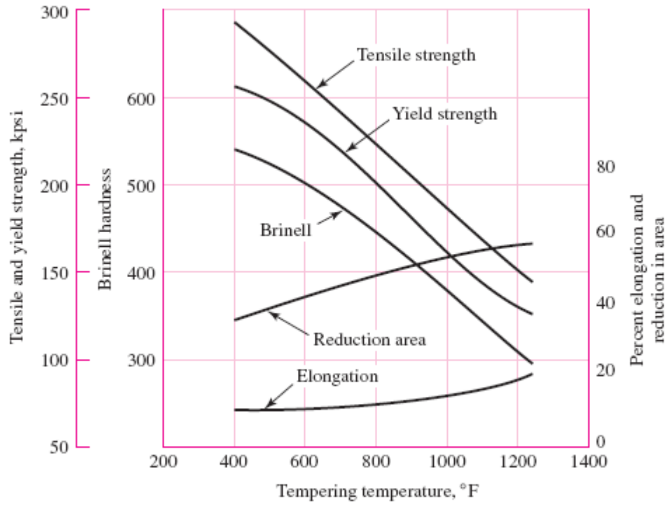
Hardness is related to ultimate strength, but defined for the special case of contact loading with a pointed tool. Hardness is useful for understanding how a surface will hold up to wear or impacts.

Density, ρ, is mass per unit volume. It helps in predicting part mass and weight.

7.2 Processing that Affects Strength

Most macroscopic inorganic solids are polycrystalline, including almost all metals, ceramics, ice, rocks, etc. Strength, hardness and ductility are sensitive to changes in crysal grain size and orientation that occur during crystallization (or recrystallization). Other properties, such as density and elastic modulus, are much less affected by crystallization. Here are some common processes used to alter the strength and ductility of a given material:

Alloying is the process of introducing small amounts of an additional material to a base material to alter its properties, largely through changes in crystal structure. Names of materials typically denote a specific alloy with a particular balance of elements, e.g. 7075 Aluminum vs. 6061 Aluminum alloy.



Condition	Tensile strength, kpsi	Yield strength, kpsi	Reduction in area, %	Elongation in 2 in, %	Brinell hardness, Bhn
Normalized	200	147	20	10	410
As rolled	190	144	18	9	380
Annealed	120	99	43	18	228

Figure 7.2: Effects of tempering. Reduction in area refers to the reduction in cross-sectional area, or 'necking', at failure, with larger reductions associated with high ductility. Elongation is elongation at failure.

Cold Working, also known as strain hardening or work hardening, is the strengthening of a metal by plastic deformation. Forming metal at a low temperature (room temperature) generally results in higher yield strength and lower ductility.

Annealing is used to (partially) reverse the effects of cold working by heating the material and allowing recrystallization. This can reduce hardness and help resolve residual stresses from working of the material.

Quenching is the process of cooling a material from the critical temperature with controlled (usually rapid) speed, usually by dousing in oil or water, to strengthen and harden steel and cast iron.

Tempering is a process in which a steel part is reheated to below the critical temperature for a period of time and then allowed to cool in still air. This relieves internal stresses that can arise as a steel specimen is fully hardened, which would

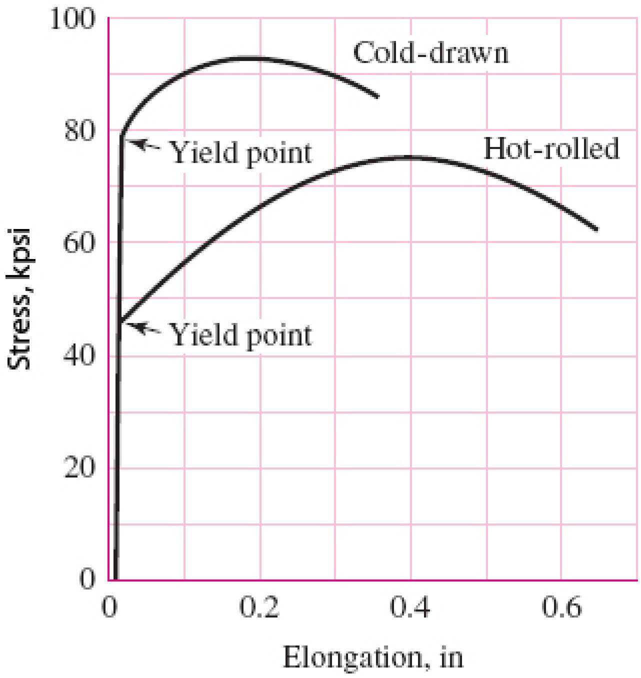


Figure 7.3: Stress-strain curves for cold-drawn and hot-rolled steel. Hot-rolled steel has a lower yield strength, but higher toughness.

otherwise make it brittle and cause it so contract with age.

The type of heat treatment that a material has been subjected to, e.g. cold working, annealing, quenching, and tempering, are typically denoted directly or by a numerical suffix, e.g. 7075-T651 Aluminum vs. 7075-O Aluminum alloy. Some examples of the effects of heat-treating operations on the mechanical properties of a low alloy steel are shown in Figures 7.2 & 7.3.

7.3 Finding Specific Material Properties

Manufacturer specifications, where available and reliable, provide the most accurate source for properties of a particular material. Manufacturers may produce a material in accordance with a standardized set of properties, specified and validated by standards organizations such as AISI, ASTM, or UNS. Generic material properties can also be found in databases (e.g. www.matweb.com), charts (e.g. [Ashby, 1999]) or tables, (e.g. [Budynas and Nisbett, 2006]).

7.4 Systematic Material Selection Approaches

7.4.1 Single Property Selection

In some design problems, the relative importance of various material properties is evident *a priori*. In such cases, a material property chart (e.g. Figure 7.4) can help you identify candidate materials with good values of the most important property. Subsequent investigation into other properties of those candidate materials will allow you to narrow your selection down to a single material. For example, one might want a dense material and find that platinum, iridium, tungsten, magnesium, gold, mercury, lead, and steel all have high density. If the design also requires a cheap, nontoxic, solid, non-radioactive material, perhaps we would choose steel.

7.4.2 Analytical Property Selection

In many design problems, the ideal set of material properties is not obvious without some initial modeling and analysis. Take, for example, the I-beam problem presented in Chapter 3, Stress Analysis for Design. We derived an equation for the beam's mass as a function of load, geometry, and material properties:

$$m \approx \frac{\rho \cdot FoS \cdot K_t \cdot F \cdot L^2}{S_y} \cdot \frac{2b+h}{bh}, \tag{7.1}$$

We can see from the first term that the mass of this part would be minimized by selecting a material with a minimum value of $\rho \cdot S_y^{-1}$. (Note that this ratio is particular to this design problem, not a general result, as we will see in our example.) Just as for a single material property, we can now use a chart to help identify candidate materials. Figure 7.6 includes both density, ρ, and yield strength, S_y, along with their ratios at various powers. This is sometimes referred to as a 'bubble chart', popularized by Ashby [1999]. After identifying candidate materials, we can again refine our selection based on other requirements or objectives.

If you prefer to think in rigorous mathematical terms, the performance metric, P, of a structural element depends on: the functional requirements, F; the geometric parameters, G; and the material properties of the structure, M, as:

$$P = f(F, G, M)$$

If the functional is *independent*, usually the case for a given qualitative design, then:

$$P = f_1(F) \cdot f_2(G) \cdot f_e(M)$$

For optimum design, we want to maximize or minimize P, which can be done by maximizing or minimizing $f_e(M)$, the *material efficiency coefficient*.

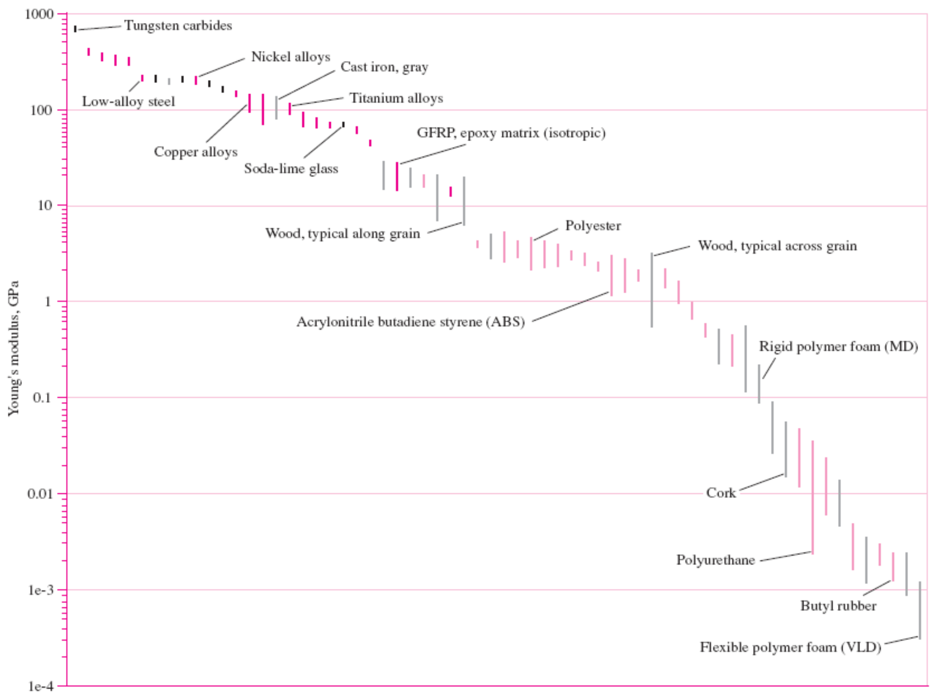


Figure 7.4: E for various materials

7.4.3 Analytical Material Selection Example:

Design a light, stiff, end-loaded cantilever beam with a circular cross-section.

Procedure:

- The performance metric to be optimized is beam mass, m.
- Determine $f_e(M)$: Stiffness is defined as $k = F \cdot \delta^{-1}$, where F is the end load and $\delta = Fl^3 \cdot (3EI)^{-1}$ is the end deflection (e.g. [Budynas and Nisbett, 2006], Table A-9). The area moment of inertia $I = \pi D^4 \cdot 64^{-1} = A^2 \cdot (4\pi)^{-1}$, where D and A are the diameter and area of the cross section (e.g. [Budynas and Nisbett, 2006], Table A-16). Combining these equations, we can solve for the area:

$$A = \left(\frac{4\pi k l^3}{3E}\right)^{1/2}$$

The beam mass is given by $m = A \cdot L \cdot \rho$. Substituting our equation for A, we have the equation for the mass of a circular cross-section beam with a

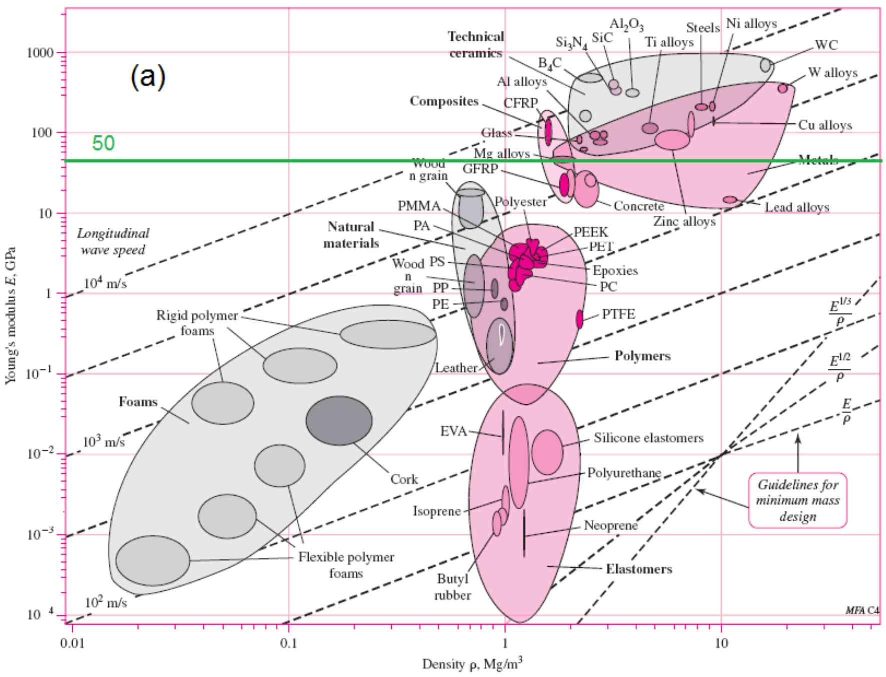


Figure 7.5: Ashby charts. (a) E vs. ρ; (b) Strength vs. ρ.

desired stiffness as a function of the length and material properties:

$$m = \underbrace{2\sqrt{\frac{\pi}{3}}(k^{1/2})}_{f_1(F)}\underbrace{(L^{5/2})}_{f_2(G)}\underbrace{\left(\frac{\rho}{E^{1/2}}\right)}_{f_3(M)}.$$

To minimize m, we want to minimize $f_e(M)$ or maximize the *material index*

$$M = \frac{E^{1/2}}{\rho}.$$

- Identify candidate materials: We now use a material selection chart (Figure 7.5) that depicts E vs. ρ. This is a log-log plot, so lines in this space have constant value of E^α/ρ. We wish to maximize $E^{1/2}/\rho$, so we use a line of the correct slope and move it up and to the left until it reaches the edge of the depicted bubbles. We see that good candidates for our design include woods, composites, and technical ceramics.
- Investigate other constraints: At this point, we would need further information to decide among the candidate materials. If, for example, cost was important, we might choose among grades of wood.

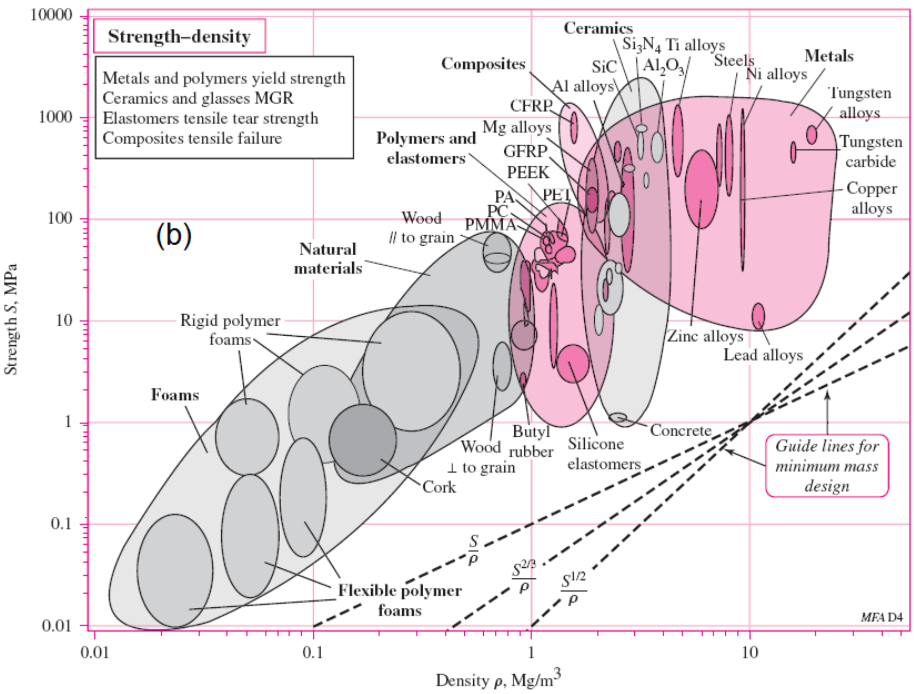


Figure 7.6: Ashby charts. (a) E vs. ρ; (b) Strength vs. ρ.

7.5 Intuitive Selection of Common Materials

In practice, we often select materials based on prior knowledge of the types of stuff that is good for making types of things. This intuitive selection of materials can be effective with practice in a given domain, especially when undergirded by use of the rigorous analytical methods described earlier. Here we present a non-exhaustive list of materials that are commonly used in robotics and biomechatronics applications, with rough guidelines for properties and use:

Aluminum
Properties: Aluminium alloys tend to be easily machined, have good strength-to-density ratios, have medium-high strength, ductility, and stiffness, and have good corrosion resistance. They can be anodized with fun colors, which also improves scratch resistance.
When to use: Aluminum alloys are good for multi-featured, medium-sized parts that experience medium-high loads, especially bending loads.
Common grades: 6061-T6 Aluminum is a common and relatively inexpensive material good for general purpose applications. 7075-T651 Aluminum is high strength, with yield strength comparable to many grades of steel, but is more expensive and slightly more difficult to machine.

Steel
Properties: Steel alloys tend to be easily machined (unless heat treated or stainless) and have medium-to-high strength, ductility, and stiffness. A wide range of properties can be obtained through processing, so care must be taken to identify treatment. Steel can have infinite fatigue life and can have high toughness, each of which can be useful in some applications.
When to use: Steel is a good choice for small parts that experience high loads or high contact stresses, e.g. shafts and ball bearings. It is also a good choice for applications with a high factor of safety, high desired toughness, and fatigue loading, e.g. bridge trusses.
Common grades: Carbon steel is a good general-purpose choice. Type 302 or 18-8 stainless steel is a good general-purpose stainless choice. Hardened shafts are often made of heat-treated 440C stainless steel.

Plastics
Properties overview: Plastics are generally easily machined, easily mass-produced via mold forming, and have low-to-medium strength and stiffness. A wide variety are available, many of which are cheap or have desirable properties such as low friction or thermal properties suitable for injection molding.
When to use: Plastics are often good for complex, low-load, inexpensive parts. They are great for rapid prototyping. They can be used for small, lightweight 'plain bearings' or 'bushings', though with higher friction than ball bearings. In mass production of products, plastics should usually be considered.
Common types: ABS is strong for plastic and is heat formable, although it can be toxic when heated. Acrylic also has decent strength and can be cut with low-power lasers.

Composites
Properties overview: Composite materials, such as carbon fiber, can have exceptional combinations of strength, stiffness and density, but are difficult to work with. Parts are typically made using a 'laying up' process with fibers soaked in resin and vacuumed onto a mold. Alternatively, pre-formed stock in simple shapes can be purchased and cut to length. Material properties are difficult to estimate, especially for in-house layups, so use an appropriate factor of safety.
When to use: Use preformed stock in simple parts where high strength and low mass are critical. Use custom layups in high performance, high cost applications with experienced manufacturers.
Common types: Fiberglass, typically S-Glass or E-Glass in epoxy, has good strain energy capacity and makes good springs. Carbon fiber is light, strong, and stiff.

7.6 Other Considerations

In addition to mechanical properties, we must consider **cost** and **manufacture** of our parts. We will consider interactions between these factors later in the semester.

It is also important to remember that mechanical properties are typically determined for a particular set of controlled testing circumstances, and may not be representative of behavior under very different conditions. Operating temperature and strain rate, for example, can significantly affect strength and ductility (see Figure 7.7).

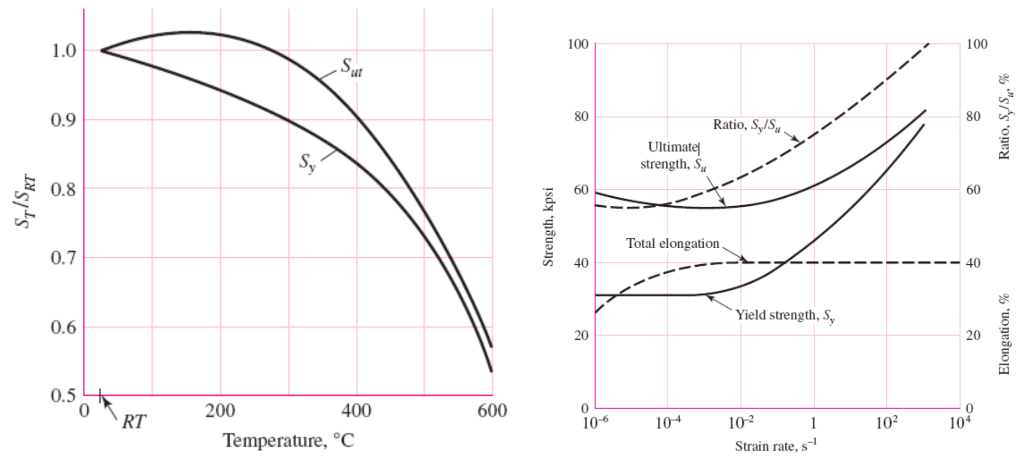


Figure 7.7: Effects of temperature and strain rate on strength and elongation at failure.

7.7 Acknowledgments

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