# Chapter 6

# Nonferrous Metals and Alloys: Production, General Properties, and Applications

## QUALITATIVE PROBLEMS

**6.15 Explain why cooking utensils are generally made of stainless steels, aluminum, or copper.**

Cooking utensils require noncorrosive materials (to maintain their appearance and prevent unpleasant taste in cooked products) as well as good thermal conductivity for even heating. These metals satisfy these requirements and are also able to be easily formed into the various shapes.

**6.16 Would it be advantageous to plot the data in Table 6.1 in terms of cost-per-unit weight rather than of cost-per-unit volume? Explain and give some examples.**

Such a table would better reflect more the actual prices of stock materials (steel, gold, copper, etc.), which is usually sold in price per weight unlike wood from a lumber yard, for instance. However, when we determine the amount of material required in a product or structure, we do so from its dimensions (hence volume), as derived from strength or aesthetic considerations. Note, for example, that the dimensions of beams and shafts for a particular application are determined from formulas in mechanics of solids textbooks. We then order the materials, the cost of which is based on weight.

**6.17 Inspect Table 6.2 and comment on which of the two hardening processes (heat treating and work hardening) is more effective in improving the strength of aluminum alloys.**

According to Table 6.2, those alloys designated with a T are heat treated, while those designated with an H are cold worked. Heat treating (Chapter 4) increases the strength to higher levels than cold working. The reason that cold working is not as effective of a hardening process is due to the low strain hardening capability of aluminum (see, for example, Table 2.3 on p. 72).

**6.18 Other than mechanical strength, what other factors should be considered in selecting metals and alloys for high-temperature applications?**

Because high temperatures tend to increase corrosion rates, the alloy should have good high-temperature corrosion resistance. Also, creep resistance should be high, since high temperatures promote creep (Section 2.8 on p. 86). If the particular application requires cycling through temperature ranges, the alloy should also possess thermal-fatigue resistance.

**6.19 Explain why you would want to know the ductility of metals and alloys before selecting them.**

It is important to know the ductility of a metal or alloy since ductility is a measure of how much the metal can be cold worked, if at all, without requiring an intermediate annealing cycle. In addition to the metal's formability, the toughness of the metal increases with increasing ductility. Materials with high ductility can be less susceptible to stress concentrations and can have better fatigue lives.

**6.20 Explain the techniques you would use to strengthen aluminum alloys.**

The main techniques used in strengthening aluminum alloys are strain hardening and precipitation hardening (see Section 4.9 on p. 134). The precipitation-hardening process is capable of imparting higher strength levels to aluminum. This process starts with a solution treatment of the alloy so that the alloying elements are in an unstable supersaturated solution. The alloy can then be either cold worked, naturally aged (at room temperature), or artificially aged (at higher temperatures). The aging process forms small precipitates in the microstructure which decrease dislocation movement and, thus, increase strength. Strain hardening involves cold working of the alloy, which produces dislocation networks that hinder dislocation motion, and, thus, increase strength.

**6.21 Assume that, for geopolitical reasons, the price of copper increases rapidly. Name two metals with similar mechanical and physical properties that can be substituted for copper. Comment on your selection and observations.**

Two metals having the closest properties to copper are probably aluminum and magnesium. Aluminum has the closest overall properties, both physical and mechanical, to copper. The table below shows the similarities of mechanical properties (see Table 3.1 on p. 103 for correlation of physical properties).

| **Property** | **Copper** | **Aluminum** | **Magnesium** |
|---|---|---|---|
| Yield stress (MPa) | 70-55 | 35-500 | 200-300 |
| Tensile strength (MPa) | 220-900 | 100-570 | 255-380 |
| Elongation (%) | 66-1700 | 45-800 | 15-700 |

**6.22 If planes (such as a Boeing 757) are made of 79% aluminum, why are automobiles predominantly made of steel?**

Automobiles are predominantly made of steel for a number of reasons. A major reason is that a design history exists with steel but not with aluminum, and material changes have a certain initial drawback (for example, aluminum is more difficult to form than steel, and welding process parameters differ). Also, the weight reduction consideration which dominates aerospace design is not as pressing in automobiles. In recent years, there have been some models of automobiles that have used very high amounts of aluminum (such as the Audi A6 and the Plymouth Prowler), demonstrating that aluminum can be successfully applied to automobiles.

**6.23 Portable (notebook) computers have their housing made of magnesium. Why?**

The main reason that the notebook computer housings are magnesium is because of the need to reduce weight. Because magnesium is the lightest of all metals (see Table 3.1 on p. 103), it can produce the lightest housing of a given volume. Furthermore, magnesium can easily be die cast into intricate shapes (see Section 11.3.5 on p. 306).

**6.24 Table 6.3 lists the manufacturing properties of wrought aluminum alloys. Compare their relative characteristics with those of other metals.**

By the student. There are many trends which can be identified in Table 6.3 on p. 171, but, as examples, note that wrought aluminums have much better corrosion resistance than wrought steels. Machinability is somewhat poorer than that for copper, but better than refractories. Weldability is usually excellent in wrought form, compared to that of other metals.

**6.25 Most household wiring is made of copper wire. By contrast, grounding wire leading to satellite dishes and the like is made of aluminum. Explain the reason for this.**

Grounding wire is used as an exterior conductor on a house for protection against lightning strikes. In this case, the current flow is extremely high. Thus, it is thus essential to minimize resistance inside the wire. Aluminum has a lower resistivity than copper, so it is the better choice for this application provided that good electrical contact is obtained using proper terminals. Aluminum is not used for conventional household wiring because it is too stiff and not as ductile as copper, and this is a drawback when the wire is bent and twisted in conduits around beams and joists during installation. (See also the example, "Electrical Wiring in Homes", on p. 97 in *Manufacturing Engineering and Technology*, 3rd ed.)

## QUANTITATIVE PROBLEMS

**6.26 A simply-supported rectangular beam is 25 mm wide and 1 m long, and it is subjected to a vertical load of 30 kg at its center. Assume that this beam could be made of any of the materials listed in Table 6.1. Select three different materials**

**and calculate for each the beam's height that causes each beam to have the same maximum deflection. Calculate the ratio of the cost for each of the three beams.**

This is a simple problem of mechanics of solids, and the student is to select three different materials. The governing equation for maximum deflection, $d$, for this type of loading of a beam is:

$$d = \frac{PL^3}{48EI}$$

where $P$ is the load (30 kg, or 294 N), $L$ is the beam length (1 m), $E$ is the elastic modulus, and $I$ is the moment of inertia, where $I = bh^3/12$ and $b = 25$ mm. For a constant deflection, the relationship between $E$ and $h$ is as follows:

$$d = \frac{PL^3}{48EI} = \frac{PL^3}{4Ebh^3} \quad \rightarrow \quad h = \sqrt[3]{\frac{PL^3}{4Ebd}}$$

For illustrative purposes, we will proceed with the following materials:

| **Material** | **Young's modulus (GPa)** |
|---|---|
| Carbon steel | 190 |
| Aluminum | 70 |
| Nickel | 180 |

Note: See Table 2.2 on p. 67.

(a) Using carbon steel as the reference, consider the beam height, $h$, required to restrict the deflection to 1 mm (0.001m). For steel, $h$ is

$$h = \sqrt[3]{\frac{(294)(1)^3}{4(190 \times 10^9)(0.025)(0.001)}} = 0.0249 \text{ m}$$

The required volume, $V$, of the steel beam is then

$$V = bhl = (25)(24.9)(1000) = 622,500 \text{ mm}^3$$

(b) For aluminum,

$$h = \sqrt[3]{\frac{(294)(1)^3}{4(70 \times 10^9)(0.025)(0.001)}} = 0.0348 \text{ m}$$

so that the required volume is 870,000 $\text{mm}^3$.

(c) For nickel,

$$h = \sqrt[3]{\frac{(294)(1)^3}{4(180 \times 10^9)(0.025)(0.001)}} = 0.0254 \text{ m}$$

so that the volume is 635,000 $\text{mm}^3$.

Table 6.1 on p. 170 allows us to calculate the relative costs. The steel beam is the reference. By comparison, the aluminum will cost, at a minimum, twice the cost of steel by volume. The aluminum beam requires a larger volume, so that the cost of the aluminum will be (827,500/592,500)(2) = 2.79 times the cost of the steel beam. Similarly, the nickel beam will cost 35.7 times the cost of the carbon steel beam.

**6.27 Obtain a few aluminum beverage cans, cut them, and measure their wall thicknesses. Using data in this chapter and simple formulas for thin-walled, closed-end pressure vessels, calculate the maximum internal pressure these cans can withstand before yielding.**

Aluminum beverage can thicknesses can vary slightly depending on the canmaker. This solution will use typical numbers of a thickness of 0.075 mm and a radius of 33 mm. Using 3003-H14 aluminum with a yield strength of 145 MPa (see Table 6.3 on p. 171), noting that the two of the principal stresses are the hoop stress and the axial stress:

$$\sigma_h = \frac{pr}{t} = 452p \qquad \sigma_a = \frac{pr}{2t} = 226p$$

The radial stress is essentially zero for a thin-walled pressure vessel. Thus, the maximum shear stress is equal to one-half the hoop stress, or $226p$. Using the maximum shear stress (Tresca yield criterion) gives

$$\frac{Y}{2} = 226p \quad \rightarrow \quad p = \frac{Y}{452} = \frac{145 \text{ MPa}}{452} = 321 \text{ kPa}$$

which is approximately three atmospheres.

**6.28 Beverage cans are usually stacked on top of each other in stores. By using information from Problem 6.27 and referring to textbooks on the mechanics of solids, make an estimate of the crushing load each of these cans can withstand.**

The buckling analysis of such cans is complicated, especially since the fluid contents can eliminate local buckling. However, considering only the effect of a compressive stress on the wall, and assuming the can contents are at ambient pressure, the effect of a load is one of an axial stress. Using the same can dimensions and material as in Problem 6.27 above,

$$\sigma_a = \frac{F}{2\pi rt} \quad \rightarrow \quad F = \sigma_a(2\pi rt) = (145 \text{ MPa})(2\pi)(0.033 \text{ m})(0.000075 \text{ m}) = 2.25 \text{ kN}$$

**6.29 Using strength and density data, determine the minimum weight of a two-foot long tension member which must support 750 pounds, if it is manufactured from (a) 3003-O aluminum, (b) 5052-H34 aluminum, (c) AZ31B-F magnesium, (d) any brass alloy, and (e) any bronze alloy.**

The cross-sectional area required is given by $\sigma_y = F/A$; $A = F/\sigma_y$. The volume is then $V = AL = FL/\sigma_y$, and the weight is $W = \rho V = \rho FL/\sigma_y$. In this case, $L = 24$ in. $= 0.610$ m, and $F = 1000$ lb $= 4440$ N. Density data comes from Table 3.1 on p. 103 and uses the lowest values in the range. Using this equation, the following can be compiled:

| **Material** | **Density** ($kg/m^3$) | **Yield strength** (MPa) | **Weight needed** (N) |
|---|---|---|---|
| 3003-O Al | 2630 | 40[1] | 1.75 |
| 5052-H34 Al | 2630 | 215[1] | 0.32 |
| AZ31B-F Mg | 1770 | 200[2] | 0.24 |
| Red brass | 7470 | 70[3] | 2.8 |
| C38500 bronze | 7470 | 140[4] | 1.4 |

Notes:

1. From Table 6.3 on p. 171.
2. From Table 6.5 on p. 176.
3. From Table 6.6 on p. 177.
4. From Table 6.7 on p. 178.

**6.30 An automobile engine operates at up to 7000 rpm. If the stroke length for a piston is 6 in. and the piston is made of a 10-lb. steel casting, estimate the inertial stress on the 1-in. diameter connecting rod. If the piston is replaced by the same volume of aluminum alloy, what would be the speed for the same inertia-induced stress?**

First, note that the operating speed is 100 rev/sec; however, the velocity distribution of the piston is a function of location in the cylinder. As a first approximation, let's assume sinusoidal motion of the piston, so that from the middle of the piston, the position is described by

$$x = (3\text{ in.})\sin(200\pi t)$$

The acceleration is, then

$$a = \ddot{x} = -120,000\pi^2\text{ in./sec}^2(\sin 200\pi t)$$

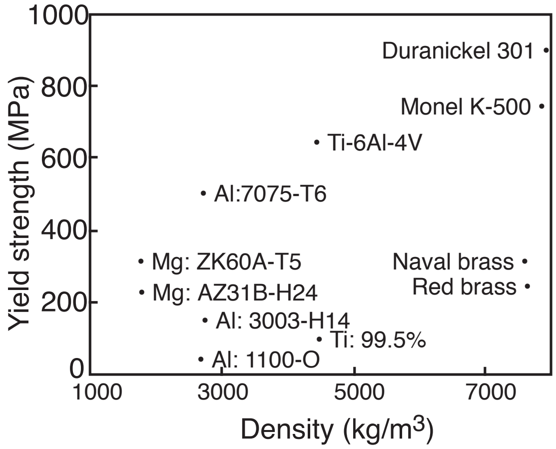
with a maximum value of $1.18 \times 10^6$ in./sec$^2$ = 98,700 ft/sec$^2$. From inertia,

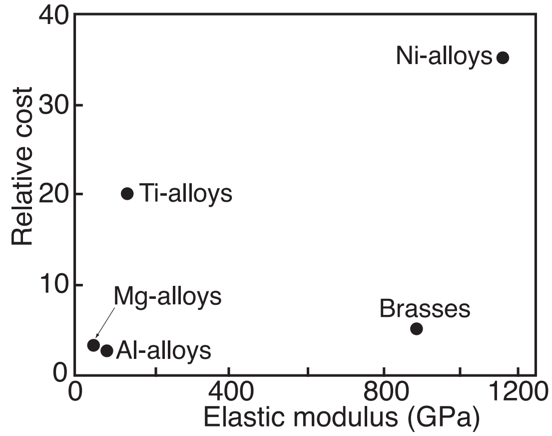
$$F = Ma = \frac{10\text{ lb}}{32.2}(98,700\text{ ft/sec}^2) = 30.6\text{ kip}$$

For a 1-in. diameter connecting rod, $A = 0.78$ in$^2$, hence the stress is 39 ksi. If the piston is made of aluminum, with the same volume as the steel, its weight will be (2700/6290)=0.429 times that of the steel piston (numbers taken from Table 3.1 on p. 103). Therefore, the weight would be about 4.3 lb. Performing the same calculation, the stress would be 16.7 ksi.

**6.31 Plot the following for the materials described in this chapter: (a) yield strength versus density, (b) modulus of elasticity versus strength, and (c) modulus of elasticity versus relative cost.**

The plot for selected materials are as follows for parts (a) and (c); part (b) is to be completed the student.




## SYNTHESIS, DESIGN AND PROJECTS

**6.32 Because of the number of processes involved in making them, the cost of raw materials for metals depends on their condition (hot or cold rolled), shape (plate, sheet, bar, tubing), and size. Make a survey of the available literature and price lists (or get in touch with suppliers) and prepare a list indicating the cost per 100 kg of the nonferrous materials described in this chapter, as available in different conditions, shapes, and sizes.**

By the student. As a helpful guide, there are some sources which deal in one particular metal, while others are sources for all materials. There will be a wide range, depending on the size of cross-sections selected. Thus, for example, the data from Small Parts, Inc. will be different than those from McMaster-Carr.

**6.33 The materials described in this chapter have numerous applications. Make a survey of the available literature and prepare a list of several specific products and applications, indicating the types of materials used.**

By the student. An example could be the stem of an artificial hip replacement (see Example I.5 on p. 26), which can be made from stainless steel, cobalt-chrome alloy, or titanium. As another example, automobile body panels can be constructed from steel, aluminum, stainless steel (the DeLorean automobile), or reinforced plastics.

**6.34 Name products that would not have been developed to their advanced stages (as we find them today) if alloys having high strength, high corrosion resistance, and high creep resistance (all at elevated temperatures) had not been developed.**

The most outstanding examples of improvements for high-temperature parts typically have occurred in the aircraft and the aerospace industry. The efficiency of many gas-turbine engines increases with higher operating temperatures. The rotors and turbine blades in these engines have constantly been improved in terms of their high-temperature strength and creep and corrosion resistance. These improvements have allowed the engines to achieve greater thrust and speeds. Also, casings and other components of rockets have made space exploration possible.

**6.35 Assume that you are the technical sales manager of a company that produces nonferrous metals. Choose any one of the metals and alloys described in this chapter and prepare a brochure, including some illustrations, for use as sales literature by your staff in their contact with potential customers.**

By the student. The brochure should mainly promote the products that the company markets. The information given in the brochure about the metal should list benefits over other competitive materials, and should also show how the company's product is better than those of the competitors. Special production processes should be described and how the metal is improved by these advances should be explained. Plant facilities, equipment, and the capabilities of the personnel at all levels are usually also shown. Important sales information such as a wide range of reliable applications, trends in sales, and any concerns that may arise regarding the material and its uses should also be given.

**6.36 Inspect several metal products and components and make an educated guess as to what materials each is made from. Give reasons for your guesses. If you list two or more possibilities, explain your reasoning.**

By the student. Students are encouraged to respond to this question by developing a comprehensive list of products and explaining their observations. As an example, a U.S. quarter or a dime, when viewed from the side clearly shows a sandwiched structure (see Example 31.1 on p. 982). The interior is clearly reddish brown, indicating a copper alloy, and the exterior is shiny and bright, as well as corrosion resistant. These properties are typical of silver, platinum, and nickel. Reviewing cost information in Table 6.1 on p. 170, a nickel-alloy appears the most likely material.

**6.37 Give applications for (a) amorphous metals, (b) precious metals, (c) low-melting alloys, and (d) nanomaterials.**

By the student. Some examples are

(a) Amorphous alloys: magnetic applications such as steel coils for electrical transformers, since they have a very low magnetic hysteresis loss. Also, their high strength and corrosion resistance can make them useful in structural applications.

(b) Precious metals: applications include jewelry, decorative fixtures, coins, dental work, tableware, and electrical contacts.

(c) Low-melting alloys: these alloys consist mainly of three elements: lead (piping, tubing, x-ray shields, solders, weight), tin (solders, coating for sheet steel for cans, bearing materials, tableware), and zinc (galvanic coating for steel, die casting, low strength and nonstructural applications).

(d) Nanomaterials: they can be used where exceptional performance is required, such as in cutting tools, medical applications, filters, and microelectromechanical systems (MEMS).

**6.38 Describe the advantages of making products with multilayer materials. (For example, aluminum bonded to the bottom of stainless-steel pots.)**

By the student. Multilayer materials are capable of incorporating and combining the beneficial properties of two distinct materials. In the case of cookware, for example, copper or aluminum provides at the bottom of the pot conducts heat evenly, whereas stainless steel has good corrosion resistance and is easy to clean because of its smooth surface. The student is encouraged to develop further applications.

**6.39 Describe applications and designs utilizing shape-memory alloys.**

By the student. Shape-memory alloys can be used for space saving applications, such as tents or antennas. The parts would be folded up at room temperature and heated to regain their initial form; this is especially useful for satellite antennas. Other applications have been described in Section 6.13 on p. 185.

**6.40 The Bronze Age is so known because the hardest metals known at the time were bronzes. Therefore, tools, weapons, and armor were made from bronze. Investigate the geographical sources of the metals needed for bronze, and identify the known sources in the Bronze Age. (Note: Does this explain the Greek interest in the British Islands?)**

By the student. Since both copper and tin are needed to produce bronze weapons and tools, sources of these materials were extremely valuable during the Bronze Age. However, at the time there were a number of Mediterranean sources of copper, but only two known sources for tin. The first and larger source was the Danube River valley in what is now Austria; the second source was in Wessex, in southern England. There is considerable evidence of Bronze Age trade, such as various Mycenean (2000 to 1100 B.C.) tools and weapons unearthed at various architectural sites in southern England. (See also Table I.2 on pp. 5-7.)

**6.41 Aluminum beverage-can tops are made from 5182 alloy, while the bottoms are made from 3004 alloy. Study the properties of these alloys and explain why they are used for these applications.**

The can tops are made of 5182 aluminum alloy mainly because of the ductility requirements in the material (see also top of p. 173). The key feature is the integral rivet which holds the pop top lever in place; this region undergoes a very large strain in forming. The 3004 alloy is a common can-making alloy because it has good formability and doesn't foul tooling. It appears that the iron-silicon constituent particles in the alloy gently remove aluminum-magnesium particles that may adhere to the tooling surfaces (galling), which is an important consideration.

**6.42 Obtain specimens of pure copper, pure aluminum, and alloys of copper and aluminum. Conduct tension tests on each, plot the stress-strain diagrams, and evaluate the results.**

By the student. Note that pure metals can undergo much higher strains to failure. Pure copper is the material of choice to demonstrate classical, well-behaved materials in stress-strain curves. Pure aluminum also gives classical-shaped curves, but with pure aluminum and aluminum alloys, there is a noise at fracture that is startling at first.

**6.43 Comment on your observations regarding the type of materials used in particular sections of the jet engine shown in Fig. 6.1.**

By the student. There will be several observations made, including:

- Nickel alloys are used in locations in the jet engine where extreme temperatures are encountered, reflecting the excellent strength and creep resistance of nickel alloys at elevated temperatures.
- When considered in combination with Table 6.1 on p. 170, it is clear that the performance requirements are pressing enough that the use of expensive materials can be justified.
- For lower-temperature locations, aluminum alloys are used, where the excellent strength-to-weight ratio of aluminum can be exploited.
- While nickel is used in some locations, it is not used for large structures such as the inlet fan due to its high cost and limited formability.

**6.44 Inspect various small or large appliances in your home and identify the metals and alloys that you think have been used in their construction.**

By the student. Examples are:

- Steel: desks, food containers, bolts and nuts, stamped parts as in toasters, screwdrivers and wrenches, sewing needles.
- Aluminum: baking trays, window frames, soda and beverage containers, aluminum foil.
- Tungsten: toaster burner and furnace elements
- Gold: printed-circuit boards in controllers.
- Lead and tin: soldered connections of all types.

**6.45 Referring to recent technical literature, comment on the trends in the use of metallic materials in (a) military vehicles, (b) sports equipment, (c) medical equipment, (d) automotive applications, and (e) aircraft.**

By the student. Each of these topic areas has extensive technical literature associated with them. Competing concerns such as reliable performance, weight, manufacturability, cost, and availability are important common themes to be explored.