Chapter 5

Ferrous Metals and Alloys: Production, General Properties, and Applications

QUALITATIVE PROBLEMS

5.16 Identify several different products that are made of stainless steel and explain why they are made of this material.

Applications for stainless steel are usually centered around its corrosion resistance (see pp. 161-162). The students are encouraged to give several applications; a few examples include:

(a) Cutlery: the appearance of the cutlery will not be diminished by rust with time.

(b) Blender blades and other food processing and kitchen equipment: stainless steel will not react chemically with food products, so no unpleasant taste remains on the utensils and so that the food does not become adulterated.

(c) Chemical storage tanks: the chemicals would attack the internal surfaces and produce holes in ordinary steels, rendering them useless.

(d) Orthopedic implants: combined with their biocompatibility, the corrosion resistance of stainless steels is essential for materials placed inside the human body.

5.17 As you may know, professional cooks prefer carbon-steel to stainless-steel knives, even though the latter are more popular with consumers. Explain the reasons for those preferences.

Professional cooks keep their knives sharp and use them more often, so that wear resistance of the knives becomes more important. Wear resistance usually is accompanied by high strength and hardness (see Section 33.5 on p. 1046). High-carbon steels can be hardened by heat treatment to a higher degree than stainless steels, thus they have better wear resistance. On the other hand, consumer users have the perception that stainless steel is preferable to carbon steel because it will give superior performance, and this perception drives demand. Also, consumers do not use their knives as often as professional cooks, so wear is not as significant an issue.

5.18 Why is the control of ingot structure important?

Control of the ingot structure is important because it will affect the requirements of further processing and the amount of waste material in the ingot. For instance, porosity accompanying semi-killed or rimmed steel should be eliminated during subsequent working of the ingot, such as by forging and rolling (Section 5.3 on p. 153). If the porosity is not eliminated, the strength and ductility of the steel will generally be reduced. The segregation of alloying elements and impurities in rimmed steel generally gives the steel nonuniform properties. On the other hand, killed steels, which typically have little or no porosity, are accompanied by a large shrinkage cavity at the top of the ingot. This pipe must be scrapped (and remelted) before the ingot is processed further.

5.19 Explain why continuous casting has been such an important technological advancement.

Continuous casting (Section 5.4 on p. 154) eliminates processing of individual ingots and also eliminates most of the porosity, elemental segregation, and shrinkage associated with ingot casting. Continuously-cast bars can be made in a variety of shapes and sizes, significantly reducing the number of subsequent rolling operations. These major benefits make continuous casting capable of producing higher quality steels at lower cost than individual ingot processing.

5.20 Describe applications in which you would not want to use carbon steels.

By the student. Applications that are not suited for carbon steels are those that mainly require high corrosion resistance. A few examples include drain spouts, gutters, and ornamental applications such as cabinet hardware, coins, and faucets. Other applications where carbon steels are not well suited are those where low density is desirable, such as portable computer or camera frames, aircraft fuselages, and automotive pistons.

5.21 Explain what would happen if the speed of the continuous-casting process (Fig. 5.4) is (a) higher or (b) lower than that indicated (typically 25 mm/s).

(a) If the speed of the continuous casting process is higher, the metal may not have sufficient time to completely solidify before it leaves the mold area. Liquid metal will eventually start spilling out of the mold. (b) Lower speeds, on the other hand, adversely affect the economics of the process, and are obviously unnecessary.

5.22 The cost of mill products of metals increases with decreasing thickness and section size. Explain why.

Smaller thickness and section size generally require more metalworking processing steps, such as in rolling, extrusion, or drawing. The more reduction passes, the higher the cost of manufacturing. The relationship between cost and thickness is also not linear, since going beyond a certain size threshold may also mean that a given machine's capabilities have been exceeded. This situation would require the use of additional machinery and manufacturing steps, leading to a larger increase in cost. Also, it should be noted that as the cross-section decreases, the cost increases but so do the mechanical properties such as yield strength and hardness.

5.23 Describe your observations regarding the information given in Table 5.7.

By the student. In general, steels with high hardness have low toughness and high resistance to wear. Also, those having very high resistance to wear have low machinability, and those with high machinability have low resistance to wear. Additional observations can be made by the student by noting the composition of individual steels in the first column of the table.

5.24 How do trace elements affect the ductility of steels?

Most trace (residual) elements tend to form inclusions or segregate to grain boundaries, causing embrittlement, thus decreasing toughness and fracture resistance, as well as severe reduction in ductility.

5.25 Comment on your observations regarding Table 5.1.

A number of observations can be made. First, a direct comparison between steel and aluminum shows that steel is cheaper per unit weight, and, when a calculation is made, by volume as well. Other tables in the chapter show the general trend that the stronger and more heavily alloyed steels are more expensive than the more common carbon steels. Finally, there is an obvious trend that additional processing is reflected in the costs of, for example, hot-rolled versus cold-rolled steels.

5.26 In Table 5.7, D2 steel is listed as a tool and die material for most applications. Why is this so?

D2 tool steel is listed for many applications because, as discussed on p. 164 and shown in Table 5.6, this material has a high resistance to wear and cracking, thus making it ideal for tooling applications. In addition, this material can be formed well because, as a dual-phase steel, it has a high n value (see Section 2.2.5 on p. 71). It also has a high ductility so that fracture is less likely.

5.27 List the common impurities in steel. Which of these are the ones most likely to be minimized if the steel is melted in a vacuum furnace?

Imperfections (such as micropores) and surface defects (such as blow holes) exist in steel, which can be reduced by hot working. Residual elements, such as antimony, hydrogen, nitrogen, oxygen and tin, can adversely affect the steel's properties. When melted in a vacuum furnace, on the other hand, the hydrogen, nitrogen and oxygen will be present in much smaller concentrations, although antimony, arsenic and tin may still be present.

5.28 Explain the purpose of the oil in Fig. 5.4 given that the molten-steel temperatures are far above the ignition temperatures of the oil.

The oil serves two purposes. First, a lubricant is needed between the steel and the mold to facilitate movement. As stated, the oil combusts at the casting temperatures, but it doesn't combust fully because of the argon-dominated atmosphere. Thus the oil can provide some lubrication. Secondly, the oil usually is a carrier for graphite flakes that have been suspended in the oil, and these flakes lubricate the mold.

5.29 Recent research has identified mold-surface textures that will either (a) inhibit a solidified steel from separating from the mold or (b) force it to stay in contact in continuous casting. What is the advantage of a mold which maintains intimate contact with the steel?

The main advantage to this kind of surface texture is that if the material keeps in contact with the mold, the thermal contact resistance between the mold and the material is much lower. Consequently, heat will be conducted faster, allowing higher traverse speeds or the use of shorter molds.

5.30 Identify products which cannot be made of steel and explain why this is so. For example, electrical contacts are commonly made of gold or copper, because their softness results in low contact resistance, while for steel the contact resistance would be very high.

By the student. There are many potential answers, and students should be encouraged to think creatively to respond to this question. The instructor may wish to further constrain this problem, such as by requiring five answers, where the rationale is different for each answer. Alternatively, one could request that students find examples in the automotive, aerospace, food processing, computer, and construction industries. Examples are:

- Gym-shoe soles cannot be made of steel because the shoe needs high coefficients of friction, and the sole material must have a high compliance for comfort.
- Steel cannot be used in building foundations, because it is far too expensive compared to cement.
- Steel is not used as aircraft-fuselage material, because its strength-to-weight ratio is too low (see Fig. 9.3 on p. 241).
- Steel is a bad material for a coffee cup, since it is thermally conductive and would burn the hands of someone drinking coffee, and would not keep the coffee hot as long as when using an insulator. Note that an evacuated design as with some thermos designs would be acceptable.
- Steel would not be suitable for jewelry because of aesthetic reasons.
- Steel is not suitable as a material for many children's toys because it is hard and can be dangerous in the hands of small children.
- Steel is not suitable as a crate or pallet material, since it is far more expensive than wood.
- Tennis racquets and golf clubs are not made of steel because they would be too heavy compared to titanium products.

QUANTITATIVE PROBLEMS

5.31 By referring to the available literature, estimate the cost of the raw materials for (a) an aluminum beverage can, (b) a stainless-steel two-quart cooking pot, and (c) the steel hood of a car.

By the student. For examples, (a) an aluminum beverage can is approximately 4 cents, (b) a stainless-steel cooking pot is around $40-$100, depending on quality and the manufacturer, and (c) the hood of the car can be as low as $75.

5.32 In Table 5.1, more than one type of steel is listed for some applications. By referring to data in the technical literature, determine the range of properties for these steels in various conditions (such as cold worked, hot worked, and annealed).

By the student. The information can be found in various textbooks and references, as also given in the Bibliography.

5.33 Some soft drinks are now available in steel cans (with aluminum tops) that look similar to aluminum cans. Obtain one of each, weigh them when empty, and determine their respective wall thicknesses.

By the student. The actual wall thicknesses vary by manufacturer. A typical thickness for an aluminum can is 0.003 in. (0.076 mm). The thickness of steel cans will typically range from this value to thinner walls, as low as 0.0015 in. (0.040 mm).

5.34 Using strength and density data, determine the minimum weight of a two-foot long tension member which must support 1000 lb. manufactured from (a) annealed 303 stainless steel, (b) normalized 8620 steel, (c) as-rolled 1080 steel, (d) any two aluminum alloys, (e) any brass alloy, or (f) pure copper.

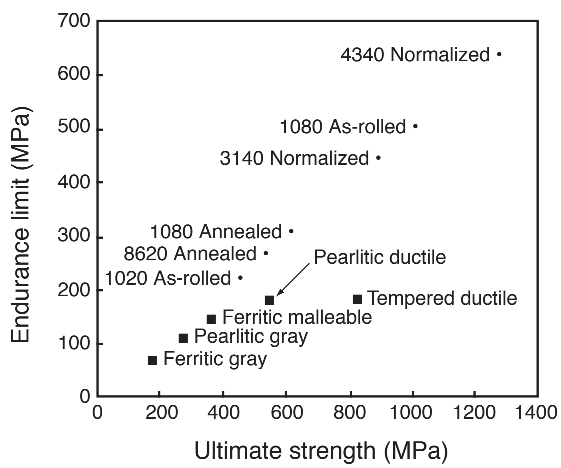
The cross-sectional area required is given by $\sigma_y = F/A$; thus $A = F/\sigma_y$. The volume is then $V = AL = FL/\sigma_y$, and the weight is $W = \rho V = \rho FL/\sigma_y$. In this case, $L = 24$ in. $= 0.610$ m, and $F = 1000$ lb $= 4440$ N. Density data below is obtained from Table 3.1 on p.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

Material	**Density** (kg/m^3)	**Yield strength** (MPa)	**Weight required**
303 stainless steel	6290	550[1]	0.031 kg (0.30 N)
8620 normalized	6290	632[1]	0.027 kg (0.26 N)
1080 as rolled	6290	1010[1]	0.017 kg (0.17 N)
Al 1100-O	2700	90[2]	0.081 kg (0.79 N)
Al 1100-H14	2700	125[2]	0.059 kg (0.58 N)
Copper	8970	220[3]	0.110 kg (1.08 N)
Red brass	7470	270[3]	0.075 kg (0.74 N)

Notes: [1] From Table 5.2 and 5.4 on pp. 159 and 162.
[2] From Table 6.3, p. 171.
[3] From Table 6.6, p. 177.

5.35 The endurance limit (fatigue life) of steel is approximately one-half the ultimate strength (see Fig. 2.16) but never higher than 100 ksi (700 MPa). For irons, the endurance limit is 40% of the ultimate strength but never higher than 24 ksi (170 MPa). Plot the endurance limit versus the ultimate strength for the steels described in this chapter and for the cast irons in Table 12.3. On the same plot, show the effect of surface finish by plotting the endurance limit, assuming the material is in the as-cast state (see Fig. 2.28).

The plot is as follows:



SYNTHESIS, DESIGN AND PROJECTS

5.36 Based on the information given in Section 5.5.1, make a table with columns for each improved property (i.e., hardenability, strength, toughness, and machinability). In each column, list the elements that improve that property and identify the element that has the most influence.

The following table indicates the elements (in alphabetical order) that influence favorably a particular property. The element that has the most influence is given in bold letters.

Hardenability	**Strength**	**Toughness**	**Machinability**
Boron	**Carbon**	Calcium	Lead
Carbon	Cobalt	Cerium	Manganese
Chromium	Chromium	Chromium	Phosphorus
Manganese	Copper	Magnesium	Selenium
Molybdenum	Manganese	Molybdenum	**Sulfur**
Phosphorus	Molybdenum	**Nickel**	Tellurium
Titanium	Nickel	Niobium	
	Niobium	Tantalum	
	Phosphorus	Tellurium	
	Silicon	Vanadium	
	Tantalum	Zirconium	
	Tungsten		
	Vanadium		

5.37 Assume that you are in charge of public relations for a steel-producing company. Outline all the attractive characteristics of steels that you would like your customers to know about.

By the student. Note that the main benefits of steels are their wide range of properties and low cost in relation to nonferrous alloys. The properties of steels can be tailored to fit a specific application. By certain alloying-element additions, properties such as strength, wear resistance, toughness, formability, corrosion resistance, and magnetic properties can be optimized to best suit a particular application.

5.38 Assume that you are in competition with the steel industry and are asked to list all the characteristics of steels that are not attractive. Make a list of these characteristics and explain their engineering relevance.

By the student. A major drawback in using steels is their density, which is higher than aluminum, titanium, or plastics. Because of its higher density, steel is not used extensively in applications where weight is an important factor, such as the aerospace industry (which uses mainly aluminum and titanium). Also, most alloys of aluminum, titanium, copper, and nickel are naturally corrosion resistant, whereas steel requires expensive alloy additions (such as chromium) to achieve this property. The thermal and electrical conductivity of steels are not particularly high, so that copper or aluminum alloys are most suited for applications requiring these properties. Further, since early 2004, the worldwide demand for steel has resulted in increased prices and unreliable supply.

5.39 In Section 5.5.1, we noted the effects of various individual elements (such as either lead alone or sulfur alone) on the properties and characteristics of steels. We did not, however, discuss the role of combinations of elements (such as lead and sulfur together). Review the available technical literature and prepare a table indicating the combined effects of several elements on steels.

By the student. References on steels will discuss this subject; the usual treatment is to explain the trends of one additive and then assume that there are not interactions if one or more are used. For important additive combinations, this is a good approximation, but usually alloys are characterized individually, based on many additives.

5.40 In the past, waterfowl hunters used lead shot in their shotguns, but this practice resulted in lead poisoning of unshot birds that ingested lead pellets (along with gravel) to help them digest food. Recently, steel and tungsten have been used as replacement materials. If all pellets have the same velocity upon exiting the shotgun barrel, what concerns would you have regarding this material substitution? Consider environmental and performance effects.

From the hunter's standpoint, steel is less dense than lead, thus it is not as effective. Tungsten has a much higher density than lead and does not have this drawback; however, it is much more expensive. From an environmental standpoint, there is an obvious advantage to replacing lead with steel or tungsten, in that the toxic lead pellets would not be thrown into the environment where they can pollute groundwater. There has been a well-known problem, in that lead particles are often ingested by birds to help digest food, leading to lead poisoning, which does not occur if the birds ingest pebbles. However, wounded waterfowl are often able to escape to nearby sanctuaries (such as national parks) where large flocks congregate. These wounded birds eventually perish and the decaying birds then spread disease among the flock. Thus, as is often the case, there are drawbacks and benefits to the material substitution and firm conclusions are difficult to obtain.

5.41 Aluminum has been cited as a possible substitute material for steel in automobiles. What concerns would you have before purchasing an aluminum automobile?

By the student. There are many concerns, a few of which are discussed here. Aluminum is more expensive than steel, and this will undoubtedly be reflected in total cost. Much of this cost is due to aluminum requiring greater energy to produce than steel, so even improved gas mileage may never pay off in the life of a car. Steel is a proven material in the automotive industry and performs well from a safety standpoint.

5.42 In the 1940s, the Yamato was the largest battleship that had ever been built. Find out the weight of this this ship, and determine how many automobiles could be built from the steel in this one ship. How long would it take to cast this much steel by continuous casting?

By the student. The research can have some minor variations, depending on the source and details of the figures obtained; thus a general outline of an acceptable approach is given here. The *Yamato* displaced about 72,000 tons. Admittedly, some of this weight was not steel, but was wood, brass and decorative material as well. Consider if it was all steel, and a typical automobile in 1995 used around 650 kg of steel (or 1430 lb = 0.715 tons). Therefore, the *Yamato's* steel could have been used to make approximately 100,000 automobiles.

As for the time needed to produce this much continuously cast steel, it is stated on p. 155 that the steel is withdrawn at a speed of around 25 mm (1 in.) per second. The largest openings for billets are 15 in. by 23 in. (see www.steel.org/learning/howmade/concast.htm), so that the highest flow rate in continuous casting can be estimated as 345 $\text{in}^3/\text{s} = 0.00565$ m^3/s. Since steel has a density of 8025 kg/m^3 (mid-range value from Table 3.1 on p. 103), the mass flow rate of steel in continuous casting is approximately 45.4 kg/s. Thus, it can be calculated that the time needed to produce the steel in the *Yamato* is 1.40×10^6 s, or 16.2 days.

5.43 Search the technical literature and add more parts and materials to those shown in Table 5.1.

By the student. Some examples are:

Product	**Steel**	**Product**	**Steel**
Screw machine parts, spindles, pins, rods	1018	Simple structural applications such as cold formed fasteners	1020
Moderate strength, cold-formed fasteners and bolts	1022	Couplings and cold-headed parts	1040
Aircraft engine mounts and welded tubing	4130	Aircraft landing-gear axles, power transmission shafts	4330
Gears and studs	1045	Hand tools such as screw-drivers and pliers	1060

Source: http://www.coburnmyers.com/technical/carbon-steel.asp.