Chapter 20 / Materials Selection and Design Considerations

Shown in this photograph is the landing of the *Atlantis* Space Shuttle Orbiter. This chapter discusses the materials that are used for its outer airframe's thermal protection system. [Photograph courtesy the National Aeronautics and Space Administration (NASA).]

Why Study *Materials Selection and Design Considerations?*

Perhaps one of the most important tasks that an engineer may be called upon to perform is that of materials selection with regard to component design. Inappropriate or improper decisions can be disastrous from both economic and safety perspectives. Therefore, it is essential that the engineering student become familiar with and versed in the procedures and protocols that are normally employed in this process. This chapter discusses materials selection issues in several contexts and from various perspectives.

Learning Objectives

After careful study of this chapter you should be able to do the following:

1. **Describe how the strength performance index for a solid cylindrical shaft is determined.**
2. **Describe the manner in which materials selection charts are employed in the materials selection process.**
3. **Briefly describe the steps that are used to ascertain whether or not a particular metal alloy is suitable for use in an automobile valve spring.**
4. **List and briefly explain six biocompatibility considerations relative to materials that are employed in artificial hip replacements.**
5. **Name the four components found in the artificial hip replacement, and, for each, list its specific material requirements.**
6. **(a) Name the three components of the thermal protection system for the Space Shuttle Orbiter. (b) Describe the composition, microstructure, and general properties of the ceramic tiles that are used on the Space Shuttle Orbiter.**
7. **Describe the components and their functions for an integrated circuit leadframe.**
8. **(a) Name and briefly describe the three processes that are carried out during integrated circuit packaging. (b) Note property requirements for each of these processes, and, in addition, cite at least two materials that are employed.**

20.1 Introduction

Virtually the entire book to this point has dealt with the properties of various materials, how the properties of a specific material are dependent on its structure, and, in many cases, how structure may be fashioned by the processing technique that is employed during production. Of late, there has been a trend to emphasize the element of *design* in engineering pedagogy. To a materials scientist or materials engineer, design can be taken in several contexts. First of all, it can mean designing new materials having unique property combinations. Alternatively, design can involve selecting a new material having a better combination of characteristics for a specific application; choice of material cannot be made without consideration of necessary manufacturing processes (e.g., forming, welding, etc.), which also rely on material properties. Or, finally, design might mean developing a process for producing a material having better properties.

One particularly effective technique for teaching design principles is the case study method. With this technique, the solutions to real-life engineering problems are carefully analyzed in detail so that the student may observe the procedures and rationale that are involved in the decision-making process. We have chosen to perform five case studies which draw upon principles that were introduced in previous chapters. These five studies involve materials that are used for the following: (1) a torsionally stressed cylindrical shaft; (2) an automobile valve spring; (3) the artificial total hip replacement; (4) the thermal protection system on the Space Shuttle Orbiter; and (5) integrated circuit packages.

MATERIALS SELECTION FOR A TORSIONALLY STRESSED CYLINDRICAL SHAFT

We begin by addressing the design process from the perspective of materials selection; that is, for some application, selecting a material having a desirable or optimum property or combination of properties. Elements of this materials selection process involve deciding on the constraints of the problem, and, from these, establishing criteria that can be used in materials selection to maximize performance.

The component or structural element we have chosen to discuss is a solid cylindrical shaft that is subjected to a torsional stress. Strength of the shaft will be considered in detail, and criteria will be developed for the maximization of strength with respect to both minimum material mass and minimum cost. Other parameters and properties that may be important in this selection process are also discussed briefly.

20.2 Strength

For this portion of the problem, we will establish a criterion for selection of light and strong materials for this shaft. It will be assumed that the twisting moment and length of the shaft are specified, whereas the radius (or cross-sectional area) may be varied. We develop an expression for the mass of material required in terms of twisting moment, shaft length, and density and strength of the material. Using this expression, it will be possible to evaluate the performance—that is, maximize the strength of this torsionally stressed shaft with respect to mass and, in addition, relative to material cost.

Consider the cylindrical shaft of length L and radius r, as shown in Figure 20.1. The application of twisting moment (or torque), M_t produces an angle of twist ϕ. Shear stress τ at radius r is defined by the equation

$$\tau = \frac{M_t r}{J} \tag{20.1}$$

Here, J is the polar moment of inertia, which for a solid cylinder is

$$J = \frac{\pi r^4}{2} \tag{20.2}$$

Thus,

$$\tau = \frac{2M_t}{\pi r^3} \tag{20.3}$$

A safe design calls for the shaft to be able to sustain some twisting moment without fracture. In order to establish a materials selection criterion for a light and strong material, we replace the shear stress in Equation 20.3 with the shear strength of the material τ_f divided by a factor of safety N, as

$$\frac{\tau_f}{N} = \frac{2M_t}{\pi r^3} \tag{20.4}$$

It is now necessary to take into consideration material mass. The mass m of any given quantity of material is just the product of its density (ρ) and volume. Since the volume of a cylinder is just $\pi r^2 L$, then

$$m = \pi r^2 L \rho \tag{20.5}$$

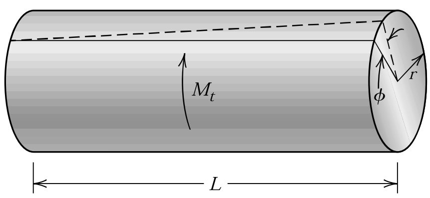

Figure 20.1 A solid cylindrical shaft that experiences an angle of twist ϕ in response to the application of a twisting moment M_t.

Or, the radius of the shaft in terms of its mass is just

$$r = \sqrt{\frac{m}{\pi L \rho}} \tag{20.6}$$

Substitution of this r expression into Equation 20.4 leads to

$$\frac{\tau_f}{N} = \frac{2M_t}{\pi\left(\sqrt{\frac{m}{\pi L \rho}}\right)^3}$$

$$= 2M_t\sqrt{\frac{\pi L^3 \rho^3}{m^3}} \tag{20.7}$$

Solving this expression for the mass m yields

$$m = (2NM_t)^{2/3}(\pi^{1/3}L)\left(\frac{\rho}{\tau_f^{2/3}}\right) \tag{20.8}$$

The parameters on the right-hand side of this equation are grouped into three sets of parentheses. Those contained within the first set (i.e., N and M_t) relate to the safe functioning of the shaft. Within the second parentheses is L, a geometric parameter. And, finally, the material properties of density and strength are contained within the last set.

The upshot of Equation 20.8 is that the best materials to be used for a light shaft which can safely sustain a specified twisting moment are those having low $\rho/\tau_f^{2/3}$ ratios. In terms of material suitability, it is sometimes preferable to work with what is termed a *performance index, P*, which is just the reciprocal of this ratio; that is

$$P = \frac{\tau_f^{2/3}}{\rho} \tag{20.9}$$

In this context we want to utilize a material having a large performance index.

At this point it becomes necessary to examine the performance indices of a variety of potential materials. This procedure is expedited by the utilization of what are termed *materials selection charts.*[1] These are plots of the values of one material property versus those of another property. Both axes are scaled logarithmically and usually span about five orders of magnitude, so as to include the properties of virtually all materials. For example, for our problem, the chart of interest is logarithm of strength versus logarithm of density, which is shown in Figure 20.2.[2] It may be noted on this plot that materials of a particular type (e.g., woods, engineering polymers, etc.) cluster together and are enclosed within an envelope delineated with a bold line. Subclasses within these clusters are enclosed using finer lines.

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[1] A comprehensive collection of these charts may be found in M. F. Ashby, *Materials Selection in Mechanical Design,* Pergamon Press, Oxford, 1992.

[2] Strength for metals and polymers is taken as yield strength, for ceramics and glasses, compressive strength, for elastomers, tear strength, and for composites, tensile failure strength.

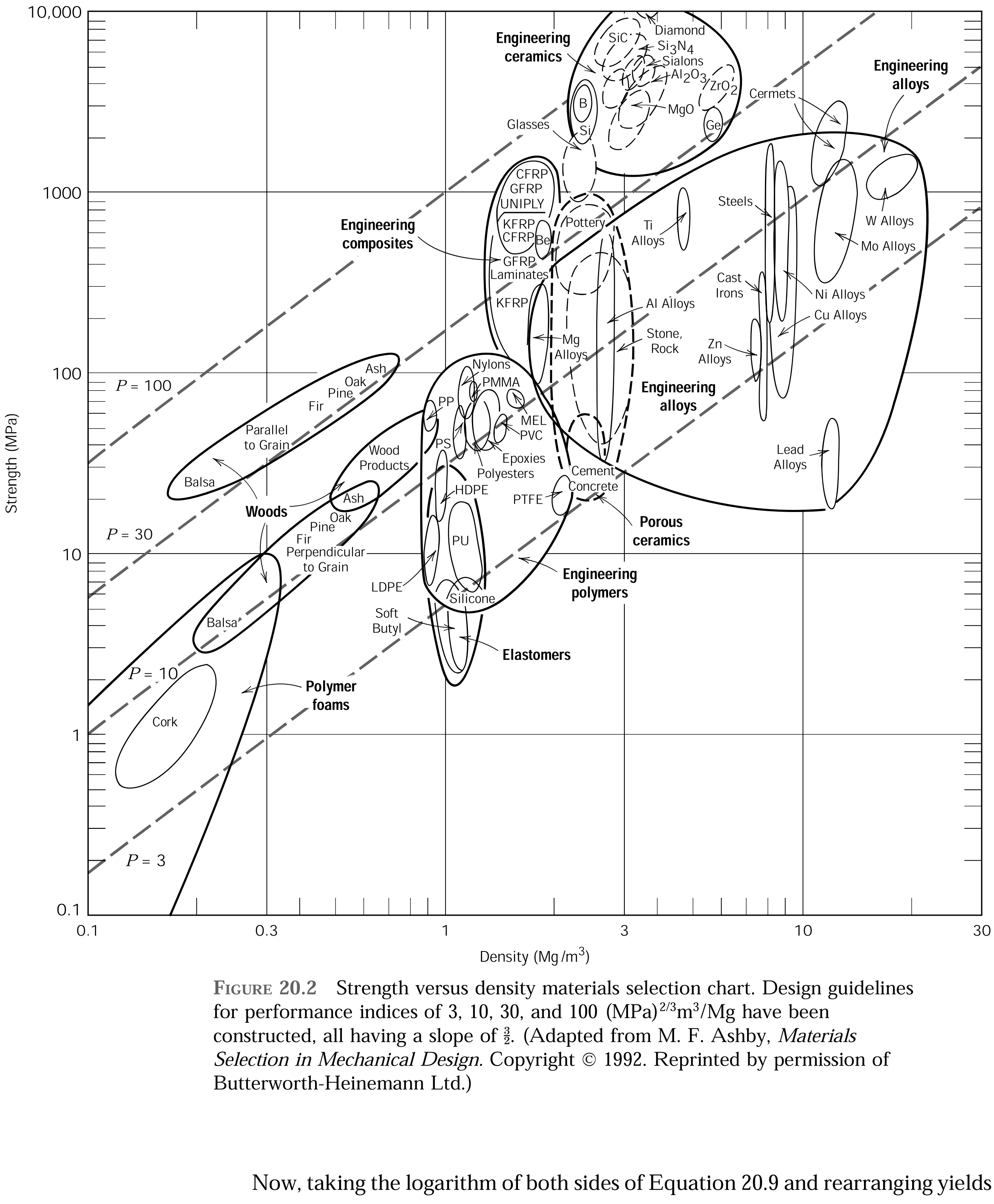

FIGURE 20.2 Strength versus density materials selection chart. Design guidelines for performance indices of 3, 10, 30, and 100 $(MPa)^{2/3}m^3/Mg$ have been constructed, all having a slope of $\frac{3}{2}$. (Adapted from M. F. Ashby, *Materials Selection in Mechanical Design.* Copyright © 1992. Reprinted by permission of Butterworth-Heinemann Ltd.)

Now, taking the logarithm of both sides of Equation 20.9 and rearranging yields

$$\log \tau_f = \frac{3}{2} \log \rho + \frac{3}{2} \log P \qquad (20.10)$$

This expression tells us that a plot of log τ_f versus log ρ will yield a family of straight and parallel lines all having a slope of $\frac{3}{2}$; each line in the family corresponds to a different performance index, P. These lines are termed *design guidelines,* and four have been included in Figure 20.2 for P values of 3, 10, 30, and 100 $(MPa)^{2/3}m^3$/Mg. All materials that lie on one of these lines will perform equally well in terms of strength-per-mass basis; materials whose positions lie above a particular line will have higher performance indices, while those lying below will exhibit poorer performances. For example, a material on the P = 30 line will yield the same strength with one-third the mass as another material that lies along the P = 10 line.

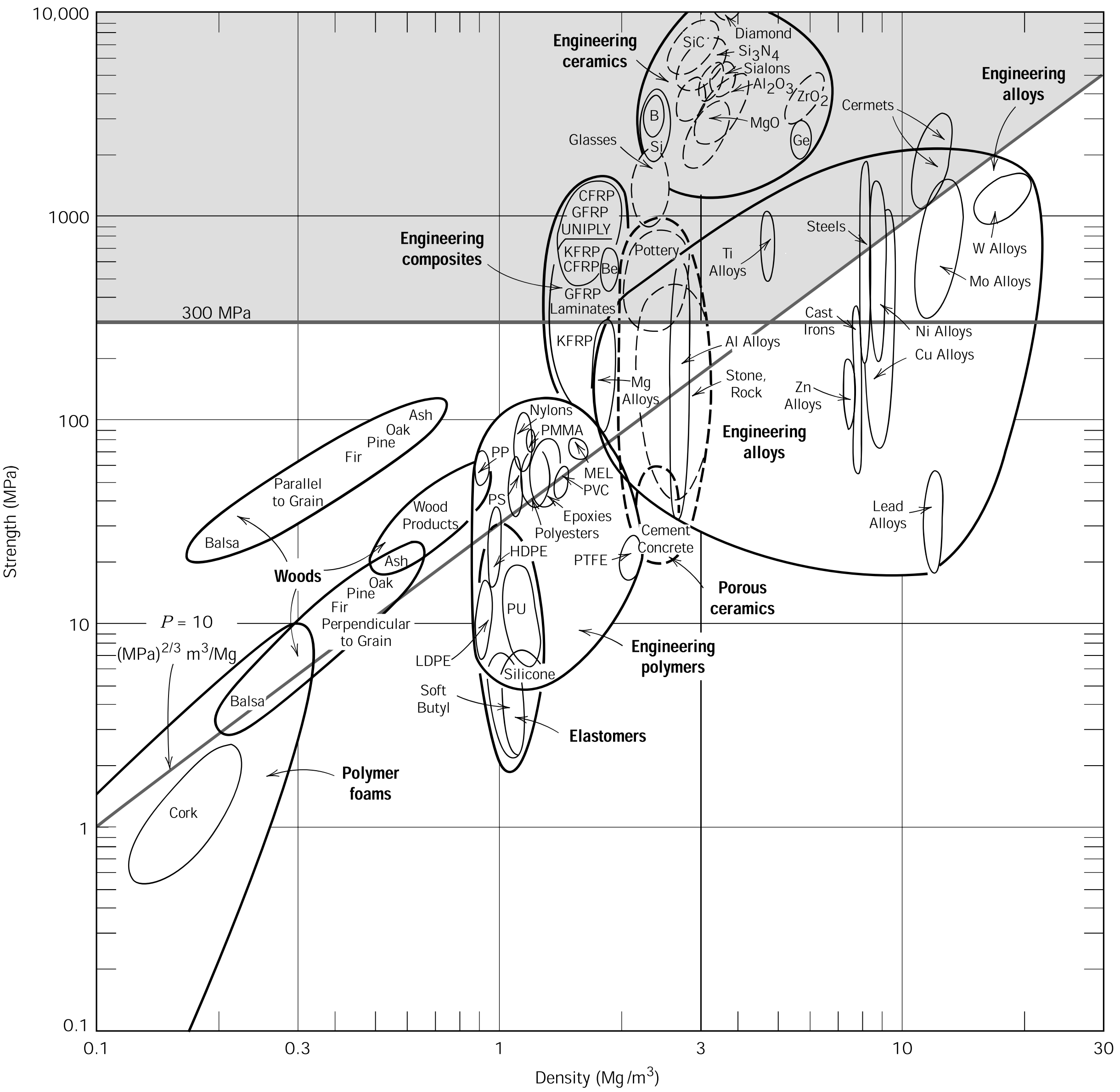

FIGURE 20.3 Strength versus density materials selection chart. Those materials lying within the shaded region are acceptable candidates for a solid cylindrical shaft which has a mass-strength performance index in excess of 10 $(MPa)^{2/3}m^3$/Mg, and a strength of at least 300 MPa (43,500 psi). (Adapted from M. F. Ashby, *Materials Selection in Mechanical Design.* Copyright © 1992. Reprinted by permission of Butterworth-Heinemann Ltd.)

The selection process now involves choosing one of these lines, a ''selection line'' that includes some subset of these materials; for the sake of argument let us pick $P = 10$ (MPa)$^{2/3}$m^3/Mg, which is represented in Figure 20.3. Materials lying along this line or above it are in the ''search region'' of the diagram and are possible candidates for this rotating shaft. These include wood products, some plastics, a number of engineering alloys, the engineering composites, and glasses and engineering ceramics. On the basis of fracture toughness considerations, the engineering ceramics and glasses are ruled out as possibilities.

Let us now impose a further constraint on the problem, namely that the strength of the shaft must equal or exceed 300 MPa (43,500 psi). This may be represented on the materials selection chart by a horizontal line constructed at 300 MPa, Figure 20.3. Now the search region is further restricted to that area above both of these lines. Thus, all wood products, all engineering polymers, other engineering alloys (viz. Mg and some Al alloys), as well as some engineering composites are eliminated as candidates; steels, titanium alloys, high-strength aluminum alloys, and the engineering composites remain as possibilities.

At this point we are in a position to evaluate and compare the strength performance behavior of specific materials. Table 20.1 presents the density, strength, and strength performance index for three engineering alloys and two engineering composites, which were deemed acceptable candidates from the analysis using the materials selection chart. In this table, strength was taken as 0.6 times the tensile yield strength (for the alloys) and 0.6 times the tensile strength (for the composites); these approximations were necessary since we are concerned with strength in torsion and torsional strengths are not readily available. Furthermore, for the two engineering composites, it is assumed that the continuous and aligned glass and carbon fibers are wound in a helical fashion (Figure 15.14), and at a 45° angle referenced to the shaft axis. The five materials in Table 20.1 are ranked according to strength performance index, from highest to lowest: carbon fiber-reinforced and glass fiber-reinforced composites, followed by aluminum, titanium, and 4340 steel alloys.

Material cost is another important consideration in the selection process. In real-life engineering situations, economics of the application often is the overriding issue and normally will dictate the material of choice. One way to determine materi-

Table 20.1 Density (ρ), Strength (τ_f), the Performance Index (P) for Five Engineering Materials

Material	ρ *(Mg/m³)*	τ_f *(MPa)*	$\tau_f^{2/3}/\rho = P$ [(MPa)$^{2/3}$m^3/Mg]
Carbon fiber-reinforced composite (0.65 fiber fraction) [a]	1.5	1140	72.8
Glass fiber-reinforced composite (0.65 fiber fraction) [a]	2.0	1060	52.0
Aluminum alloy (2024-T6)	2.8	300	16.0
Titanium alloy (Ti-6Al-4V)	4.4	525	14.8
4340 Steel (oil-quenched and tempered)	7.8	780	10.9

[a] The fibers in these composites are continuous, aligned, and wound in a helical fashion at a 45° angle relative to the shaft axis.

Table 20.2 Tabulation of the $\rho/\tau_f^{2/3}$ Ratio, Relative Cost ($\bar{c}$), and the Product of $\rho/\tau_f^{2/3}$ and $\bar{c}$ for Five Engineering Materials[a]

Material	$\rho/\tau_f^{2/3}$ [10^{-2} {$Mg/(MPa)^{2/3}m^3$}]	$\bar{c}$ (\$/\$)	$\bar{c}(\rho/\tau_f^{2/3})$ [10^{-2} (\$/\$){$Mg/(MPa)^{2/3}m^3$}]
4340 Steel (oil-quenched and tempered)	9.2	5	46
Glass fiber-reinforced composite (0.65 fiber fraction)[b]	1.9	40	76
Aluminum alloy (2024-T6)	6.2	15	93
Carbon fiber-reinforced composite (0.65 fiber fraction)[b]	1.4	80	112
Titanium alloy (Ti-6Al-4V)	6.8	110	748

[a] The relative cost is the ratio of the prices per unit mass of the material and low-carbon steel.

[b] The fibers in these composites are continuous, aligned, and wound in a helical fashion at a 45° angle relative to the shaft axis.

als cost is by taking the product of the price (on a per-unit mass basis) and the required mass of material.

Cost considerations for these five remaining candidate materials—steel, aluminum, and titanium alloys, and two engineering composites—are presented in Table 20.2. In the first column is tabulated $\rho/\tau_f^{2/3}$. The next column lists the approximate relative cost, denoted as $\bar{c}$; this parameter is simply the per-unit mass cost of material divided by the per-unit mass cost for low-carbon steel, one of the common engineering materials. The underlying rationale for using $\bar{c}$ is that while the price of a specific material will vary over time, the price ratio between that material and another will, most likely, change more slowly.

Finally, the right-hand column of Table 20.2 shows the product of $\rho/\tau_f^{2/3}$ and $\bar{c}$. This product provides a comparison of these several materials on the basis of the cost of materials for a cylindrical shaft that would not fracture in response to the twisting moment M_t. We use this product inasmuch as $\rho/\tau_f^{2/3}$ is proportional to the mass of material required (Equation 20.8) and $\bar{c}$ is the relative cost on a per-unit mass basis. Now the most economical is the 4340 steel, followed by the glass fiber-reinforced composite, 2024-T6 aluminum, the carbon fiber-reinforced composite, and the titanium alloy. Thus, when the issue of economics is considered, there is a significant alteration within the ranking scheme. For example, inasmuch as the carbon fiber-reinforced composite is relatively expensive, it is significantly less desirable; or, in other words, the higher cost of this material may not outweigh the enhanced strength it provides.

20.3 Other Property Considerations and the Final Decision

To this point in our materials selection process we have considered only the strength of materials. Other properties relative to the performance of the cylindrical shaft may be important—for example, stiffness, and, if the shaft rotates, fatigue behavior. Furthermore, fabrication costs should also be considered; in our analysis they have been neglected.

Relative to stiffness, a stiffness-to-mass performance analysis similar to that above could be conducted. For this case, the stiffness performance index P_s is

$$P_s = \frac{\sqrt{G}}{\rho} \tag{20.11}$$

where G is the shear modulus. The appropriate materials selection chart (log G versus log ρ) would be used in the preliminary selection process. Subsequently, performance index and per-unit-mass cost data would be collected on specific candidate materials; from these analyses the materials would be ranked on the basis of stiffness performance and cost.

In deciding on the best material, it may be worthwhile to make a table employing the results of the various criteria that were used. The tabulation would include, for all candidate materials, performance index, cost, etc. for each criterion, as well as comments relative to any other important considerations. This table puts in perspective the important issues and facilitates the final decision process.

AUTOMOBILE VALVE SPRING

20.4 INTRODUCTION

The basic function of a spring is to store mechanical energy as it is initially elastically deformed and then recoup this energy at a later time as the spring recoils. In this section helical springs that are used in mattresses and in retractable pens and as suspension springs in automobiles are discussed. A stress analysis will be conducted on this type of spring, and the results will then be applied to a valve spring that is utilized in automobile engines.

Consider the helical spring shown in Figure 20.4, which has been constructed of wire having a circular cross section of diameter d; the coil center-to-center diameter is denoted as D. The application of a compressive force F causes a twisting force, or moment, denoted T, as shown in the figure. A combination of shear stresses result, the sum of which, τ, is

$$\tau = \frac{8FD}{\pi d^3} K_w \tag{20.12}$$

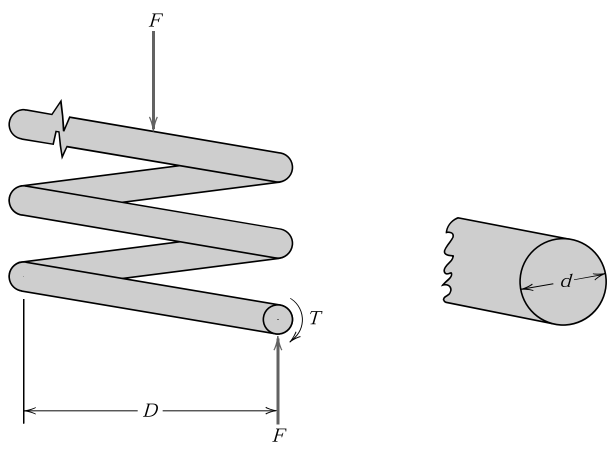

FIGURE 20.4 Schematic diagram of a helical spring showing the twisting moment T that results from the compressive force F. (Adapted from K. Edwards and P. McKee, *Fundamentals of Mechanical Component Design.* Copyright © 1991 by McGraw-Hill, Inc. Reproduced with permission of The McGraw-Hill Companies.)