Chapter 3

Physical Properties of Materials

QUALITATIVE PROBLEMS

3.13 What is the fundamental difference between mechanical properties of materials discussed in Chapter 2, and physical properties of materials, described in this chapter?

Mechanical properties are strength and elastic modulus; physical properties include density, magnetic properties, melting point and specific heat. A basic difference is that, given the chemistry of a material, the physical properties are essentially constant, while the mechanical properties can be changed due to the manufacturing strategy used.

3.14 Describe the significance of structures and machine components made of two materials with different coefficients of thermal expansion.

The structural fit of the machine components will depend on the thermal expansion coefficient. For instance, if two materials with different thermal expansion coefficients are assembled together by some means and then heated, the structure will develop internal stresses due to uneven expansion. If these stresses are high enough, the structure will warp, bend, or buckle in order to balance or relieve the stresses; it will possibly retain some internal (residual) stresses as well. If prevented from warping, the structure will develop high internal stresses which can lead to cracks. This is not always detrimental; shrink fits are designed recognizing that materials may have different coefficients of thermal expansion, and some machine elements such as thermocouples and temperature probes are based on a mismatch of thermal expansion coefficients.

3.15 Which of the properties described in this chapter are important for (a) pots and pans, (b) cookie sheets for baking, (c) rulers, (d) paper clips, (e) music wire, and (f) beverage cans? Explain your answers.

i. Pots and pans: These require a high melting point so that they don't change phase during use; they should be corrosion resistant, cleanable in water solutions, and have a high thermal conductivity. The requirements are similar to a cookie sheet described next.

ii. Cookie sheet: Requires corrosion resistance at high temperatures, the specific heat should allow for rapid heating of the sheet, and a high thermal conductivity should allow for even distribution of heat across the sheet. The melting temperature should be high enough that the sheet can safely withstand baking temperatures.
iii. Ruler: Should have low thermal expansion to maintain the measurements accurately and a low density to make it easy to carry.
iv. Paper clip: Should be corrosion resistant, with a stiffness that holds papers together without requiring excessive force.
v. Music wire: Music wire, as used for guitars, is preloaded to a very high tension in order to achieve desired resonance. As such, it should have a very high strength and the proper combination of stiffness and density to achieve the proper acoustics.
vi. Beverage can: Should have a high thermal conductivity, low density, and good corrosion resistance.

3.16 Note in Table 3.1 that the properties of the alloys of metals have a wide range compared with the properties of the pure metals. Explain why.

Alloying elements tend to disturb the crystal lattice of the base metal, and they do so by distorting the lattice by occupying lattice sites (substitutional atoms), spaces between lattice sites (interstitials), or forming a second phase (an intermetallic compound of the two elements). Lattice distortion will reduce properties that depend on a repeating lattice, such as thermal conductivity and melting points. Properties such as density and specific heat generally depend on the properties of the alloying elements, and range around the value for the alloy base metal. Also, 'alloys' is a generic term, and can include a very wide range of concentration and types of alloying element, whereas pure metals have, by definition, only one chemistry.

3.17 Rank the following in order of increasing thermal conductivity: aluminum, copper, silicon, titanium, ceramics, and plastics. Comment on how this ranking influences applications of these materials.

Thermal conductivity data is contained in Table 3.1 on p. 89. These materials, in order of increasing thermal conductivity, are ranked plastics (0.1-0.4 W/m K), ceramics (10-17), titanium (17), aluminum (222), copper (393). This ranking shows why materials such as aluminum and copper are used as heat sink materials, and why polymers are used as a insulator. Titanium and ceramic materials, having an intermediate value of thermal conductivity, are suitable for neither insulation or heat dissipation, and therefore do not have many thermal applications.

3.18 Does corrosion have any beneficial effects? Explain.

Corrosion is thought of mainly as a detrimental phenomenon. However, such manufacturing processes as chemical machining and chemical mechanical polishing rely on corrosion effects. Also, to some extent, cleaning of surfaces relies on corrosion.

3.19 Explain how thermal conductivity can play a role in the development of residual stresses in metals.

Thermal conductivity is one of the most important material properties affecting thermal stress (along with thermal expansion). In terms of residual stresses, it is much less important than the processing history. However, uneven cooling of castings (Part II) or welds (Part VI), for example, can cause warpage and residual stresses.

3.20 What material properties are desirable for heat shields such as those placed on the space shuttle?

Material properties required for heat shields are sufficient strength so that they do not fail upon takeoff, reentry, and landing; they must have a high melting point so that they do not change phase or degrade at the high temperatures developed during reentry, and they must be exceptionally high thermal insulators so that the shuttle cabin does not heat significantly during reentry.

3.21 List examples of products where materials that are transparent are desired. List applications for opaque materials.

This is an open-ended problem, and students should be encouraged to develop their own examples based on their insights and experiences. The following are examples of products where transparency is desired: windows and windshields, bottles, fluid containers (to allow direct observation of content volumes), wrapping and packaging, and glasses (eyewear). The following are examples of products where opacity is desired: windows in restrooms (if present), glass in light bulbs to produce a diffuse light, food packaging to protect the contents from light radiation and associated degradation, and product housings for aesthetic reasons.

3.22 Refer to Fig. 3.2 and explain why the trends seen are to be expected.

This is an open-ended problem and students should be encouraged to develop their own obstervations. The trends are not too surprising qualitatively, but the quantitative nature of the trends is at first very surprising. For example, it is not surprising that high-modulus graphite outperforms steel, as people are exposed to sporting equipment such as tennis racquets that are made of the former but never the latter. However, people don't expect graphite to be 14 times better than steel. Another surprise in the trends is the poor performance of glass fibers in an epoxy matrix. However, glass is pretty dense, so weight savings are not generally the reasons for using glass reinforcement.

3.23 Two physical properties that have a major influence on the cracking of workpieces, tools, or dies during thermal cycling are thermal conductivity and thermal expansion. Explain why.

Cracking results from thermal stresses that develop in the part during thermal cycling. Thermal stresses may be caused both by temperature gradients and by anisotropy of thermal expansion. High thermal conductivity allows the heat to be dissipated faster and more evenly throughout the part, thus reducing the temperature gradient. If the thermal expansion is low, the stresses will be lower for a given temperature gradient. When thermal stresses reach a certain level in the part, cracking will occur. If a material has higher ductility, it will be able to undergo more by plastic deformation before possible fracture, and the tendency for cracking will thus decrease.

3.24 Which of the materials described in this chapter has the highest (a) density, (b) electrical conductivity, (c) thermal conductivity, (d) specific heat, (e) melting point, and (f) cost.

As can be seen from Table 3.1 on p. 89, the highest density is for tungsten, and the highest electrical conductivity and thermal conductivity in silver. The highest specific heat is for Monel K-500 at 1050 MPa, and the highest cost (which varies from time to time) is usually is associated with superalloys.

3.25 Which properties described in this chapter can be affected by applying a coating?

A coating can affect the density if the coating is very large, it can affect the electrical, magnetic and optical properties as discussed in Section 3.7, and it can affect the thermal conductivity (Section 3.6) and, especially, corrosion resistance (Section 3.8).

QUANTITATIVE PROBLEMS

3.26 If we assume that all the work done in plastic deformation is converted into heat, the temperature rise in a workpiece is (1) directly proportional to the work done per unit volume and (2) inversely proportional to the product of the specific heat and the density of the workpiece. Using Fig. 2.5, and letting the areas under the curves be the unit work done, calculate the temperature rise for (a) 8650 steel, (b) 304 stainless steel, and (c) 1100-H14 aluminum.

We use the following information given in Chapters 2 and 3: The area under the true stress-true strain curve and the physical properties for each of the three metals. We then follow the procedure discussed on p. 62 and use Eq. (2.16) on p. 81. Thus, for (a) 8650 steel, the area under the curve in Fig. 2.5 on p. 62 is about $u = 72,000$ in-lb/in^3. Assume a density of $\rho = 0.3$ lb/in^3 and a specific heat $c = 0.12$ BTU/lb °F. Therefore,

$$\Delta T = \frac{72,000}{(0.3)(0.12)(778)(12)} = 214^\circ\text{F}$$

For (b) 304 stainless steel, we have $u = 175,000$, $\rho = 0.3$ and $c = 0.12$, hence $\Delta T = 520^\circ$F. For (c) 1100-H14 aluminum, we have $u = 25,000$ in.-lb/in^3, $\rho = 0.0975$ and $c = 0.215$; hence $\Delta T = 128^\circ$F.

3.27 The natural frequency, f, of a cantilever beam is given by

$$\boldsymbol{f = 0.56\sqrt{\frac{EIg}{wL^4}},}$$

where E is the modulus of elasticity, I is the moment of inertia, g is the gravitational constant, w is the weight of the beam per unit length, and L is the length of the beam. How does the natural frequency of the beam change, if at all, as its temperature is increased? Assume that the material is steel.

Let's assume that the beam has a square cross section with a side of length h. Note, however, that any cross section will result in the same trends, so students shouldn't be discouraged from considering, for example, circular cross sections. The moment of inertia for a square cross section is

$$I = \frac{h^4}{12}$$

The moment of inertia will increase as temperature increases, because the cross section will become larger due to thermal expansion. The weight per length, w, is given by

$$w = \frac{W}{L}$$

where W is the weight of the beam. Since L increases with increasing temperature, the weight per length will decrease with increasing temperature. Also note that the modulus of elasticity will decrease with increasing temperature (see Fig. 2.6 on p. 63). Consider the ratio of initial frequency (subscript 1) to frequency at elevated temperature (subscript 2):

$$\frac{f_1}{f_2} = \frac{0.56\sqrt{\dfrac{E_1 I_1 g}{w_1 L_1^4}}}{0.56\sqrt{\dfrac{E_2 I_2 g}{w_2 L_2^4}}} = \frac{\sqrt{\dfrac{E_1 I_1}{(W/L_1)L_1^4}}}{\sqrt{\dfrac{E_2 I_2}{(W/L_2)L_2^4}}} = \frac{\sqrt{\dfrac{E_1 I_1}{L_1^3}}}{\sqrt{\dfrac{E_2 I_2}{L_2^3}}}$$

Simplifying further,

$$\frac{f_1}{f_2} = \sqrt{\frac{E_1 I_1 L_2^3}{E_2 I_2 L_1^3}} = \sqrt{\frac{E_1 h_1^4 L_2^3}{E_2 h_2^4 L_a^3}}$$

Letting α be the coefficient of thermal expansion, we can write

$$h_2 = h_1 (1 + \alpha \Delta T)$$

$$L_2 = L_1 (1 + \alpha \Delta T)$$

Therefore, the frequency ratio is

$$\frac{f_1}{f_2} = \sqrt{\frac{E_1 h_1^4 L_2^3}{E_2 h_2^4 L_1^3}} = \sqrt{\frac{E_1 h_1^4 L_1^3 (1 + \alpha\Delta T)^3}{E_2 h_1^4 (1 + \alpha\Delta T)^4 L_1^3}} = \sqrt{\frac{E_1}{E_2 (1 + \alpha\Delta T)}}$$

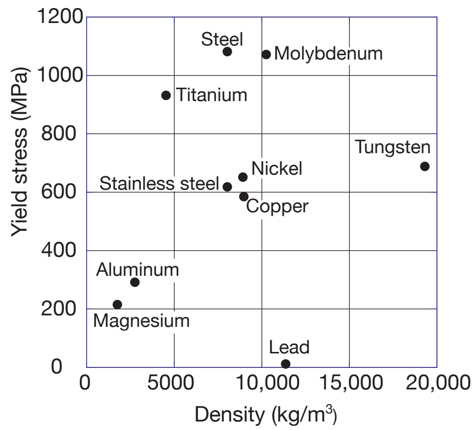
To compare these effects, consider the case of carbon steel. Figure 2.6 on p. 63 shows a drop in elastic modulus from 190 to 130 GPa over a temperature increase of 1000°C. From Table 3.1 on p. 89, the coefficient of thermal expansion for steel is 14.5 μm/m°C (average of the extreme values given in the table), so that the change in frequency is:

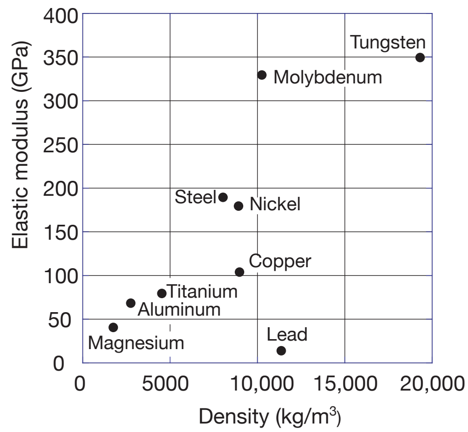
$$\frac{f_1}{f_2} = \sqrt{\frac{E_1}{E_2 (1 + \alpha\Delta T)}} = \sqrt{\frac{190}{130 \left[1 + (14.5 \times 10^{-6})(1000)\right]}} = 1.20$$

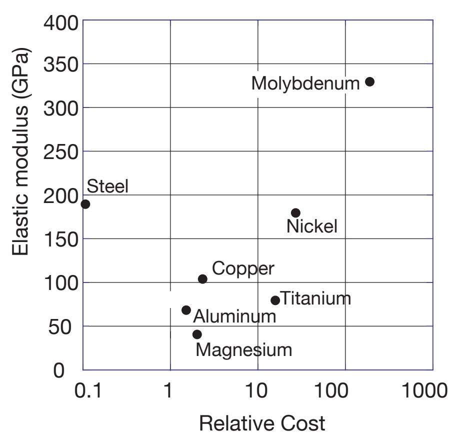
Thus, the natural frequency of the beam decreases when heated. This is a general trend (and not just for carbon steel), namely that the thermal changes in elastic modulus plays a larger role than the thermal expansion of the beam.

3.28 Plot the following for the materials described in this chapter: elastic modulus versus density, yield stress versus density, thermal conductivity versus density. Comment on the implications of these plots.

The plots are shown below, based on the data given in Tables 2.2 on p. 58, and 3.1 on p. 89. Average values have been used to obtain these plots.







3.29 It can be shown that thermal distortion in precision devices is low for high values of thermal conductivity divided by the thermal expansion coefficient. Rank the materials in Table 3.1 according to their ability to resist thermal distortion.

The calculations using the data in Table 3.1 on p. 89 are as follows. When a range of values is given for an alloy, the average value has been used. These materials have been ranked according to the ratio of thermal conductivity to thermal expansion coefficient.

Material	Thermal conductivity, k	Thermal expansion coefficient, α	k/α
Tungsten	166	4.5	36.9
Molybdenum alloys	142	5.1	27.8
Copper	393	16.5	23.8
Silver	429	19.3	22.2
Silicon	148	7.63	19.4
Beryllium	146	8.5	17.2
Gold	317	19.3	16.4
Copper alloys	234	18	13.0
Aluminum	222	23.6	9.41
Tantalum alloys	54	6.5	8.31
Aluminum alloys	180	23	7.72
Columbium (niobium)	52	7.1	7.32
Nickel	92	13.3	6.92
Iron	74	11.5	6.43
Magnesium	154	26	5.92
Magnesium alloys	106	26	4.10
Nickel alloys	37	15.5	2.42
Steels	33	14.5	2.28
Titanium	17	8.35	2.04
Lead alloys	35	29.1	1.20
Lead	35	29.4	1.19
Titanium alloys	10	8.8	1.14

3.30 Add a column to Table 3.1 that lists the volumetric heat capacity of the materials listed, expressed in units of J/cm^3-K. Compare the results to the value for liquid water (4.184 J/cm^3-K). Note that the volumetric heat capacity of a material is the product of its density and specific heat.

The additional column is calculated as follows. Note that one needs to be careful about keeping consistent units.

Material	Density (kg/m^3)	Specific heat (J/kg K)	Volumetric heat capacity (J/cm^3 K)	Relative volumetric heat capacity
Aluminum	2700	900	2.43	0.58
Aluminum alloys	2630-2820	880-920	2.31-2.59	0.55-0.62
Beryllium	1854	1884	3.49	0.83
Columbium (niobium)	8580	272	2.33	0.56
Copper	8970	385	3.45	0.82
Copper alloys	7470-8940	377-435	2.81-3.89	0.67-0.93
Gold	19,300	129	2.49	0.59
Iron	7860	460	3.61	0.86
Steels	6920-9130	448-502	3.10-4.58	0.74-1.09
Lead	11,350	130	1.47	0.35
Lead alloys	8850-11,350	126-188	1.12-2.13	0.27-0.51
Magnesium	1745	1025	1.79	0.43
Magnesium alloys	1770-1780	1046	1.85	0.44
Molybdenum alloys	10,210	276	2.83	0.68
Nickel	8910	440	3.92	0.94
Nickel alloys	7750-8850	381-544	2.95-4.81	0.70-1.15
Silicon	2330	712	1.66	0.40
Silver	10,500	235	2.47	0.59
Tantalum alloys	16,600	142	2.36	0.56
Titanium	4510	519	2.34	0.56
Titanium alloys	4430-4700	502-544	2.22-2.56	0.53-0.61
Tungsten	19,290	138	2.66	0.64
Zinc	7140	385	2.75	0.66
Zinc alloys	6640-7200	402	2.67-2.89	0.64-0.69
Ceramics	2300-5500	750-950	1.72-5.22	0.41-1.25
Glasses	2400-2700	500-850	1.2-2.3	0.29-0.55
Graphite	1900-2200	840	1.60-1.85	0.38-0.44
Plastics	900-2000	1000-2000	0.9-4.0	0.21-0.96
Wood	400-700	2400-2800	0.96-1.96	0.23-0.47

SYNTHESIS, DESIGN AND PROJECTS

3.31 Conduct a literature search and add the following materials to Table 3.1: cork, cement, ice, sugar, lithium, graphene, and chromium.

The additions are as below. Note that specific values may change depending on source cited.

i. Cork: density = 193 kg/m^3, melting point is unavailable (cork doesn't melt), specific heat = 2000 J/kg K, thermal conductivity = 0.05 W/m K, coefficient of thermal expansion = 30-50 μm/m °C, electrical resistivity up to 10^{10} Ω cm.

ii. Cement: density = 3120 kg/m^3, melting point is unavailable (cement doesn't melt), specific heat = 3300 J/kg K, thermal conductivity = 0.1 W/m K, coefficient of thermal expansion =7.4-13 μm/m °C.

iii. Ice: density = 920 kg/m^3, melting point is 0C, specific heat = 2100 J/kg K, thermal conductivity = 2 W/mK, coefficient of thermal expansion =50 μm/m °C, electrical resistivity = 182 kΩ-m.

iv. Sugar: density=1587 kg/m^3, melting point = 185°C, specific heat = 1250 J/kg K,

v. Lithium: density = 535 kg/m^3, melting point = 180°, specific heat = 3582 J/kg K, thermal conductivity = 84.8 W/m K, electrical resistivity = 92.8×10^{-9} Ω-m.

3.32 From your own experience, make a list of parts, components, or products that have corroded and have had to be replaced or discarded.

By the student. This is an open-ended problem that have many possible answers, and these will vary depending on the background of the student. There are many parts, usually associated with rusted steel, e.g., automobile frames and bodies, bolts, bicycle pedals, etc. Other parts that are commonly corroded include automotive battery cable terminals, marine parts of all kinds (especially if ocean going), nameplates on old machinery, etc. If one extends the discussion to corrosion-assisted failure, one can include just about all parts which fail by fatigue, including shafts, and airplane fuselages as shown below. This photograph is a dramatic example of corrosion-assisted fatigue of an aircraft fuselage that occurred mid-flight. (*Source:* From Hamrock, B.J., et al., *Fundamentals of Machine Elements*, 2nd ed., New York, McGraw-Hill, 2005, p. 265.).

3.33 List applications where the following properties would be desirable: (a) high density, (b) low density, (c) high melting point, (d) low melting point, (e) high thermal conductivity, and (f) low thermal conductivity.

By the student. This is an open-ended problem, and many possible answers exist. Some examples are:

i. High density: Adding weight to a part (like an anchor, bar bells or a boat), as an inertial element in a self-winding watch, and weights for vertically sliding windows. Also, projectiles such as bullets and shotgun particles are applications where high density is advantageous.

ii. Low density: Airplane components, aluminum tubing for tents, ladders, and high-speed machinery elements. Most sporting goods give better performance if density and hence weight is low, such as tennis rackets, skis, etc.

iii. High melting point: Creep-resistant materials such as for gas-turbine blades or oven insulation. Mold materials for die casting need to have high melting points, as do filaments for light bulbs.

iv. Low melting point: Soldering wire, fuse elements, wax for investment casting, and lubricants that depend on a phase change are examples of such applications.

v. High thermal conductivity: Rapid extraction of heat in radiators and heat exchangers, and cooling fins for electrical circuits and transformers. Cutting tools with high thermal conductivity can help keep temperatures low in machining. Dies in injection molding with high thermal conductivity can extract heat more quickly allowing higher production rates.

vi. Low thermal conductivity: Coffee cups, winter clothing, and oven insulation require low thermal conductivity. In addition, handles on cookware, lubricants for hot forging, and thermos materials (unless evacuated) need low thermal conductivities.

3.34 Describe several applications in which both specific strength and specific stiffness are important.

By the student. This problem is open-ended and the students should be encouraged to develop answers based on their experience and training. Two examples are: (a) Tent tubing: requires lightweight material for ease of carrying, while possessing sufficiently high strength and stiffness to support the weight of the tent tarp without excessive bending or bowing. (b) Racquetball or tennis racquet: requires lightweight material for control over the racquet's direction; also, high strength and stiffness are required to efficiently transfer the energy of the racquet to the ball.

3.35 Design several mechanisms or instruments based on utilizing the differences in thermal expansion of materials, such as bimetallic strips that develop a curvature when heated.

By the student. Instruments will have a common principle of measuring or regulating temperatures such as thermometers or butterfly valves which regulate fluid flow when temperatures vary.

3.36 For the materials listed in Table 3.1, determine the specific strength and specific stiffness. Describe your observations.

Selected results are as follows (the values which give highest possible quantities have been used, e.g., high stiffness and low density). Data is taken from Table 2.2 on p. 58.

Material	Y (MPa)	E (GPa)	Density (kg/m^3)	Spec. strength (m $\times 10^3$)	Spec. stiffness (m $\times 10^6$)
Aluminum	35	69	2700	1.3	2.6
Al alloys	550	79	2630	21.3	3.1
Copper	76	105	8970	0.86	1.2
Cu alloys	1100	150	7470	15.0	2.05
Iron	205	190	7860	2.66	2.5
Steels	1725	200	6920	25.4	2.9
Lead	14	14	11,350	0.13	0.126
Pb alloys	14	14	8850	0.161	0.16
Magnesium	130	41	1745	7.6	2.4
Mg alloys	305	45	1770	17.6	2.6
Mo alloys	2070	360	10,210	20.7	3.6
Nickel	105	180	8910	1.2	2.06
Ni alloys	1200	214	7750	15.8	2.8
Titanium	344	80	4510	7.8	1.8
Ti alloys	1380	130	4430	31.7	3.0
Tungsten	550	350	19,290	2.9	1.8

3.37 The maximum compressive force that a lightweight column can withstand before buckling depends on the ratio of the square root of the stiffness to the density for the material. For the materials listed in Table 2.2, determine (a) the ratio of tensile strength to density and (b) the ratio of elastic modulus to density. Comment on the suitability of each for being made into lightweight columns.

This problem uses the results from Problem 3.36. To make a lightweight column, one has to maximize the specific strength and the specific stiffness. Reviewing the values obtained, one can observe that: (a) Pure metals are not useful whereas alloys are much more preferable; (b) Titanium alloys have the highest specific strength (31,700 m); (c) Aluminum alloys have the highest specific stiffness (3.1); and (d) Among the lest desirable materials are lead and copper. Note that these results are consistent with the materials of choice for modern aircraft.

3.38 Describe possible applications and designs using alloys exhibiting the Invar effect of low thermal expansion.

By the student. If there is essentially no thermal expansion, the material is exceptional for situations where thermal fatigue is a consideration, or for precision instruments where no thermal expansion would be highly desirable. Examples of the former include furnace sensors and electrical components, and examples of the latter include micromanipulators and micro-electromechanical systems (MEMS); see Ch. 29.

3.39 Collect some pieces of different metallic and nonmetallic materials listed in Table 3.2. Using simple tests and/or instruments, determine the validity of the descending order of the physical properties shown in the table.

By the student. This is a good project for students, and some differences in the trends can be observed depending on the alloy, its source, and amount of cold work, heat treating or annealing it has undergone.

3.40 Design an actuator to turn on a switch when the temperature drops below a certain level. Use two materials with different coefficients of thermal expansion in your design.

This is an open-ended problem with a large number of acceptable answers. The thermal expansion effect can be used to deform a cantilever, for example, to actuate a switch. Alternatively, two materials that are long and thin can be welded at their ends. They can then be wrapped around a mandrel, so that after elastic recovery they take on the shape of a spiral. The angular displacement of the ends varies with temperature; a peg attached to one end while fixing the other will turn on a switch as soon as the peg translates to another peg in a retaining fixture. This principal was used to great success in carburators in automobiles before the 1980s in order to achieve proper air/fuel ratios as functions of temperature.

3.41 Conduct an Internet and technical literature review and write a one-page paper highlighting applications of piezoelectric materials.

By the student. Piezoelectric materials are widely used as actuators and resonators, especially at small scale, and for sensors such as pressure measuring sensors. Piezoelectric materials can be applied as coatings and in desired shapes for memos devices as well.

3.42 It has been widely reported that mechanical properties such as strength and ductility can be very different for micro-scale devices than are measured at normal length scales. Explain whether or not you would expect the physical properties described in this chapter to be scale dependent.

Since nanomaterials have fine structure, they have very high strength, hardness, and strength-to-weight ratios compared to traditional materials. However, physical properties are not as scale dependent. That is, a material's density is the same at large and small length scales. There is a limit to this, of course - a volume of ten atoms with one vacancy has a lower density than a large volume where the vacancies are not in general 10% of the volume. Students should be encouraged to obtain estimates of micro and nanoscale values and compare them to values such as in Table 3.1.

3.43 If you were given a metal (not an alloy) and asked to identify it, list (in order) the experiments or measurements you would perform. Explain what influence the shape of the metal would have on your prioritization.

By the student. This is an outstanding problem for a group assignment. Students should be encouraged to develop as many tests as possible. Some students will immediately turn to the most advanced methods possible - chromatography, for example. However, they should be encouraged to thin of simpler tests - measuring density, for example. Simple, inexpensive tests can be preferred over elaborate tests with expensive equipment. For example, a tension test can produce a lot of data that can be used to estimate a material class. Students should consider mechanical properties from Chapter 2 and physical properties from this chapter as characteristics that can differentiate materials.