# Chapter four
# Materials Science & Thermodynamics

Materials science is concerned with the interrelationship of the structure of a material and its processing to produce an observable property. For example, cast aluminum ingots out of the furnace have a crystalline structure that depends on how the metal was cooled; larger crystals form during slow cooling, smaller during fast cooling. These ingots can then be run through rollers to produce sheets of aluminum, bars, or even foil. Doing this actually changes the shape and number of the crystals, a process called cold-working, and that makes the metal stronger.

In telescope making we don't often have the luxury of specifying custom materials; instead, we choose from them based on availability and suitability for our purpose. This is done by choosing for the properties desired, including cost.

We characterize materials by many properties, such as density, which is the amount of mass in a unit volume, usually written as the Greek letter rho:

$$\rho = \frac{m}{v}$$

We know by experience some things about density; how the heft of a steel bar is heavier than an aluminum bar, or a wooden one of the same size. Density is useful to our design calculations because we can calculate a rough weight for a part without having it handy to weigh. Simply calculate the volume of the part, and then multiply by the density. Two warnings about this: first, be careful to make sure units are consistent; volume in cubic inches requires density in pounds per cubic inch; second, the result you get very strongly depends on how accurate your calculations – or measurements – are.

We refer to the stress on a body as the force per unit area, and denote it by the Greek letter sigma:

$$\sigma = \vec{F} / A$$

Stress has units of force over area, such as pounds per square inch or Newtons per square meter. The strain on the body is the change in length, denoted by epsilon:

$$\varepsilon = \frac{\Delta L}{L}$$

Strain has units of length over length, like inches per inch. This can be said to be a unitless number, since the units cancel out.

The ratio of stress (force/area) to strain (length change) is one of the most important characteristics of any material and is called Young's modulus or the modulus of elasticity. This is written:

$$E = \sigma / \varepsilon$$

and has the same units as stress does (force over area). We will use this property more than any other in our analyses.

When a stress is applied to a material as a pulling force (tension), it begins to lengthen, or experience strain. In most materials, there is a region where an amount of stress produces a linearly predictable strain; this is described by Young's modulus. The material is acting like a spring as described in Hooke's law. At some point, depending on the material, this relationship breaks down, and increasing the stress causes the material to start to deform permanently. This is called the yield strength of the material. If you continue to apply stress, ductile materials like metals will often start to “neck down”, getting smaller in diameter in one portion of the part, and then eventually break. Brittle materials like ceramics don't. Instead, they abruptly fail as the stress goes beyond the yield strength. A stress vs. strain curve for a ductile metal is shown in Figure 1.

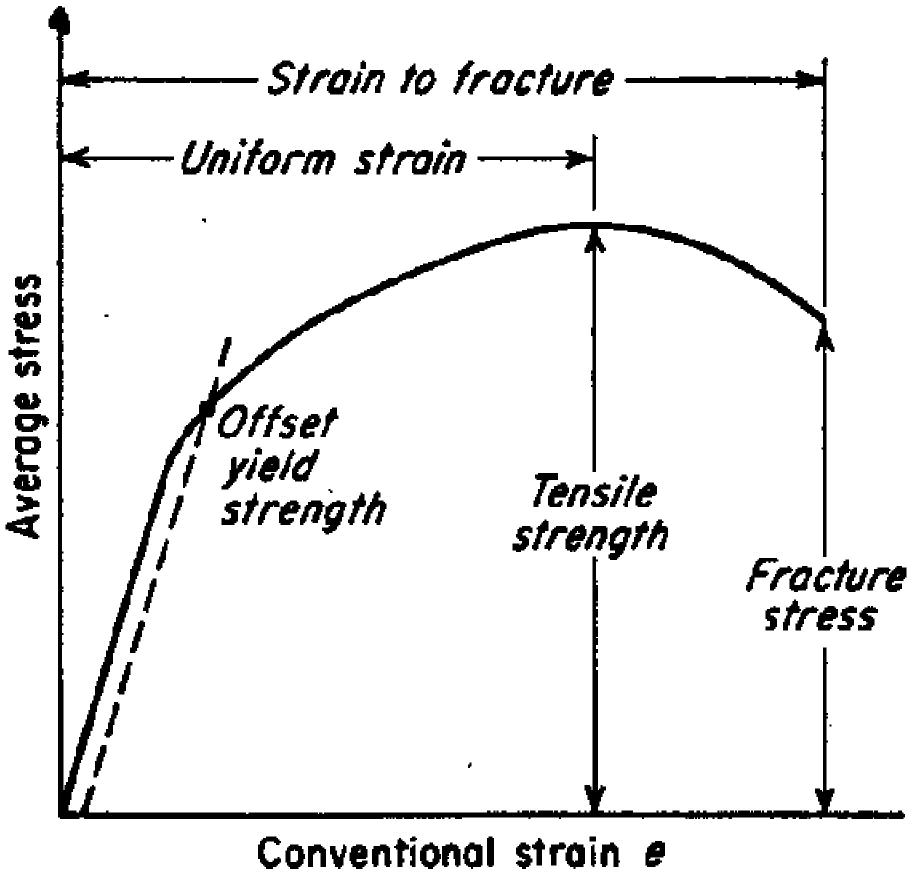

Figure 1 A stress vs. strain curve.

If you could monitor the stress during the pull test of a ductile metal, you would find that the force applied to produce elongation suddenly becomes more or less constant, and the metal continues to lengthen with no additional force applied. Sort of like a taffy pull, once you get it started it continues to stretch. Immediately before failure, you will notice the force applied going down as the material necks down and the area of the sample gets smaller. Eventually, the sample breaks at the material's fracture strength. We will always design to keep the stresses in our mounts low enough to ensure the material is always in the linear region. This is ordinarily not difficult to do.

One of the main reasons for looking into this subject is to cover composite materials. Composites are a combination of two or more materials. Straw has been used to reinforce mud bricks for centuries; in this century, we have used steel bars to reinforce concrete, glass fiber to reinforce plastics and many other combinations. Chances are the tires on your car use steel fibers to reinforce the rubber, which in turn is reinforced by the addition of carbon black particles.

All of those examples, except the last, use a flexible fiber embedded in a matrix. The composites can exhibit properties that the components don't. Fiberglass (more properly called fiberglass reinforced plastic, or FRP) is flexible glass cloth embedded in epoxy or other plastic. The glass fibers themselves can be easily separated and broken; the plastic is brittle and breaks fairly easily. The composite behaves quite differently from either the cloth fiber or the matrix.

The properties of a composite can be predicted by the Rule of Mixtures, which relates the volume fraction of the constituents in the mixture:

$$P_c = f_m\, p_m + f_f\, p_f$$

where m and f are the constituents, the matrix and the fiber.

This messy-looking expression says that the property of the composite is equal to the fraction of the matrix times the property of the matrix plus the fraction of the fiber times the property of the fiber. For example, let's say we want to calculate Young's modulus for a piece of FRP. We'll assume it is 75% by volume type E fiberglass, and 25% epoxy. Then:

$$E_c = f_f\, E_f + f_m\, E_m$$

$$E_c = 0.75 * (10.5x\, 10^6) + 0.25 * (500x\, 10^3)$$

$$E_c = 8x\, 10^6$$

Note that the units are unchanged by this simple ratio operation. They remain PSI, pounds per square inch.

The fraction of the resultant value delivered by the fiberglass is:

$$f = \frac{1}{1 + \frac{\sigma_m}{\sigma_f}} = 0.9545$$

so over 95% of the performance is delivered by the 75% of the volume taken up by glass fibers.

This calculation assumes perfect wetting of the glass fibers. When less than perfect wetting occurs, the material is weaker. Another factor is the length of the fibers; the longer the fibers, the stronger the composite is in their direction. The weave of the cloth is important; a weave with equal numbers of equally sized fibers set at right angles to each other will be equally strong in both directions. You will find fiberglass cloth with large bundles in one direction and smaller ones perpendicular to it. This weave is stronger in the direction of the bigger bundles. The weakest fiberglass, called matte, has short, chopped fibers in a random orientation. Because the fibers are discontinuous, it is held together with a minimal amount of epoxy or it would turn into a random pile of glass fibers. Avoid this stuff. It is useful only for the least critical applications.

You may be wondering about this sensitivity to direction and how it affects our parts. Many materials don't have the same properties in all directions (that is, they are anisotropic or not isotropic). Wood is a familiar example. This can be troublesome because the part is not the same strength in every direction and a load may come from an unexpected direction. Furthermore, when a real object is under stress, that stress is transformed into different directions in the material. It is best to stay with weaves that are as isotropic as you can get. In addition, a very strong fiberglass part may be crushed fairly easily by the pressure from a small screw. That merely means that we need to use a large surface area washer under any screws, or wider bands to fasten things.

Table 1 shows the mechanical parameters for several common materials:

| Material | E-Mod. of Elasticity | Density | Tensile Strength | Yield Strength |
|---|---|---|---|---|
| Units | $10^6$ PSI | lb.s/in$^3$ | $10^3$ PSI | $10^3$ PSI |
| E glass | 10.5 | 0.092 | 500 | |
| S glass | 12.6 | 0.090 | 650 | |
| Kevlar | 18.0 | 0.052 | 525 | |
| Graphite HS | 40.0 | 0.054 | 400 | |
| Graphite HM | 77.0 | 0.069 | 270 | |
| Epoxy (avg.) | 0.40 | 0.043 | 5 | 5 |
| Glass, soda-lime | 10 | 0.089 | | |
| Steel | 29 | 0.284 | 50 (min) | 35 |
| Aluminum #6061-T6 | 10 | 0.096 | 42 | 37 |
| Oak avg. | 1.8 | 0.023 | | 14.3 |
| Plywood (3-ply) | 1.4 | 0.026 | | 8 |
| Douglas Fir | | | | |
| with grain | 2.0 | 0.017 | 12.2 | 12.2 |
| across " | 0.19 | 0.017 | 12.2 | 12.2 |
| Pine (eastern) | 1.2 | 0.012 | 8.6 | 8.6 |
| Sonotube® | .18 | 0.065 | | |

Table 1 Mechanical properties of some ATM materials.

Soda lime glass has been included because hollow glass beads are often mixed with epoxy to form a mixture called “micro”. This is used as an improved glue in fabricating composite structures. For the glass bubbles (80% air, 20% glass):

$$E_c = f_g E_g + f_a E_a$$
$$E_c = 0.20x(10x\,10^6) + 0.80x(0)$$

or

$$E_c = 2x\,10^6$$

Then for a 50/50 mix by volume of epoxy and glass beads:

$$E_m = 0.5x(2x\,10^6) + 0.5x(0.40x\,10^6)$$
$$E_m = 1.20x\,10^6$$

This is lower than the fiberglass value we calculated earlier, but not by much. It will be lighter than the epoxy (40% of the mixture is air) and have three times the modulus of elasticity of the plain epoxy. This represents a phenomenon called dispersion strengthening; it is how carbon black reinforces the rubber in car tires.

Glass can be used to illustrate another important concept, that something can be strong in one manner, but not in another. Glass is very strong in compression. It is a pretty well known building material, although it is most often used in decorative applications. If you apply the same force in a manner that causes the glass to bend, though, it breaks relatively easily. This is reflected in a property called the shear modulus, which is lower in value than Young's modulus. This also demonstrates an important characteristic of a brittle material; the yield strength and the tensile strength are virtually the same, which is why there are no yield strength entries for the glasses (including the fiberglass fibers) in the above table.

The form given the material matters, too. “You can’t push on a rope” is an appropriate old saying. A wire will show the full strength of the metal it is made from under tension, but collapses under compression or side loads.

## Thermodynamics and Heat Transfer

Thermodynamics is a difficult subject, usually concerned with boilers and steam in pipes when it is presented to the engineering student. Arguably, it has little or nothing to do with telescope design. Heat transfer, a cousin subject, is worth knowing a few things about, and what I'll be going over here is largely from the chapter on the subject in most college physics books. This is how to analyze the hot air currents in your telescope, dew problems on your objective, and other things.

Let's start with something that has caused a lot of discussions; what color should your telescope be. Both black and white have been recommended by experts, including some big names. The crowd that argues for white says that it reflects the heat and doesn't get as hot. The black crowd says it radiates the heat away better. What both groups seem to miss is that the color as you see it, in the visible spectrum, really doesn't matter quite as much as the color in the infrared.

This problem, the cause of thermal air currents and dew formation, can be addressed by looking at heat transfer between the telescope and its surroundings. Heat transfer can only occur in three ways, although any given situation may involve all three. These are conduction, convection and radiation.

Conduction is generally the most effective way to get heat out of something, and works best when two thermal conductors are in very good contact. Convection occurs when a heated body heats the air in contact with it; when this happens, the heated air rises and is replaced by cooler air from the surroundings. This is the process that causes the air currents in your tube. As the air rises it creates air movement; on the large scale, this is a breeze like the sea breezes that keep tropical shores cool. The process can be aided by the wind or a fan and is then called forced convection. The last, and least efficient, process is radiation. In the temperature range we live, this occurs as infrared light.

Heat transfer, of course, always only occurs from hotter bodies to cooler ones. Given enough time, then, the temperatures reach some equilibrium and no further heat transfer takes place. Heat stored in the tube, mirror and other parts, radiates into the night sky or is carried away by the wind.

Radiation is a strong function of temperature, specifically the *absolute* temperature of the body. The absolute temperature scale begins at what is called absolute zero, the temperature at which all molecular motion (which is what heat really is) ceases. By definition, there are no negative temperatures. Absolute zero is around -460 $^{o}$F or -273 $^{o}$C. Although I don't think you'll ever need to solve this equation, it will help explain something important. The radiation from a perfect black body has been studied for quite some time and is described by:

$$H = Ae\sigma T^4 \tag{1}$$

where A is the radiating area, σ (sigma) is a physical constant called the Stefan-Boltzmann constant, and T is the absolute temperature in degrees Kelvin. This leaves e, the emissivity of the body. Emissivity is a measure of how well the object emits radiation; it is generally higher for rough dark surfaces and lower for smooth light surfaces.

At the moderate temperatures that we are concerned with, the radiation is primarily in the infrared, so the emissivity in the infrared (IR) is what determines the heat radiation. Simply put, it doesn't matter if the tube is black, or white, or pink as long as the finish has good emissivity in the IR. I was somewhat shocked when I first learned this, as I imagine you are. I think we all pretty well know that if you go outside on a hot summer's day in a black shirt, you'll be hotter than if you wore a lighter color, and we've seen this effect many different ways. Then I found that makers of aluminum heat sinks (parts used in the electronics industry to remove heat from electronic components) specify the same emissivity for any color of anodized aluminum. Later, I was told that any color of the paint we used on aluminum had the same emissivity.

At this point, you may ask, "if the thing is radiating heat, why doesn't it radiate all of its heat away and go to absolute zero?" It would do so if the environment were not radiating back on to it. At equilibrium, the rate of heat radiating away equals the rate of heat being absorbed. Another way to say this is that **any good heat emitter is a good heat absorber**; if it were a better emitter, it would eventually go to absolute zero. Likewise, if it were a better absorber, it would eventually get so hot that it would melt then vaporize. ***Anything that gets hot quickly cools off quickly.***

Getting back to our original question, what's the best color? The color in the visual spectrum doesn't matter. It probably matters more which type of finish you use: oil paint, latex paint, polyurethane, etc.. A matte finish will radiate heat better than a glossy one. It definitely matters more what material the tube is made of. ATM Robert Bunge of Laurel, Maryland, has run experiments with various finishes on wood, and the results are in Table 2. On the night this test was run there was a slight breeze, so cooling was by forced convection as well as by radiation. While there are small differences between the finishes, they are very similar. The brown wood stain (Minwax® Special Walnut) had the best results. It is interesting to note that on a breezeless night the temperature of the sample may go below the ambient air temperature.

Below the air temperature? As we said before, any object radiates to its environment and the environment is rarely the same temperature in all directions. In particular, a telescope, a car parked outside, or the roof of a house, all see the sky over part of the sphere they radiate into, and the sky looks very cold. The side of the object facing the clear night sky gets colder than the sides facing the ground or nearby objects. If there is no forced convection, no breeze to keep a supply of warm air moving over it, and little conduction of heat from the rest of the body, the object can go below the ambient air temperature. If the temperature falls below a certain critical value, dew forms on its surface.

This is how dew forms, so you've witnessed the phenomenon of something cooling below the air temperature all your life. Dew doesn't fall from the sky; it forms on a surface that is cooler than the *dew point* of the air. The dew point is expressed as a temperature and depends on the moisture content of the air; in a way, it is another measure of humidity. A related phenomenon is frost on the roof of a house when the air temperature is above freezing. It is commonly thought that the house is in a cold pocket where the local temperature is freezing or below, but that is not necessary. If the temperature is a couple of degrees above freezing, radiative cooling can take the roof below freezing. You will note that this happens most often to objects that are poor heat conductors; a good heat conductor carries heat from the sides facing the warmer surroundings to the side facing the cold sky so that it never gets colder than ambient. It also happens on the roof of a car; here the thin members attaching the roof to the body don't allow fast enough heat transfer to keep the roof and body at the same temperature.

| **Time** | **Air Temp** | **Brown Stain** | **All black** | **No Paint** |
|---|---|---|---|---|
| 0 | 45.0 | 71.2 | 71.2 | 71.2 |
| 5 | 44.8 | 62.4 | 62.4 | 64.0 |
| 10 | 44.5 | 54.7 | 55.0 | 55.9 |
| 15 | 44.2 | 50.2 | 50.9 | 51.4 |
| 20 | 44.1 | 47.3 | 48.0 | 48.4 |
| 25 | 44.0 | 45.7 | 46.7 | 46.8 |
| 30 | 43.9 | 44.8 | 45.7 | 46.0 |
| 35 | 43.8 | 44.4 | 44.9 | 45.5 |

Table 2 Change in temperature of wooden telescope tube with time. R. Bunge 1992

Dew on the optics of a telescope is more of a problem in designs that leave them exposed to the sky over a wide field of view. Schmidt-Cassegrains are notorious dew collectors, but Maksutovs, Wright-Newtonians, and refractors are all susceptible. A plain Newtonian in a solid tube is as close to dew-proof as a telescope gets because such a small amount of the area in front of the mirror is covered by cold sky. The secondary of a Newtonian will often get covered by dew long before the primary, thanks to its position being able to see more of the sky. An obvious way to control dew is to extend the tube beyond the front glass a few tube diameters. This is called a dew shield. There are more drastic solutions that use small heaters to keep the glass surfaces warm. Small heat ropes, available from some surplus dealers, or electrical resistors with values chosen especially to generate heat, are used here. The goal is to keep it warm enough to prevent dew, but not warm enough to cause air turbulence.

The dew shield protected SCT and the Newtonian will sometimes suffer from dew when the air is very humid (i.e., the dew point is close to the air temperature), and it is easy for the mirror's temperature to go below the dew point. Under such circumstances, a heater may be the only way to keep observing.

What about air currents? The most common trouble is that convection occurs along the tube walls and the resulting air turbulence degrades the seeing for the edge of the mirror where it is most sensitive. There are a few potential solutions for this: the first is to use a larger tube and keep the turbulent boundary layer away from the mirror. This has its limits; you wouldn't want to put a 10 inch mirror in a 20 inch tube. The second solution is brutally simple: cool the tube. Since the problem is caused by the tube not being in equilibrium with the air, cool the tube off either by setting it outside a half hour to an hour before observing, perhaps with a small fan moving air over it. There are places in the country where the temperature falls quickly all night and the scope will never cool off properly.

Other tricks may be necessary. In an environment with continually dropping temperatures, the better conductivity of a metal telescope tube may help get the heat out of the tube's parts more quickly. Getting the heat out of the mirror may well be the biggest problem.

The problem of getting heat out of the thermally non-conductive glass primary has gotten a lot of attention from the professional astronomy community. The honeycombed mirrors from the University of Arizona's Mirror Lab address this problem by reducing the thermal mass of the mirror and by getting a large surface area of glass in contact with the air. They are said to be excellent in this regard. The Hale telescope on Mount Palomar adopted this approach 50 years ago. The thin blanks produced by other glass suppliers are another alternative; by minimizing the thermal mass of the mirror, it can be cooled quicker. It has become common practice in commercial and amateur telescopes to build one or a few fans into the telescope to blow on the back of the mirror. Again, glass isn’t very thermally conductive and these fans need to run all night.

The third trick mentioned above is to blow a steady flow of air over the front of the mirror. This may sound heretical, but has worked successfully many times. In these cases, the turbulence is not along the tube walls, but in a boundary layer over the mirror. The fan blows this layer away. If a low velocity air flow, laminar and not turbulent, breaks up this boundary layer, seeing improves. Of course, if you put a very high speed fan and have more turbulence because of it, you’re trading one problem for another.

## Real World Caveats

In the course of the last several dozen pages we have looked at a lot of mechanical engineering, and it's pretty powerful stuff. Although not sufficient to make you a structural engineer, it is enough to help you understand the analysis and designs that follow.

At this point I need to re-emphasize that the mathematical models are simplifications of reality, and that real engineers incorporate a safety factor into their designs. As in the discussion above about buckling, they tend to design a structure to handle two or three times its expected load. I recommend a safety factor of two to four for telescope mounts: the margin should be adequate for protection from variations in material, processing, and the mis-calculated load.

It is sometimes helpful to build models or even a full-sized prototype of a design.

It is tricky to scale all aspects of a design, but a good challenge to the skilled worker. A full size prototype can be all you make if it exceeds the design expectations. Don't feel bad doing this, real companies do it all the time.

Finally, engineers often would have you believe that theirs is a totally scientific profession. Given a problem and set of requirements, the answers will always come out the same. This attitude belies the fact that there is a great deal of creativity in engineering; there is a lot of art in it. Colleges often have competitions where engineering students are given a problem to solve, say how to throw an egg some distance from the top of a tall building without damaging it, and sometimes they all are even given kits of the same parts to use. The results generally bear no resemblance to each other, even given the same problem to solve and the same kit of parts to solve it with. Don't be afraid to be creative!

# References and Further Reading

(In addition to the following, the interested reader can find many solved problems in the Schaum's Outline series of books from MacGraw-Hill. These are available in many public and college libraries, as well as larger bookstores and college bookstores.)

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