5 Material Selection Based on Performance

Material selection is a difficult task. Regardless of whether the material in question is wood, metal, stone, or plastic, selecting the proper material for a given application is a complex process. Before one even begins thinking about the materials, one must consider the requirements of the manufacturing processes involved, cost targets (and constraints), environmental concerns (in-use and post use), regulatory agency requirements, and often cultural and political considerations as well.

Then, as one begins to evaluate materials, one must consider chemical families, grades, versions, property data (and/or the lack thereof), testing and verification, agency approvals, sourcing and supply chain issues, and proper processing. Sadly, many engineers and designers short circuit the selection process by jumping immediately into property data, combing databases and material data sheets to find the highest value of one specific property in order to determine the best material for the application.

However, material selection is not about finding the "best" possible material for an application. Rather, it is about finding one or more suitable materials that—in combination with an effective design, proper processing, and eventual integration into a final system—result in a product that meets its intended use and satisfies (and hopefully delights) the needs of the end user. Far too often, in our quest to find the best material, we often forget that the real goal is to make the best possible product.

The ultimate goal of effective material selection is to optimize the performance of the product itself. While this may seem like a trivial statement, it is an important one.

5.1 What is Performance?

Performance is another one of those words that has a number of different meanings. In engineering, it is commonly used to describe the function of a system and how well it achieves its intended purpose.

When we talk about product performance, we are referring to an overall assessment of a product based on an evaluation of a number of measured parameters. For example, for an automobile we may measure acceleration, handling on the road, cornering, roominess of the interior, the sound levels

Thermoplastic Material Selection. http://dx.doi.org/10.1016/B978-0-323-31299-8.00005-2

while driving, and riding comfort. The performance criteria for a race car will be distinctly different than for a family sedan, or for a sports coupe. For sports equipment we may measure weight, stiffness, handling at high speed, vibration characteristics, the feel in our hands, as well as output at specific loading conditions (e.g., the launch angle and spin rate of a golf ball when struck by the clubhead of a driver at a specific head velocity). For a medical device we may measure the reliability and consistency of its operation under a wide variety of use scenarios, including mis-use (unintended or intentional).

One of the great challenges in design is in establishing the proper criteria for product performance. What parameters are going to be measured? What are the desired values for each parameter? How do each of these parameters contribute to the overall product performance?

Many companies have a formal process to develop these criteria. It usually begins with a list of product features based on marketing requirements, wish lists, desirables, and gotta-haves. It also often includes a list of *must not* requirements, such as the product must not cause injury when used in a certain way. Engineering requirements are then added to the list, addressing structure, durability, safety, etc. These typically also address the environmental conditions the product will be exposed to, and what the measured parameters must be under those conditions. Finally there are manufacturing requirements, including cost targets, and the desired levels of accuracy, precision, and overall quality.

As a result of this process, there will be a list of product specifications. This list should describe the criteria for product performance. Hopefully, every item on that list should clearly and specifically describe what is to be measured, how it is to be measured, and what the desired values are for that parameter. Done properly, a product that meets all of its specifications will have the desired product performance.

It is important to remember that performance is NOT an absolute measurement in and of itself. Rather it is a subjective evaluation based on a series of comparisons to an established benchmark. Benchmarks are an important tool, and not just in business analysis. Benchmarks help establish a set of expectations, a threshold for what is—and what is not—an acceptable performance level.

Several years ago, I needed to buy new tires for my car. I don't remember what car I was driving, but I was looking for a tire that would provide a nice ride and decent handling, and would also perform in all four seasons (since I live in southern California, "four seasons" may mean something different than in other parts of the world). Since I hate buying tires,

Figure 5.1 A set of new tires. ER_09/Shutterstock.com.

I wanted tires that would last, and while I wanted them to be reasonably priced, I was willing to pay a small premium for longer wearing tires.

I did a little research, and settled on a performance category titled, *Grand Touring All Season*. I started comparing brands and models, and read numerous reviews. The funny thing was, all of the reviews I read compared the performance of the tire under review to a tire made by Michelin, the MXV4. *The blah–blah tire offers a quieter ride than the MVX4, but it doesn't last as long*. *The yadda–yadda tire offers better handling than the MVX4, but does not perform as well in the rain*. At a certain point, I remember asking myself, "Why don't I just buy the MXV4 tires?" I realized the Michelin MVV4 was the benchmark for this category of tires. I bought a set the next day (Figure 5.1).

5.2 Predicting Performance

Predicting the overall performance of a new product is a challenging task. An analogy can be made from the world of sports. Every sport involves its own unique set of skills. In most sports there are coaches and trainers, whose jobs consist of developing and honing the skills of an athlete in order to achieve optimum performance. These coaches and trainers often rely on scouts and talent agents, whose job it is to find new athletes with promising athletic ability.

There are countless ways to evaluate specific aspects of athletic ability: strength, agility, hand–eye coordination, how high one can jump, how fast one can run, etc. Yet, at the end of the day, after all of the measurements are in, there is always a debate—which athlete will be the best performer?

The same can be said for product performance. Even with the best list of specifications, and the use of benchmarks, there are times when the product itself is less than the sum total of its parts. Why is this? I think there are several reasons. First and foremost, there is the issue of correlation.

5.2.1 Correlation

There are times when the correlation between a specific parameter and the product performance is clear. For instance, in an automobile of a specific size and weight, the more horsepower the engine has, the faster the car can accelerate, and the higher its top end speed (Figure 5.2).

There are other times when the correlation is not easy to determine. As an example, how does the relative stiffness of the membrane used to support the key pad on a laptop computer affect the overall product performance?

Furthermore, the issue of correlation extends not just to the parameter being measured, but to the properties of the materials that are used in the system. If we look at the intake manifold on the engine of a car, and instead of making it out of aluminum (perhaps using a die casting process)

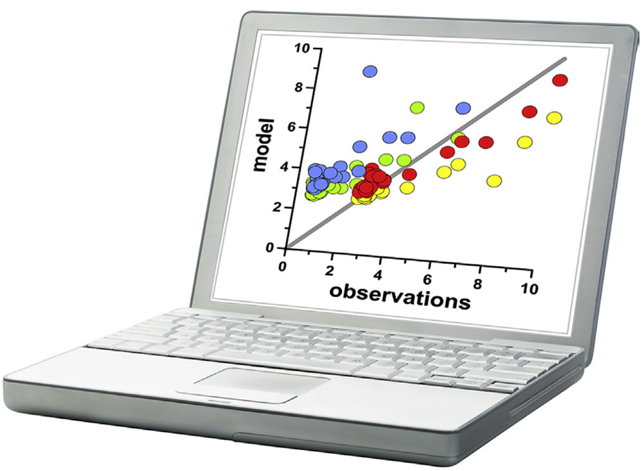

Figure 5.2 A correlation model. marekuliasz/Shutterstock.com.

we make it out of glass-reinforced nylon (using an injection molding process), will the engine have more horsepower? What other effects might this have on the engine? And on the overall performance of the car? Often these correlations are hard to determine. Also, changing one parameter may have unintended consequences in other areas of performance. For example, how would an engine with more horsepower affect the overall handling of the car?

5.2.2 Wrong Criteria

There are also times when we are simply measuring the wrong parameters. Going back to our sports example, let us look at the world of professional baseball. For decades, coaches and scouts and general managers relied on a traditional set of parameters to evaluate players. In the early 2000 season, the Oakland Athletics began to use a new method of evaluation, based on a completely different set of parameters. As described in Michael Lewis' book *Moneyball* [1] (later made into a movie), the use of these new parameters changed the sport.

Business managers and scouts in other sports have since adopted similar ideas, and are looking at and evaluating all kinds of performance data in all kinds of ways. We need to do the same kinds of things in the world of material selection. We need to make sure we are evaluating the right parameters, and we need to understand how those parameters correlate to actual product performance.

5.2.3 Disruptive Innovation

As much as we may enjoy working on new things, for most of us, our day-to-day job usually involves working on things that we are familiar with. In the engineering world, we may sometimes get involved in refining an established methodology, or in implementing a new and improved version of something, or in exploring a new technology. In most of these situations, there are examples of products in the real world that we can use to compare and contrast, either as benchmarks, or as a stretch goal of something to improve upon.

On rare occasions, we may be offered an opportunity to work on something completely new, perhaps even a product or technology that can change the world. These opportunities don't happen all that often, but when they do, they present a unique set of challenges. One of those challenges is in correlating material properties, evaluation parameters, and the performance of the new product—when nothing like it has ever been made before.

In other words, *how do you predict performance when there is no existing benchmark?* While I don't claim to have an answer to this question, you have to admit, it is a nice problem to have.

5.3 How Material Selection Affects Performance

As difficult as it is to correlate the effect of a specific parameter on overall product performance, it is even harder to determine the effects of a specific material that is used on a particular component in that product. Even if the evaluation criteria are perfect, the behavior of the materials used are sometimes so complex that it is impossible to determine which material property is making the difference. In most cases, it is not one specific property that makes the difference, but a combination of properties.

In the 1980s, there was a major effort among the major resin suppliers to seek out new applications by replacing parts and systems that had been traditionally made out of metal with parts and systems that were injection molded from engineering plastics (acetal, nylon, polycarbonate, polyester, etc.). These applications were in a wide range of industries, including automobiles, industrial equipment, household appliances, and office furniture [2].

One of the targeted applications in the office furniture industry was the classic five-legged chair base. Up until then, chair bases had been made out of pieces of tubular steel that were welded together, or out of a single large piece of die cast aluminum (or even zinc). In either case, there was not only the cost of the raw material, but the cost of fabrication, plus the cost of deburring and cleaning, followed by the cost of painting or plating or whatever secondary finish was required. Would it not be better to make a five-legged chair base out of an engineering plastic in a single part with a molded-in finish (Figure 5.3)?

DuPont did some investigation and was convinced that this could be done. In order to convince the experts in the office furniture industry, they went and had a mold made, and then fabricated parts in their own test lab using a very large injection molding machine. The initial prototypes were molded using a glass-reinforced polyester. This material was selected because it had exceptionally high tensile strength, as well as high stiffness. The resulting parts were stiff and strong, and met the basic performance requirements.

After some further evaluation, there was some doubt as to whether glass-reinforced polyester was the optimum material. So, as an exploration, DuPont molded some additional prototypes using a glass-reinforced

Figure 5.3 A traditional chair base made of metal. chaoss/Shutterstock.com.

nylon. These parts were molded in the exact same mold, with no design changes. However, these parts were distinctly different. They looked different, they felt different, they even sounded different. And they had different performance characteristics—almost all of which were better.

One of the interesting things was that when the parts were tested, a chair base molded in glass-reinforced nylon could actually withstand a higher ultimate load than a chair base molded in glass-reinforced polyester. How could this be? The stiffness and strength of glass-reinforced polyester is significantly higher. Processing was not an issue, as the parts were molded in a test lab under carefully controlled conditions. One of the theories postulated was that during loading, something was occurring on a localized level, where the stiffening ribs joined the main structural wall in each leg. At these junctures, there was a higher level of stress. In the glass-reinforced polyester, the local strain exceeded the maximum allowable strain, and a crack was initiated, which then propagated through the part, leading to structural failure. In the parts molded of glass-reinforced nylon, the material was able to yield, and the localized stresses were redistributed, allowing for a higher ultimate load. Another theory was that glass-reinforced nylon had better toughness than glass-reinforced polyester. (We will discuss the concept of material toughness in greater detail later in this chapter.)

Regardless of the exact technical phenomena, the bottom line was that a chair base molded from glass-reinforced nylon had better structural performance than a chair base molded from glass-reinforced polyester. Over time, and after extensive testing, it became obvious that chair bases molded from glass-reinforced nylon outperformed chair bases molded from glass-reinforced polyester (or any other thermoplastic material). Not only were they stronger, they could withstand impact better, they had a better surface finish, and they even sounded better when the chair was rolled across the floor. Today, some 30 years later, there are hundreds of thousands of chair bases made every year, and most of them are molded out of glass-reinforced nylon.

5.3.1 Evaluating Property Data

As challenging as it is to determine what specific material properties affect product performance, it can be even more challenging to quantify the effects of a change in the values of one or more properties. In other words, if you are evaluating material A and material B, and they have slightly different properties, what is the effect on performance by changing from material A to material B? This is an important question, but it can be arduous to evaluate.

In the initial phase of material selection, instead of focusing on the required value of a specific property, it is often easier to evaluate the types of material properties that are important. In other words, looking at mechanical properties (if there are structural requirements), or thermal properties (if there are temperature requirements), or properties related to toughness (if there are impact requirements). In this early phase, the evaluation is general and qualitative.

This initial phase may also involve a de-selection process. Quite often, there are some performance requirements that simply cannot be met by a large number of materials. Perhaps there is a structural requirement at high temperature, or an impact requirement at low temperature, or a requirement for long-term stability when exposed to a specific chemical (we will discuss some of these situations later in this chapter). These kinds of requirements can often be used to make a quick first cut to eliminate a number of material candidates. It is kind of like making the first cut when you are trying out for the varsity team, or auditioning for a role in a play. Many times this de-selection process is overlooked, but acknowledging it (and documenting it) can be an important tool later in the process, or in subsequent projects.

5.3.2 The Importance of Design

It is important to remember that material selection and design are interrelated. When you evaluate the performance of the end product, which is worse: a good design with the wrong material or a bad design with the right material? Neither is optimal. Furthermore, many design decisions one must make can affect the requirements of the material, and many material properties will affect your design decisions.

As an example, there are many times where the stiffness of a given part is an important criteria in the overall product performance. Often, those tasked with material selection will try to find the stiffest possible material. In the process, they may overlook the importance of other material properties, or the importance of good design.

The stiffness of a given design is easy to calculate—provided you have the basic dimensions in place (length, width, thickness, etc.), and you have an idea of the material you would like to use. There are a number of standard engineering equations one can use, based on classic beam and/or plate theory. As long as you understand the constraints, you can easily solve for any number of desired variables (deflection, stress, strain, etc.), simply by inputting some basic data.

In almost all of these equations, there are two important input variables. One of these is the elastic modulus of the material, E, as described in Chapter 3. This is then combined with the stiffness of the structure, which is determined by its moment of inertia, or I.·E and I can be measured (or calculated) in any given direction, or in any mode of motion. In bending applications, the applicable modulus of elasticity is the flexural modulus, and the moment of inertia will depend on the shape of the structure. While the equations to determine it can be complex, I is almost always based on the cube of the thickness (Figure 5.4).

As an example, let us look at a cantilevered beam. It is one of the simplest structures. If we assume the beam has a load at the free end, the deflection at the tip is determined by the following equation:

$$y = \frac{PL^3}{3*E*I}$$

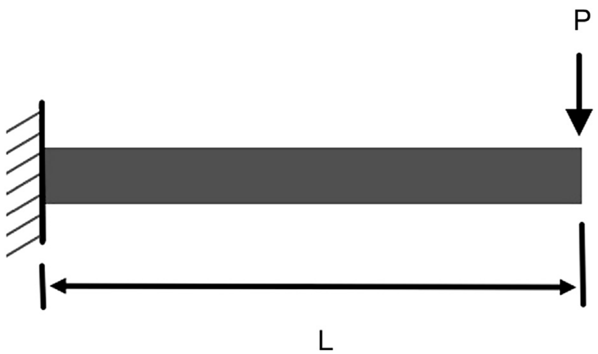

Figure 5.4 Cantilevered beam with end load.

where y is the deflection, L is the length, of the beam, and P is the force applied at the tip. For a beam with rectangular cross section, the cross sectional moment of inertia I is calculated as follows:

$$I = \frac{b*h^3}{12}$$

where b is the width and h is the height (or the thickness). From the deflection equation, the deflection is inversely proportional to the product of E times I. Both E and I are input variables and are a result of the stiffness of the material times the stiffness of the structure. In essence, this EI product is a design variable. Some refer to this variable as "the stiffness factor," but I like to call it the Old McDonald factor (from the children's song *Old McDonald had a farm, E, I, E, I, O!*).

What is interesting to note is that if you double the value of E—that is, if you select a material that is twice as stiff—you will cut the deflection in half. However, if you used the same value of E, and instead increased the thickness by 25%, the value of I would almost double, which would also cut the deflection in half (actually it would reduce it by 48.8%, since 1.25 cubed = 1.953, and 1/1.953 = 0.512).

Selecting materials for stiffness—based solely on the published value of their flexural modulus—is often counterproductive. It overlooks the stiffness contribution of the structure itself and neglects to account for minor changes in the design—many of which can have major effects on the overall structure.

While the relationship between stiffness and thickness is straightforward, there are many other design–material relationships, some of which are quite complicated. These relationships need to be addressed during the material selection process. (We will explore some of these relationships in greater detail later in this book.)

5.3.3 The Importance of Processing

Just as material selection and design are interrelated, the processing of thermoplastic materials also affects product performance. One of the primary reasons is that processing affects the properties of the material.

First and foremost, you need to remember that published material property data are generated from test samples. These samples were made from prime, 100% virgin resin, and were carefully prepared under controlled conditions, and then tested under controlled conditions. They were not molded by a production molder who was trying to optimize the molding process for maximum cycle time efficiency and lowest production cost. Furthermore, the test lab was not tasked with minimizing warpage or maintaining specific tolerances or achieving a high gloss Class A surface with no visible cosmetic defects. And the test lab was probably not all that concerned about the size and location of the gate, or of the ejector pins, or the amount of visible flash at the parting line.

In a production environment, most plastic processors are tasked with delivering plastic parts or subassemblies which contain plastic parts. They usually have very specific requirements that they are responsible for (usually dimensional requirements, but also on occasion other performance criteria). However, very rarely are they held directly responsible for the material properties of the material itself in the final molded parts. It is often impossible to measure those properties, to say nothing of correlating the actual in-use material properties in the molded part to the part performance (just as it is in the design phase).

One of the main reasons that material properties are affected is due to changes in the molecular weight distribution of the polymer chains in the molded resin. This is especially true in processes like extrusion and injection molding where the resin is taken to a molten state by the application of shear and high pressure. Even with processing methods where the material does not undergo high rates of shear—(such as thermoforming, rotational molding, pressure molding, or ultrasonic welding)—the properties of the material can be affected. What properties are affected, and how they are affected, will depend on the materials involved, and what production processes are involved. The important thing to remember:

> Every plastic manufacturing process can have an effect on material properties.

We will explore how to account for this phenomenon in the material selection process in a later section.

5.3.4 Property Data—A Final Caveat

Time and time again I encounter someone who asks me a variation of the following:

> I am looking for a material where property ABC has a minimum value of 123 units. What material do you recommend?

As a general rule, I try not to get involved in these kinds of questions. It is a sign that the questioner is not experienced with plastic material selection. As a consultant, and someone engaged in new business development, you might ask, *How could you pass up a new client opportunity?* The truth of the matter is, working with clients like this is often more of a bother than it is worth. And sometimes the questions they ask make you shake your head.

The fact of the matter is, you cannot select a material—any material—based solely on the measured value of one single material property. You have to evaluate a number of properties, and correlate them to the desired performance of the end product.

Recently, I came across a post in an online forum where someone was looking for an injection molding resin with a heat deflection temperature (HDT) of 450 °F or higher. At first glance, one might think this is a challenging question being posed by a very sophisticated user of materials. However, it is really nothing more than a variation of the ABC-123 question.

However, one of the things I have learned in my career as a consultant is that there is a distinct difference between saying, "That's a stupid idea" and asking the question, "Can you tell me a little bit more about the decision process you used when you selected this particular material?" In this case, I did not have the opportunity to ask that question, but in looking behind his focus on HDT, it was obvious that they were looking for a specialty material, one that had exceptional performance at some very high temperatures (most likely excellent strength, stiffness, etc.). However, he made no mention of any other performance requirements (chemical, environmental, etc.), nor did he describe the application in any detail. So how could anyone possibly recommend the absolute best material?

But rather than lecture him on that, I simply advised him to not focus on HDT, and suggested he carefully evaluate other performance requirements. I encouraged him to look at LCP, polyimides (PI, PEI, PAI), polysulfones, the ketone family (PEK, PEEK, PEKK, etc.), PPS, and perhaps even high-temperature nylons (HTN, PPA, etc.).

Ironically, many of these specialty materials are used in the aerospace industry. However, while evaluating their suitability for a given application may take a little bit of effort, it is not exactly rocket science [3].

5.4 Environmental Effects

In any material selection process, one must consider how the environment that a product is used in will affect its performance. One aspect of this is in the measurement of specific performance criteria, such as the road handling of a car using a specific tire on a wet road. On a material selection level, we are not only concerned with how the specific tire performs, but also with how the environment affects the material used in the tire. There are a number of environmental phenomena that can affect materials. These effects can be loosely grouped into two main categories: those that are reversible and those that are not.

Reversible changes in materials happen all the time, in all types of materials. As an example, almost all materials expand with the application of heat and contract when they are exposed to cold. Also, most materials become more flexible at high temperature and get stiffer when they are cold. Some materials may soften when they get wet, but will return to their original hardness when they dry out. These types of changes are common, and under most situations they are fully reversible as long as the material has not gone through a permanent phase change (such as cement turning into concrete). While these kinds of reversible changes need to be accounted for in the selection of the material (and in the design), they are normally not a big deal.

What is a big deal is when exposure to the environment causes irreversible changes in the material itself. These changes include chemical reactions, structural changes in the polymer matrix, degradation of the polymer, and sometimes even a complete depolymerization of the polymer molecules (a breakdown of the polymer chain into its base monomers).

The environmental factors which cause these changes can be grouped into four main areas: temperature, chemicals, radiation, and time. Exposure to any of them—and all of them—can wreak havoc on the material properties of thermoplastics. I like to call them *The Four Horsemen of the Plastic Apocalypse* (Figure 5.5).

Figure 5.5 The four horsemen of the plastic apocalypse.

5.4.1 Temperature

As described in an earlier chapter, all thermoplastics soften (and/or melt) at high temperature. However, even at temperatures much lower than T_g or T_m, long-term exposure to heat will have a detrimental effect on a thermoplastic material. The primary reason is that this exposure to heat causes a breakdown of the polymer chains, resulting in a lower molecular weight distribution and a loss of properties. The most common losses are in elasticity and toughness, but other properties are affected as well. The temperature at which this degradation begins to occur will vary, depending on the chemical family of the polymer, as does the exact chemical mechanism involved (oxidation, depolymerization, etc.). Occasionally, this degradation can be reduced through the use of additives known as heat stabilizers. It still occurs, but at a higher temperature and at a lower rate.

One commonly referenced material property is known as the HDT. This is a standard test where a specimen of a material is subjected to a defined load and then slowly heated while measuring the deflection. As the material gets warmer, it becomes less stiff and the deflection will increase. Once a defined amount of deflection is achieved, the test is complete and the temperature is recorded. This temperature is the HDT for that material. Occasionally, the HDT will be measured using different loads (most data sheets will reference the load along with the measured HDT).

The test itself is simple to conduct, however, the test is merely an assessment of material stiffness at elevated temperature. It is NOT an assessment of the actual service temperature of that material, nor does it make any prediction of polymer degradation. Also, since the test is short term in nature, it should not be used to evaluate long-term performance.

A more useful piece of data for material selection is the Continuous Service Temperature (sometimes also referred to simply as Service Temperature, and also known as the Relative Thermal Index). It is the highest temperature at which a material can function for an extended period of time without failing. Unfortunately, the Service Temperature is often difficult to determine. What amount of time is "an extended period?" And what functions need to occur without failing? There are some defined tests which can be used to quantify service temperature, based on electrical properties, mechanical properties, etc. And while it is easy to detect major differences in service temperatures between materials, it is often only through extensive testing that one can quantify the long-term performance of a given material at a given temperature.

At the other end of the temperature spectrum, thermoplastics are also affected by extreme cold. Most of this effect is seen in brittleness, in that there is a loss (sometimes a complete loss) of ductility, and even low stresses will cause brittle fracture. While there may also be some polymer degradation at extremely low temperatures, these phenomena are rarely studied.

5.4.2 Chemicals

Like most materials, thermoplastics are also susceptible to chemical attack. Normally, when we think of chemicals, we think of acids and bases, alcohols, gasoline and other fuels, solvents (paint and lacquer thinner, acetone, toluene, etc.), and detergents and cleaning solutions. But there also chemicals in fats, oils, greases, lubricants, pesticides, and disinfectants. And then there is salt, not just the standard sodium chloride in sea water or table salt, but an entire category of chemical compounds, some of which are found in nature, others which are synthesized. Then there are airborne chemicals, gases and vapors and fumes, oh my!

The manner in which a thermoplastic material is affected by exposure to a given chemical depends on a number of variables. First and foremost is whether the thermoplastic reacts with that chemical. It may be completely impervious to that chemical, no matter what. Or it may be unaffected at low temperature, but affected by exposure at high temperature. Then there is the relative concentration of the chemical, whether the exposure is constant or intermittent, and the duration of the exposure. Finally, there is the chemical mechanism involved. Is the chemical acting as a plasticizer, and if so, is it a reversible action, or permanent? Is the chemical causing an oxidation reaction, polymer degradation, or simply a discoloration of the surface, etc.?

While some of these questions may involve some detailed testing and analysis, most resin suppliers will publish some test data of the affect of chemical exposure on some basic material properties, such as stiffness, tensile strength, etc. They will also publish guidelines on whether a given material is suitable for use with, not suitable for use with, or slightly affected by various common chemicals.

One chemical that is often overlooked is H_2O, water. Most of us think of water as an inert material, but for some materials, such as raw iron, exposure to water causes an immediate chemical reaction. Fortunately, most thermoplastics do not chemically react with water. But there are some thermoplastics, such as nylon, which absorb water. This absorption process, which is fully reversible, causes the material to swell, and also acts as a plasticizer, making the material tougher, more flexible, and more ductile although it also reduces its strength.

However, if you can combine exposure to water with exposure to high heat, many thermoplastics will decompose as the bonds in the polymer chains are broken down. This process is known as hydrolysis, and literally means water splitting (from the Greek words *hydro-*, meaning “water,” and *lysis*, meaning “separation”). The temperature at which this occurs depends on the thermoplastic.

Water can also act as a solvent for other chemicals. In those situations the exposure to water is not the issue, it is the chemical(s) contained in the water. Regardless of whether the water is used for irrigation or potable use (or other), it is important to know its source. Understanding the source—be it a well, a river, a stream, a lake, a dam, or even the ocean—will provide insight into what chemicals and minerals it may contain. Even tap water can contain chemicals, as municipal water treatment centers in various parts of the world frequently treat the water to remove pathogens. So if you are selecting a material that will be in contact with water, you need to be aware of what chemicals could be in that water.

Another aspect of chemical reactivity is flammability. Flammability is an assessment of how easily a material will ignite and burn. While combustion (the act of burning) is a complex phenomenon, it is basically a series of chemical reactions. These reactions involve polymer decomposition, gas generation, oxidation, and more. While I would not categorize the introduction of an open flame as a chemical exposure, I think you would agree that the act of combustion would have a detrimental effect on the material properties.

5.4.3 Radiation

Another environmental factor which affects thermoplastics is radiation. Most people think of the term radiation as it pertains to radioactivity, which describes a material which emits particles and energy as part of nuclear decay. But radiation is actually a much broader term, and describes the process by which electromagnetic waves travel through space.

Electromagnetic waves are a form of energy that is composed of an electrical field and a magnetic field. These waves can have a wavelength of as small as 1 pm (10^{-12} m) to as large as 100 Mm (10^{6} m, or 1000 km). This range of wavelengths, commonly known as the electromagnetic spectrum, begins with gamma rays (at 1 pm), and includes X-rays, ultraviolet UV light, visible light, infrared, microwaves, and radio waves (Figure 5.6).

The amount of energy carried by these waves decreases as the wavelength increases. Gamma rays carry the most energy, followed by X-rays, then UV light. In physics, EM waves are collectively described as “light” waves, although the term “light” typically is used to describe visible light which are electromagnetic waves with wavelengths between roughly 390 and 750 nm (Figure 5.7).

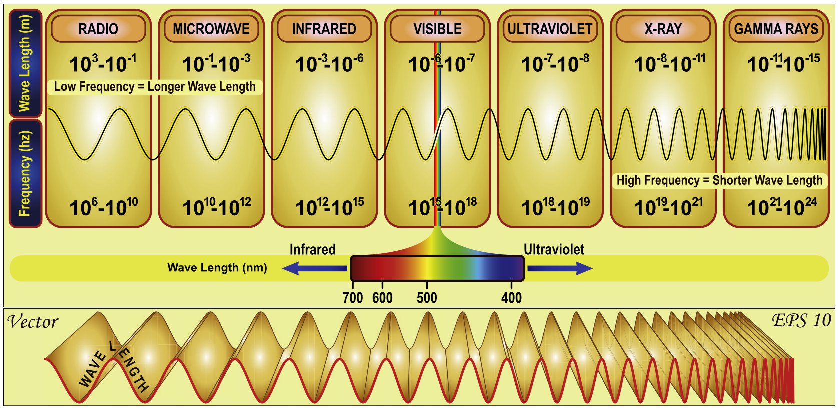

Figure 5.6 Electromagnetic spectrum. Fouad A. Saad/Shutterstock.com.

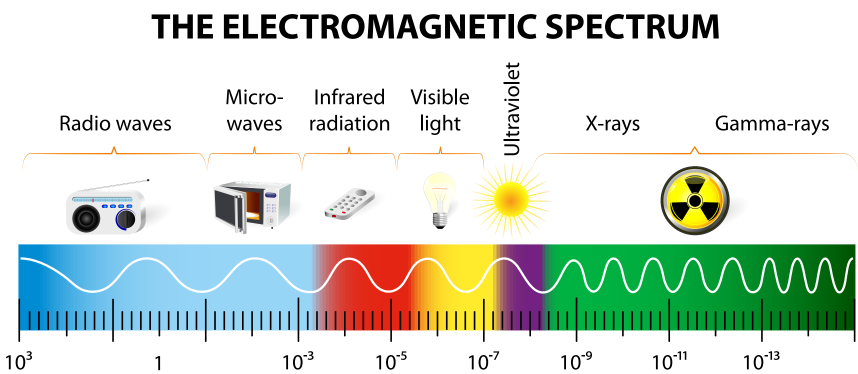

Figure 5.7 The electromagnetic spectrum, shown in order of decreasing wavelength and increasing frequency. Designua/Shutterstock.com.

In thermoplastic material selection, we are sometimes concerned with whether a given thermoplastic—and the additives it contains—will block a given frequency of EM waves, or transmits them without loss. For example, in optical applications, we typically want all light in the visible spectrum to be transmitted, without concern for other wavelengths. Or, in the case of sunglasses, we may want to block a certain amount of visible light or wavelengths in the UV range. Or, in an electronic shielding application, we may want to block transmission of EM waves in a certain band of the radiofrequency (RF) spectrum.

However, we also need to account for the effects of any EM waves on the polymer itself. Basically, we are putting energy into the polymer matrix, especially at the lower end of the spectrum (gamma rays through UV). If the polymer is transparent to those waves, the energy passes through. However, if the polymer blocks that transmission, the energy will be absorbed, and either converted into heat or it may break down the polymer chains.

One of the reasons sunlight is so devastating to materials (all materials, not just thermoplastics) is that it contains not just EM waves in the visible spectrum, but also in the infrared and UV spectrum. Long-term continuous exposure to direct sunlight means the material will absorb a lot of energy, usually with detrimental effects.

Another type of radiation is an electromagnetic pulse, or EMP. An EMP is a short burst of very high intensity and can be caused by a number of factors, including lightning strikes, electrostatic discharge, electrical power surges, and solar flares. There are also man-made EMP events, such as nuclear explosions, and the discharge of high-energy weapons (which may cause a non-nuclear electromagnetic pulse). The effects of this type of radiation on thermoplastics have not been well documented.

5.4.4 Time

The final environmental factor, and in some ways the most critical, is time. Time, in combination with one or more other environmental effects, will almost always result in polymer degradation. In fact, most of the test data that is used to evaluate environmental effects is created using time as a variable.

For instance, heat aging tests, which are used to evaluate the effect of long-term exposure to elevated temperatures, can be used to show the change in a given property value, say tensile strength, as a function of time. The graphs show sample data from different versions of nylon (Figure 5.8).

In a similar manner, weatherability tests are often used to assess the long-term effects of exposure to an outdoor environment. These tests typically address a combination of temperature, chemical, and radiation (primarily UV) effects, measured over the course of days, weeks, months, or years. These tests may include a variety of factors: for instance, an Arizona weathering test typically addresses high heat and high UV in a dry environment, while a Florida weathering test addresses high humidity and high UV in a subtropical environment, sometimes with the added effect of salt spray. While these tests are often conducted on an accelerated time scale, the intent is to predict long-term performance over months and years of exposure.

What is unknown is whether time in and of itself causes polymer degradation. In other words, do the polymer molecules in a thermoplastic

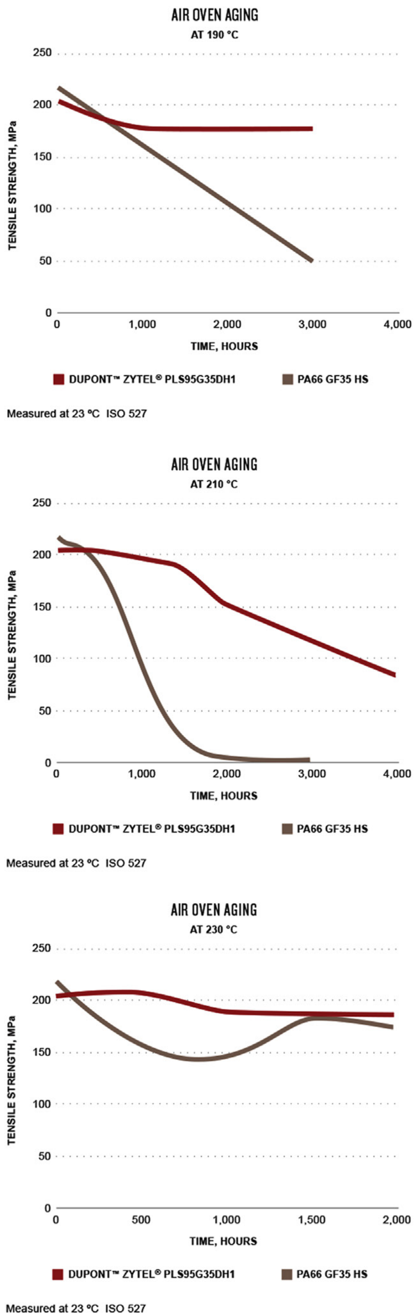

Figure 5.8 Effects of oven aging on nylon 6/6.

material degrade as a function of time? (Without exposure to heat, chemicals, or radiation?)

To evaluate that, we would need to make a special time capsule. Let us say we take four materials—a piece of wood, a piece of stone, a piece of steel, and a piece of plastic—and we place them in glass container. We seal the container, pump out the air inside, and as a precaution, re-fill it with nitrogen. Then we bury this container inside a deep cave, where the ambient temperature is a constant 73 °F, and there is no sunlight, and no radiation of any kind. Then we come back in 10,000 years.

So here we have four materials—two natural and two synthetic, two made of minerals and two made of polymers—that have been exposed to nothing but an inert gas, and time. What would we find inside that container? I would surmise that the piece of steel would be unchanged, chemically identical to time zero. I would assume the piece of stone would also be unchanged, although perhaps some of the chemical bonds that bond the various minerals together might have broken down. Perhaps we would see some dust particles as a result. However, I would expect the piece of wood might have some changes. Wood is made from the fibrous tissue of a tree, and consists of cellulose and lignin, two naturally occurring polymers. For some reason, I would expect the tissue in the wood to break down over time, even in the absence of any outside agent. So while there might be some structure to the piece of wood, I would expect to see a lot of sawdust. But what about the piece of plastic? Would it be completely intact, chemically identical to the original? Or would it decompose into a fine powder? This is an interesting question, and I don't know the answer. I also think the answer has implications to the future of our planet.

5.5 Key Mechanical Properties

When it comes to thermoplastic material selection, there are three primary mechanical behaviors that should always be considered: strength, stiffness, and toughness. Knowing the properties of a given material in these three areas will provide a fundamental understanding of the structural performance of the end product.

5.5.1 Strength

The strength of a material is its ability to withstand an applied force without failure.

At first glance, selecting materials based on strength seems like a straightforward task. You look at the structure involved, determine the loads, calculate the stresses, and then pick a material with sufficient strength. Property data on tensile strength is readily available for almost every material known to man, often at different temperatures, and under different environmental conditions.

The problem with this approach is that most products are three-dimensional objects, and are subjected to forces in all kinds of different directions. Unless you are dealing with rope or fishing line (in which case tensile strength is the critical property), you need to evaluate the strength requirements under a number of different loading conditions (Figure 5.9).

There are a number of methods of doing this. A common means is structural analysis using the finite element method. This type of analysis is well suited for identifying areas of high stress. A key question to then ask, *What is the primary stress state of the material in these high stress areas (tension, compression, or shear)?*

Once the stress state is understood, one can then look at the appropriate property data, whether it is tensile strength, compressive strength, shear strength, or bending/flexural strength. Also, one needs to consider which is more important, the yield strength (the point at which yielding occurs) or the ultimate strength (the strength at the point of failure).

Another important strength property which is especially important for injection molding applications is knit line strength. A knit line, also called a weld line, occurs when two flow fronts in a mold come together. This normally occurs when there are holes in the molded part and the flow front separates to flow around the steel that forms the hole, and then reconnects and knits on the opposite side. The strength across a knit line is almost always less than in the base material. In addition, if the material has any

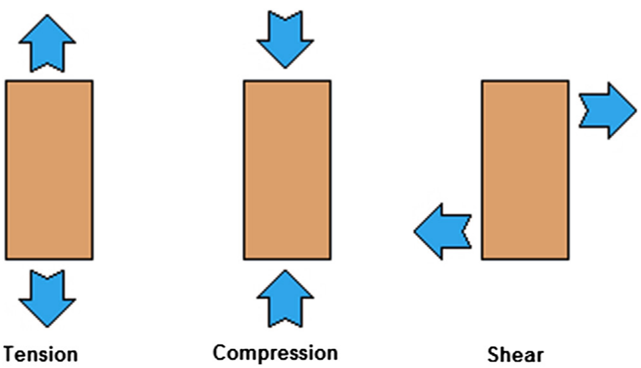

Figure 5.9 Types of loads.

reinforcement (glass fiber, mineral, etc.), the reinforcing agent will NOT cross the knit line, and the knit line strength will be dependent solely on the strength of the base material.

Unfortunately, there is very little published property data for knit line strength. Knit line strength is also heavily dependent on processing conditions.

Regardless of the type of strength, it is important to remember that strength is always evaluated on a force per cross sectional area basis. Sometimes, in an effort to find the highest strength material, we may forget that we could increase the ultimate load of the structure simply by increasing the cross sectional area, perhaps by increasing the thickness. Conversely, we may be limited on the size of the structure in certain cross sections, and must therefore select a material based on the loads in those specific areas.

5.5.2 Stiffness

Stiffness refers to the ability of a material to withstand an applied force without deformation. Typically, we think of stiffness as how well an object resists bending. In this scenario, the stiffness of the object is dependent not only on the flexural modulus of the material, but the moment of inertia of the structure itself.

Thermoplastic materials are often used in applications where resistance to bending is an important performance parameter. Furthermore, determining the flexural modulus of a material is relatively easy, and there is published property data for most thermoplastic materials. For most applications, selecting a material with the appropriate bending stiffness is a simple task. Again, it is important to remember that the stiffness of an object is also highly dependent on design.

However, there are situations where flexural modulus data is simply not available. This is especially true with fiber-reinforced materials, in which the flexural modulus of the material varies in different directions, depending on the orientation of the fibers. Often times the fibers will be oriented in the direction of flow, resulting in a much higher modulus in that direction than when measured across the flow. Property data for reinforced materials is typically prepared from molded test specimens, which have fiber alignment in the same orientation as the length of the test specimen. To measure the modulus across the flow, the test specimens need to be machined from a larger part (usually a plate or sheet) and cut so that the fiber orientation is perpendicular to the length of the test specimen. This adds time, and cost, and requires additional testing. Quite often, this testing is not done, and property data for cross flow flexural modulus is simply not available.

Furthermore, it is important to remember that the intrinsic stiffness of a material is much more than just the flexural modulus. As discussed earlier in Chapter 3, the stiffness of a material is dependent on the relationship between stress (due to the applied loads) and strain (the amount of deformation that results). For any given stress load, materials that have low strain are described as being stiff, and those with high strain are described as being flexible. This is true regardless of whether we are evaluating bending, tension, compression, or shear.

So, in order to evaluate materials based upon stiffness, we often have to look beyond flexural modulus, and evaluate tensile modulus, compressive modulus, and shear modulus as well. Sometimes, it is helpful to look at the actual stress–strain curves. As in the example of the plastic chair base mentioned earlier, we may find that in our quest for structural performance we have made an unrealistic requirement for high stiffness, when what we really should be looking for is an overall balance of strength, stiffness, and toughness.

5.5.3 Toughness

The toughness of a material is its ability to withstand sudden impact (Figure 5.10a).

Unlike strength and stiffness, which are evaluated using measurements based on force, toughness is evaluated using measurements based on energy, which means that not only are forces involved, but units of length and time as well. The toughness of a material is basically the amount of energy it can absorb without breaking, either through a brittle or ductile failure.

Just as there multiple ways to evaluate strength and stiffness, there are multiple ways to evaluate toughness, and there are a number of standard tests that are used to quantify the toughness of thermoplastic materials. Some of these tests are simple, and can be easily performed on a bench top with minimal equipment. Some tests are quite sophisticated and involved advanced equipment and extensive instrumentation. Regardless of what

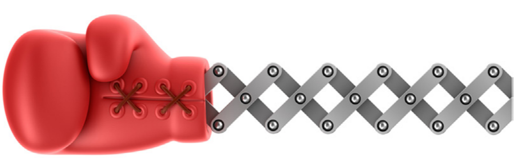

Figure 5.10a Sudden impact. Alex Mit/Shutterstock.com.

tests are used, it is important to understand exactly what aspect of toughness is being measured.

First, what is the stress state of the material as it is being impacted? It is a pure tensile impact? A shear impact? Or does it involve a combination of stress states? Second, what is the mode of failure of the test specimen? In many impact tests, the mode of failure is a brittle fracture. This is important because brittle fracture is often due to cracks.

Fracture mechanics is a field of mechanical engineering that studies how cracks form and propagate in various materials. It is a complex and important field of engineering. Understanding how cracks form and propagate in steel is critical for the construction of bridges and buildings. For airplanes, the same holds true for aluminum. The formation and propagation of cracks in thermoplastics is a science in and of itself.

Regardless of the material, crack initiation and propagation is an important aspect of toughness. In some materials, such as window glass, cracks propagate easily. Indeed, the standard means of cutting window glass is to lightly score the surface, creating a crack or notch. Then, with a slight tap, the crack propagates, and the window pane breaks off. The term *notch sensitivity* is used to describe how a material responds to this type of crack propagation. Some thermoplastic materials have high notch sensitivity (although perhaps not as high as window glass). Other thermoplastic materials have low notch sensitivity (Figure 5.10b).

Another aspect of toughness is tear resistance. While we often think of this in relation to materials in a film or sheet form, it also applies to thick solids. The typical chew toy that you might give your pet is most likely from a material with high tear resistance (Figure 5.11).

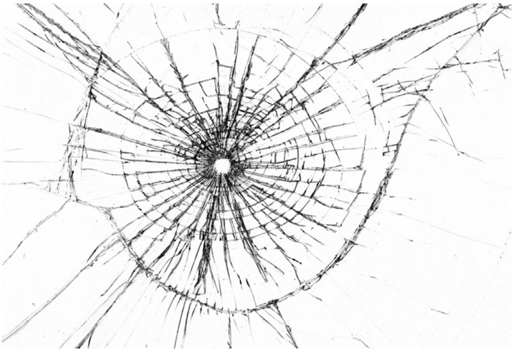

Figure 5.10b Window glass is notch sensitive. JoLin/Shutterstock.com.

Figure 5.11 Chew toys require good tear resistance. Mila Atkovska/ Shutterstock.com.

Selecting a thermoplastic material based on toughness is a complex task. I would describe it as the single most difficult task in the field of plastics engineering. There are many reasons for this.

Impact analysis involves a huge number of variables: the stress states of the material(s) being impacted (tension, compression, shear, etc.); the rate of loading (i.e., the speed at which the impact occurs); the overall energy of the impact (involving not only the speed of impact but the masses of the components in the systems, including both the system that is delivering the impact and the system that is absorbing the impact); along with dozens of other variables. Identifying each of these variables can be a difficult task, to say nothing of what is involved in isolating and measuring the values of each variable in the system.

We also need to understand that impact analysis is an imprecise science. Even if we focus exclusively on the behavior of the material(s) under impact, there are dozens—if not hundreds—of assumptions on the behavior of the components in the system prior to and during impact. The validity and accuracy of these assumptions is often a topic of heated debate, even among experienced professionals. The behavior of the material(s) under impact will also be affected by temperature, and/or other environmental factors (exposure to chemicals, radiation, etc.). Quite often, the best assessment of impact is real-life testing of the actual system under the appropriate end-use conditions.

As a result, quantifying the toughness of a given material in a given application is a highly subjective assessment. Sometimes the toughness of a material is evaluated based on structural failure as the result of sudden impact, by looking at the loads and structural deformations when a device or test specimen completely fails. There are also situations where a device or system is subject to repeated loads, with forces lower than what would cause failure in a single impact. (Think of repeatedly hitting something with a hammer until it eventually breaks.) This type of toughness, commonly described as impact fatigue, is evaluated based upon the damage progression as the specimen undergoes repeated impact. In this case we need to account for not only all of the previously described variables, but the frequency of the loading (how often the impacts occur), and how many impacts occur. At an extreme level, one could say that vibration is a type of repeated impact. There are entire fields of engineering dedicated to vibration.

Regardless of the science involved, the fact remains that toughness is an important issue for many applications where thermoplastic materials are being considered. Quite often, the toughness of a material is the most important factor in product performance.

5.6 Measuring Toughness

There are a number of standardized tests that are used to quantify various aspects of material toughness. The following section discusses some of the more commonly used tests.

5.6.1 Izod Test

The Izod test is typically a bench top test. (The test is named for its inventor Edwin Gilbert Izod, and has nothing to do with a famous clothing maker.) In this test a small test specimen is clamped in a vise. This specimen has a V-shaped notch in it, facing forward. A pendulum arm is then raised to a certain height and released. The arm swings into the specimen, breaking it, and then continues swinging to the opposite side. A needle on a dial measures how high upward the arm swings. The difference in height between the starting position and the end position is used to calculate the difference in energy, which is the energy that was absorbed by the test specimen as it broke. The speed of the impact depends on the length of the arm, and height from which it is dropped.

The Izod test is a simple test to conduct, and Izod test data is readily available. It is important to remember that this test is a measurement of impact in almost a pure shear loading condition, and the specimen has a substantial notch. While the resulting data may be useful for material comparison, it represents an unusual end-use loading condition (Figure 5.12).

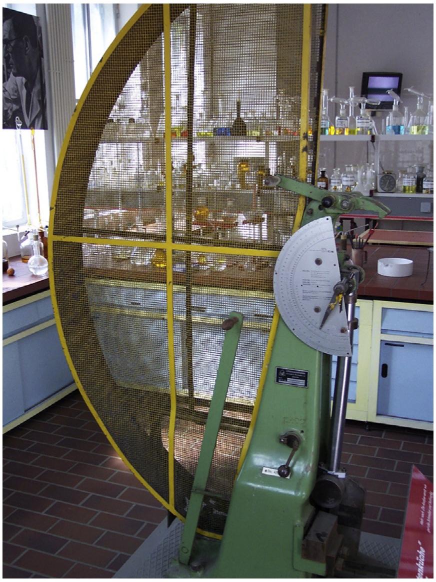

Figure 5.12 Schematic diagram of a typical pendulum test.

5.6.2 Un-Notched Izod Test

This test utilizes the same equipment and procedure as in the Izod test, except the test specimen has no notch. While the load case is still a pure shear loading condition, the fracture of the test specimen is independent of any notch. This test allows one to quickly compare impact data for a given material in a notched versus un-notched state. This comparison can provide insight into the notch sensitivity of the material.

5.6.3 Charpy Test

The Charpy test is similar to the Izod test. It is named after Georges Charpy, a French engineer and scientist who developed and standardized the test methods in the early 1900s. It is also a pendulum type test, but in this test the specimen is clamped sideways, by securing it at each end. The specimen could have a V-shaped or U-shaped notch, and the notch faces away from the pendulum. The test device itself could a bench top size, or a larger, floor size model.

The Charpy test is also simple to conduct. Charpy data is not as widely available as Izod data, but is usually easy to obtain. The loading is in pure shear. The data is useful for material comparison, and for evaluating the notch sensitivity (Figure 5.13).

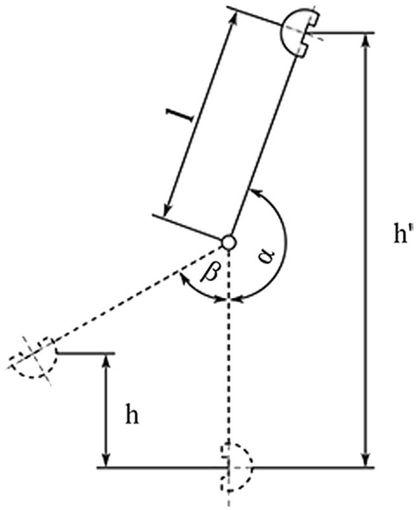

Figure 5.13 A Charpy-type impact test machine.

5.6.4 Gardner Impact Testing

Gardner impact testing refers to a type of impact testing that involves a weight that is dropped onto fixed object. Generically known as falling weight testing, the name Gardner comes from Paul N. Gardner, founder of the Paul N. Gardner Company.

The typical Gardner tester is a floor-based test, and uses a falling dart rather a pendulum. The “dart” is typically a weight with a rounded nose. The test specimen is a plaque, and rests on a plate with a hole in the center of a prescribed diameter. The dart is lifted to a specific height, and then dropped on the specimen. If the specimen breaks, the test result is recorded as Fail, if the specimen is intact, the test result is recorded as Pass. A typical test scenario involves a dart of a specific weight, a defined drop height, and the number of drops before the specimen breaks. The amount of energy is calculated based on the weight and height.

Gardner impact tests, and other similar falling weight tests, are simple to conduct. The equipment is relatively inexpensive, and while the data can sometimes be hard to compare (due to different weights, drop heights, and/or the number of Pass/Fail cycles), it does represent real-life conditions. Products get hit by falling objects all the time (or they are falling objects themselves), and this test can provide useful insight on impact under those conditions.

One minor caveat, since the weight is free falling, it is accelerating under gravity. So, the impact velocity of the weight will increase as the height increases. Since plastics are rate sensitive, this will affect the test results. One could have very different impact performance between the impact of a heavy weight falling from a low height and a lighter weight falling from a higher height, even though the kinetic energy is the same. This might be an important issue in some applications.

5.6.5 Instrumented Impact Tests

As the name implies, instrumented testing involves the use of equipment which can precisely record the variables involved in the test. It is a general term, and can be used to describe a wide variety of tests. For instance, one could attach some sensors and gauges to an Izod tester, connect them to a laptop computer, and then record the data as the pendulum is released and impacts the test specimen. Technically, this would be an instrumented impact test. However, the phrase *Instrumented Impact Testing* is normally used to describe testing where one cannot only measure and record the test variables, but can also have precise control over the actual test parameters, such as the rate of loading and the velocity of impact.

While instrumented impact testing can be quite simple (as in the instrumented Izod test described earlier), the real value of instrumented testing lies in the ability to isolate and control the various test parameters and to precisely record the output data. When applied properly, instrumented testing can provide valuable data on almost aspect of material toughness. The primary disadvantage of instrumented testing is that the equipment can be quite complex (and expensive).

5.6.6 High-Speed Tensile Tests

High-speed tensile tests are a form of instrumented impact testing. (They are the high-tech version of playing with silly putty.) They involve the use of standard tensile test specimens and standard tensile test equipment. However, traditional tensile tests are typically conducted at a very low rate of strain, typically ranging from fractions of inches per minute to about 20 in/min. (Even 20 in/min is a very slow rate of movement. It is less than 0.02 miles/h, or approximately 0.03 km/h. Compared to these rates, most turtles are moving at light speed.)

In high-speed tensile tests, the rate of loading is substantially increased, often times to a rate of loading that is hundreds—or even thousands—of times faster than in traditional tensile tests. While these rates of loading are quite common in the real world, in the traditional world of material science these rates of loading are unheard of.

The advantage of this type of testing is that it utilizes existing equipment and can be easily standardized. It can also provide a comparison of to real-life end-use conditions. Also, while comprehensive test data is not available for all materials, it can easily be generated on an as-needed basis. The disadvantage of this type of testing is that it is new and different. There is very little material property data available, and even with the data that exists, the correlation between measured data and actual end-use performance is still uncertain.

5.6.7 Projectile Testing

Projectile testing involves taking an object, and then, through the application of force by the test device, sending that object through space to impact against a test specimen. The object being projected could be a weight, a steel ball, a brick, a piece of organic matter (such as a head of lettuce or a frozen bird), and the force could be applied by compressed air, hydraulics, or other mechanical means. The test specimen could be a standard test specimen, a material sample, or a prototype or production part.

While projectile testing is common, the tests and equipment are not standardized. In general, resin suppliers to do not provide any test data for projectile testing. Instead, projectile testing is usually done with customized equipment with a specific intent, such as evaluating the impact resistance of automobile fascia when impacted by road debris, or of aircraft windshields when subjected to bird strikes.

The advantage of projectile testing is that the test can be developed to mimic the actual end-use conditions and materials can be evaluated in that context. The disadvantage is that the equipment, and the actual tests, are not standardized, and it may not be possible to correlate the results of these tests with other types of toughness tests (Figure 5.14).

5.6.8 Drop Testing

Drop testing is another type of impact testing involving a falling object. However, unlike other impact tests, the falling object is the actual test specimen. The test specimen is typically a fully assembled product, but could also be a subassembly, or a single part.

Drop testing can be conducted at a variety of heights, and the test specimens can be dropped onto different surfaces (concrete, hard packed dirt, carpeted floors, etc.). Just as in falling weight tests, the impact energy will be dependent on the height of the drop and the mass of the object. The

Figure 5.14 A drop test? Or a Gardener test gone wrong?

testing can also be used to assess the impact performance of the test specimen against different surfaces.

A major advantage of drop testing is that the testing can be developed to mimic actual end-use conditions, and materials can be evaluated in that context. One disadvantage is that drop tests often require fully assembled products. While this can provide valuable feedback to confirm the validity of a given design, drop testing rarely provides any useful information in the early phases of design and material selection.

5.6.9 Tumble Testing

Tumble testing is another type of impact testing, which involves a number of different parameters. In a typical tumble test, one takes a number of test specimens and places them in a closed container. Quite often, other items will also be placed in the container, such as rocks, small pebbles, and abrasive media. The container is then placed in a test machine which will tumble the container, in a more or less random manner, for a period of time. In the process, whatever is inside the container will be subjected to a wide variety of low-speed impacts, in a diverse number of loading conditions (in common English, the test specimens are in for a jolly good ride).

At the end of the test, the container is opened, and the test specimens are inspected and evaluated. While the evaluation may involve quantitative measurements (such as weight loss due to pieces being broken off or abraded away, or the change in measured value of a specific performance parameter), qualitative assessments are often more valuable. Qualitative assessments may include a description of common failure modes, observations of high wear areas, and commentary on overall performance.

A major advantage of tumble testing is that evaluation can often be done very quickly. Unlike other impact test methods, where test specimens are evaluated in a solitary manner and the results are then summarized, tumble testing is typically done on a lot basis, where a number of given samples are tested together. As such, tumble testing can often provide the fastest feedback in a trial-and-error type of evaluation. In this type of scenario, a number of samples are prepared and tested en-masse, using a given set of test parameters (which normally mimic actual end-use conditions). The entire lot is then evaluated in a collective manner, and quickly evaluated. Based on the results, the materials can be changed, and/or the test parameters can be adjusted, and another lot can be prepared and tested.

A disadvantage of tumble testing is that it can be difficult—and sometimes impossible—to obtain quantitative data on specific individual parts. However, tumble testing is rarely used for this type of analysis.

The beauty of tumble testing is that it is an all-encompassing test. It is a rock-and-roll, take-no-prisoners, sink-or-swim, do-or-die kind of test. It is the engineering equivalent of playing No-Limit Hold 'Em poker, looking at your cards, evaluating the bets on the table, and then declaring, *I'm all in* (Tables 5.1–5.2).

5.7 But Is It Tough Enough?

In a practical matter, the term toughness is often used to describe the ability of a material to withstand abuse. After all the engineering analysis is said and done, very rarely are we concerned with quantifying exactly how tough a material is under 27 different test methods. What we really want to know is whether a given material will provide the desired performance in the end product for a prescribed amount of time. Sometimes, this involves making some tough decisions, based on a combination of published property data, and a mix of custom test methods (some very precise, some not). The two key questions in this process: *What kind of toughness do I need?* and *Is this material tough enough?* (Figure 5.15)

Table 5.1 Comparing Various Impact Tests

Test Type	Test Details				Rate of Impact (Velocity)				Useful for
	Shapes	Complexity	Machine Cost	Cycle Time	mm/s	in/s	km/h	miles/h	
Standard Tensile	Test bar	Medium–high	$$–$$$	Minutes	0.08/0.8	0.003/ 0.03	0.00029/ 0.0029	0.00018/ 0.0018	Basic property data
Izod (ASTM D256)	Test bar	Low	$–$$	Seconds	3500	138	12.6	7.83	Material comparisons, evaluating notch sensitivity
Un-notched Izod	Test bar	Low	$–$$	Seconds	3500	138	12.6	7.83	Material comparisons, evaluating notch sensitivity
Charpy (ISO 179)	Test bar	Low	$–$$	Seconds	3800	150	13.7	8.5	Material comparisons, evaluating notch sensitivity
Gardner[a]	Discrete parts	Medium	$–$$	Seconds	5970	235	21.5	13.4	Material comparisons, impact fatigue
Falling weight[a]	Discrete parts	Medium	$–$$	Seconds	5970	235	21.5	13.4	Material comparisons, impact fatigue
Instrumented	Any	Medium–high	$$–$$$	Minutes	Varies	Varies	Varies	Varies	Comprehensive analysis

Continued

Table 5.1 Comparing Various Impact Tests—cont'd

Test Type	Test Details				Rate of Impact (Velocity)				Useful for
	Shapes	Complexity	Machine Cost	Cycle Time	mm/s	in/s	km/h	miles/h	
High-speed tensile	Test bar	Medium–high	$$–$$$	Minutes	10,000	393.7	36	22.4	Tensile impact at high rates of loading
Projectile	Any	High	$$–$$$	Minutes	Varies	Varies	Varies	Varies	Comprehensive analysis, real-life simulation
Drop[a]	Complete assemblies	Medium–high	$–$$	Minutes	5970	235	21.5	13.4	Qualitative analysis, real-life simulation
Tumble	Complete assemblies	Medium–high	$$	Minutes	Varies	Varies	Varies	Varies	Comprehensive analysis, real-life simulation

[a] *Velocity at impact after a 6-ft drop.*

Table 5.2 Comparing Velocities

Object/ Animal	Description	Velocity				Compares to
		mm/s	in/s	km/h	miles/h	
Garden snail	Average speed	4	0.2	0.02	0.01	50× faster than tensile test
Galapagos tortoise	Walking, typical speed	90	3.5	0.32	0.20	
Mouse	Common house mouse, running	3584	141.1	12.90	8.00	Izod test
Roadrunner bird	*Geococcyx californianus,* top speed	8960	352.8	32.26	20.00	Faster than 6-foot drop
African elephant	Charging bull elephant, enraged	11,200	441.0	40.32	25.00	High-speed tensile test
Usain Bolt	World's fastest human, top speed	12,455	490.3	44.84	27.80	
Sparrow	Eunladen European, in flight	14,023	552.1	50.48	31.30	
Sparrow	English, in flight	17,473	687.9	62.90	39.00	
Cheetah	World's fastest land ani-mal, top speed	31,361	1234.7	112.90	70.00	
Toyota Prius	Downhill, following wind, on a good day	45,250	1781.5	162.90	101.00	
Baseball pitch	Fastest recorded velocity	47,042	1852.0	169.35	105.00	

Figure 5.15 So you think you are tough?

5.7.1 Are You Ready to Rumble?

One of my first experiences with evaluating the toughness of thermoplastic materials came when I was working as a product development engineer for a small company named Kransco Manufacturing. Kransco made a number of recreational products, mostly in the swimming and surfing area. They made floating swimming pool lounges, water basketball games, even boogie boards. One of their products was a knee board sold under the brand name Hydroslide. The user would kneel on the board, and then get towed behind a boat. It was similar to water skiing, but much easier, and a whole lot more fun.

The Hydroslide was a rotationally molded product. I had been to a seminar on rotational molding, and had learned a few things about the process and the materials that were used, and we decided to explore some different materials in this product. Among other things, we wanted to evaluate how each of these materials performed during the rotational molding process. Were they easier to mold? Were the parts stiffer or more flexible? Was the color more vibrant? Did they assemble easier? So we had some samples made in various versions of polyethylene—LLDPE, HDPE, etc. We then went about evaluating them.

One of the things we discovered was that there were some subtle differences in the surface characteristics of each version. Sometimes this was helpful, as it made easier to attach the foam knee pad to the board, and sometimes it was not. We also began to notice differences in their durability. In an attempt to quantify this, my boss and I hooked up a bunch of samples behind his car, and we drove around the parking lot for 15 min or so, towing the boards behind us, and doing everything we could to make them tumble and spin and bounce and collide. While there was no alcohol involved—and no animals were harmed in the testing—we did have a lot of fun. And we were also able to determine which materials had the best durability.

A day or so later, I heard someone in the company—probably one of the bean counters—had seen us driving around the parking lot and had marched into the president's office, and said something to the effect of, *Do you know what those idiots in product development are doing right now? They are driving around the parking lot, towing a bunch of plastic junk behind them.* He looked up from his desk, looked her straight in the eye, and responded, "They are doing exactly what they need to be doing." We never had a single complaint about our test methods after that.

5.7.2 Cutting the Grass

In the mid-1980s I found myself working for a small company named Allegretti and Company. They made a line of motorized lawn and garden tools that were sold by Sears. Their main products were leaf blowers, edge trimmers, and weed wackers (Figure 5.16).

The performance requirements of these products were similar to traditional power tools, with one additional requirement. They had to withstand projectile impacts—at a high velocity. These tools all had high-speed motors with whirring blades and knives and fans. Any of those items could make impact with a stone, or a piece of steel, or a chunk of wood, and

Figure 5.16 Leaf blower. momopixs/Shutterstock.com.

then propel it outward at high velocity. Hopefully, it would either hit the ground, or hit the protective shroud and then exit the exhaust chute.

The shrouds and exhaust chutes were made from tough materials like polycarbonate, ABS, occasionally even polypropylene. The key was projectile testing, specifically small objects weighing grams or ounces that were projected at fairly high speed. The performance requirements might vary, minor deformation allowed, no structural failure allowed, etc. While projectile testing can be a slow and tedious process, it can provide valuable information on performance in real-world applications.

Sometime in the early 1990s, a DuPont colleague of mine went to a trade show for the lawn and garden industry. This was a manufacturer's show, where new equipment was showcased. It involved not just weed-wackers, but lawnmowers and chain saws and snowblowers, not just for consumer use, but commercial equipment as well, even heavy machinery used in agriculture. GE Plastics had an exhibit at the show, promoting the use of their materials. They were always very good at marketing.

They had gotten an injection mold made, a very large injection mold, and had molded a lawnmower deck. Not just the deck of small four-wheel push-type lawnmower, but a big industrial lawnmower. The blades under these decks can turn rocks and other objects into deadly weapons, so the decks themselves needed to be able to withstand a tremendous amount of impact energy. They had one of these decks in a protective enclosure in their booth, hanging sideways like a giant gong. Every hour, on the hour, they fired a projectile from a cannon, and it would strike the deck with tremendous velocity. The deck would ring like a giant gong, reverberating throughout the convention hall, while the projectile would simply fall to the floor.

While some might think that the purpose of this demonstration was to prove the toughness of thermoplastics from GE Plastics, I prefer to think of it a subtle reminder of importance of projectile testing when evaluating the use of thermoplastics in an application subject to high velocity impacts.

5.7.3 Chicago Style

In the mid-1990s I relocated to Chicago. Chicago is a great American city. Not only is it an alpha global city [4], it is in many ways the epicenter of manufacturing in the Midwestern United States. Or as I like to describe it, Chicago is the buckle of the rust belt.

There are hundreds of manufacturing companies in the midwest, making everything from auto parts to zebra printers. Many of these companies use thermoplastics in their products, sometimes to reduce costs, sometimes to reduce weight, but often times because they can achieve a level of performance due to the toughness of a specific thermoplastic. Many of these companies have their own test labs, where they develop testing protocols that are tailored to their unique application.

Imagine you are working for a company like Whirlpool and are tasked with selecting a material to be used in the drive train of washing machine. And you know that many of the components in that machine are covered under an extended warranty, lasting 3, 5, perhaps even 10 years. Are you going to select a material based solely on published values of Izod test data? I doubt it. You are going to develop some prototypes, choose some candidate materials, and put them in your test lab and test them for days, weeks, months, perhaps even years. If, or more likely when they fail, you are going to look at them under a microscope and evaluate the failure mode. Or you may take high-speed video to see what is happening dynamically during the moment of impact.

Or imagine you are working for a manufacturer of power tools, making drills, saws, sanders, grinders, nail guns. Are you going to select a material based on Gardner impact test results? Or are you going to do more in-depth evaluation?

In many of these kinds of situations, the selection of a material with the right amount of toughness is dependent on the performance level of the end product. The level of performance that is required is very often related to the sales price of the end product, which in turn affects the expectations of the consumer. No one expects a cordless drill that sells for $19.99 to have the same level of performance as one that sells for $199. However, if you went and bought a $199 drill, and then the first time you used it, you dropped it onto a concrete floor, and it broke, you probably would not be very happy.

So companies that make these kinds of products devise all kinds of performance tests, dropping them from the roof onto concrete, running them over with a truck, dragging them through mud, doing everything they can to abuse them, and evaluate their toughness.

Now one might say, "These tests are statistically invalid, the measurements are inaccurate, and the results are not reliable and repeatable. Even if they are performed under controlled conditions, they have no correlation to the actual in-use performance of the material in the intended application."

To all of that, I will readily agree. However, I will also argue that these kinds of tests represent real-life, in-use scenarios, and if the product—and the materials that are selected—cannot pass these tests, then you have no business using those materials in the application.

The 1987 movie *The Untouchables* featured Kevin Costner playing Elliot Ness, the federal agent tasked with bringing down the famous Chicago gangster Al Capone. In one scene, a Canadian Mountie chastized his interrogation techniques. "Mr. Ness, I don't approve of your methods." His response: *Oh yeah? Well, you're not from Chicago.*

5.7.4 The Thrill of Victory (and the Agony of Defeat)

Throughout history, people have always played sports. And just as with other man-made things, the materials that have been used to make sports equipment have changed throughout history. Today, while sports equipment is still made from traditional materials like wood, leather, and metal, thermoplastics are increasingly used in a diverse numbers of ways. In some cases, the sporting goods industry is at the forefront of plastics engineering.

Just as in other industries, thermoplastics are used to reduce weight and decrease the cost of manufacture. They are also used specifically to improve product performance. And while strength and stiffness and chemical resistance have always been an important part of performance, the toughness of the material is often a critical parameter.

One important material is polycarbonate, which is used in all kinds of applications, ranging from football helmets to face guards and safety glasses. The toughness of polycarbonate is outstanding and it excels in all aspects of impact testing, especially with Gardner-type impact and projectile testing (Figure 5.17).

Another important material is nylon, which is used in rope and webbing, and also in high-performance sports fabrics. In these the toughness requirement is in pure tension. Tensile impact testing and high-speed tensile testing are useful in these applications. The elongation of the material is often equally important.

Thermoplastics are often used in high-performance zippers on backpacks and tents and sports clothing. These not only require tensile toughness, but often low-temperature toughness as well. Finding impact data at very low temperatures can be challenging. Thorough product testing is often required.

Equipment in many sports often has specific structural requirements, combined with a need to withstand impact and abuse. Whether this is the frame that supports the basket on a lacrosse stick, or structural support for the wheels used on an inline skate, these need to have the big three: strength, stiffness, and toughness.

Figure 5.17 Football helmet. pbombaert/Shutterstock.com.

Ironically, the toughness requirement for the frame of an inline skate is similar to the carrier on a nail gun. They are both subject to repeated impact over long periods of time, with occasional high-energy impacts due to drops or collisions. It is no coincidence that toughened, glass-reinforced nylon is used in both of these applications.

One interesting aspect of sporting equipment is that most products are rarely used in a continuous manner for extended periods of time. This is very different than most industrial applications, or even power tools. While a sports product may be expected to last for several years, it is typically only used for a short period of time, perhaps a few minutes, perhaps a few hours or days. The product may then be stored in a garage, or outside in the sun, even partially submersed in water. However, the next time the product is used, the same level of performance is typically expected. As a result, evaluating the toughness of a material for a given application often means accounting for exposure to temperature, chemicals, radiation, and time (remember the Four Horsemen?). Quite often, property data is simply not available, and extended life testing of the actual product is required.

5.7.5 Dealing with JRA

Another classic example of toughness in the sporting goods world comes from the bicycle industry. SRAM was a manufacturer of bicycle components, which they primarily sold to bicycle manufacturers, but they also sold parts in the aftermarket. Their primary product was a rotary shifting mechanism known by the brand name GripShift. It consisted of a rotating plastic cylinder that acted as a cam to pull and release the shifting cable in a precise manner. It was a very simple solution to a complex problem.

SRAM had recently started manufacturing a rear derailleur. A derailleur is a mechanism that moves the chain from one set of sprocket teeth to another, allowing a bicyclist to change gears. The rear derailleur is a complex mechanism that involves a parallelogram, several springs, and a couple of pulleys. It not only allows for changing gears, but also provides for proper chain tensioning through the entire range of gearing. SRAM had developed a design that allowed for more precise positioning of the chain to the individual gear teeth. An SRAM derailleur was used to win the gold medal in the first Olympic mountain bike race in Atlanta in 1996.

There were two main parts in the derailleur that were made of plastic. Known as the knuckles, they were injection molded of a reinforced grade of nylon. The reinforcing agent was a type of ceramic, and the resulting parts were incredibly stiff, allowing the mechanism to be extremely precise. Unfortunately, SRAM begin experiencing a high rate of returns due to field failures, known as FFR. I was asked to investigate the issue and determine what could be done.

Rear derailleurs take a tremendous amount of abuse, especially in mountain biking. Riders hit rocks and tree branches and stumps, and occasionally, these bumps will force the derailleur directing in the spokes of the spinning rear wheel, at which point all hell breaks loose. We were getting returns of broken derailleurs showing all kinds of different failure modes. However, one common description of the activity was described as *Just Riding Along*, or JRA. It is the bicyclist's version of the classic excuse, *I wasn't doing anything wrong*. Replicating a field failure from JRA was practically impossible. However, it was easy to replicate failure modes from a side or frontal impact.

The theory we developed was that these derailleurs were failing due to impact fatigue. The rider would be out for a ride, hit something hard, but keep on going. Sometime later, maybe the next time out, they would put a little force on the chain and the derailleur would snap. That extra force was the proverbial straw that broke the camel's back.

We began exploring the use of different versions of nylon, with different reinforcing agents and different toughening additives. Our test methods involved not just pendulum-type impact tests, but also drop tests, with different weights dropped at different heights. Our goal was not just the highest possible impact strength, but the ability to withstand a high number of impacts at lower impact energies. We eventually settled on an aromatic polyamide (a type of nylon), with 50% glass reinforcement, and a

Figure 5.18 A severely damaged rear derailleur.

proprietary toughening agent. This material was TOUGH. Ironically, it was a material that was being widely used in other applications in the sporting goods industry, including bindings on snow skis. It was stiff, it was strong, and it was unbelievably tough.

The FFR dropped substantially, and several months later one of the field technical reps dropped a broken derailleur on my desk. It was a derailleur that had gotten into somebody's rear wheel. The aluminum connecting links were severed, the aluminum plates that held the pulleys were twisted and bent, but the plastic knuckles were more or less intact. Now that's toughness (Figure 5.18).

5.7.6 The Shupe Test

SRAM also had plans to manufacture a set of brake levers made 100% from plastic, using the same material that worked so well in the derailleur knuckles. Jeff Shupe, the Vice President of Manufacturing, was not in favor of making a plastic brake lever. He used to stroll into the R&D lab every now and again, grab a prototype brake lever, and then twist, pull, yank it every which way until it broke. He would then toss the broken brake lever on the work bench and walk out, without saying a word. The implication was clear. If he could break it, what was going to happen in the real world?

So the engineering team went all out in their efforts to make a robust design, knowing we had a material that was stiff enough, strong enough, and tough enough. Along with other performance tests, we also created a test where we would mount the brake lever assembly to a solid steel bar, and then bolt the steel bar to a mounting plate. We would then have Jeff come in, and he would first wrap a towel around his hand (kind of like how a prize fighter would tape his hands before a big fight), put on a set of safety goggles, and then grab the lever and do everything he could to try and break it. We called it "The Shupe Test." We eventually were able to create a design that he could not break. The design went into production a few months later.

Each year there is a huge trade show for the bicycle industry, called Interbike. We decided to bring "The Shupe Test" to the show. For those of you who are serious cyclists, you can appreciate the level of testosterone that exists at a show like this. When prospective buyers came to the booth, we would casually show them the new plastic brake lever, and when they expressed doubt that a plastic brake lever could work—let alone stand up to the abuse that a mountain bike endures—we would invite them to take the Shupe test. *Go ahead, grab it. Bend it. Twist it. Break it. Come on, can't you break it, what's the matter, are you a pussy?* Inevitably, they would work themselves into a frenzy trying to break it, only to eventually give up, and say something to the effect of, "I can't believe how tough that is." SRAM sold a lot of plastic brake levers that year.

5.7.7 The Bottom Line on Toughness

The toughness of a given material cannot always be evaluated by simply looking at the published values of one specific test. When it comes to material selection, toughness should always be evaluated using a variety of different methods. The methods should include a mix of quantitative and qualitative criteria, including tests that can be correlated to the actual in-use performance of the final product.

I remember a quote from Bill Miller, a mutual fund manager who ran a fund named Legg Mason Value Trust (LMVTX), which at one point had the distinction of beating the annual return of the Standard & Poor 500 Index for 15 consecutive years. (Full disclosure: I invested some money with him for some of that period, thank you very much.) The quote said something to the effect—"At LMTVX, we use a multi-factorial value analysis approach. That is, we seek to evaluate real value using a variety of different methods [5]." I would encourage a similar multifactorial analysis approach for thermoplastic material selection, especially when it comes to evaluating toughness (Figure 5.19).

5.8 Surface Properties

Another key set of mechanical properties has to do surface characteristics of the material, specifically with how the material interacts with another material when they are in motion relative to one another. These

Figure 5.19 Selecting materials based on toughness. totallyPic.com/Shutterstock.com.

characteristics include friction, lubricity, and wear, the study of which is known as tribology. Other surface characteristics include hardness.

5.8.1 Friction

Friction is the force that provides resistance as two objects slide against one another. It can be measured in many different ways, the two primary ones being static (stationary) and dynamic (moving) friction. It is typically expressed through the coefficient of friction, which is a dimensionless ratio comparing the sliding force to the normal force. While friction is an inherent material property, it varies depending on what material it is measured against. Material pairs with a high coefficient of friction are considered sticky, while those with a low coefficient of friction are considered slippery. Thermoplastic materials are selected for either reason, depending on the application. For teflon-against-teflon (PTFE), the coefficient of friction is 0.04, one of the slipperiest combinations known to man.

5.8.2 Lubricity

The lubricity of a material is not a specific property. Rather it is an assessment of a material in a given system. Many thermoplastics have inherently excellent lubricity in a wide range of environments, and there also additives which can be used to enhance the lubricity. Friction and lubricity are often related, and while data for coefficients of friction is frequently published, data is less available for lubricity.

5.8.3 Wear

Wear describes the change in a material as it in motion against another material. It includes permanent deformation due to yielding, loss of material due to abrasion, surface changes to crack propagation, and erosion, which is a loss of material due to the cutting action of liquids or small particles.

5.8.4 Hardness

Hardness is the resistance of a solid material to permanent deformation when localized forces are applied. It is a form of compressive strength. It is commonly measured via scratch hardness and indentation hardness. Scratch hardness, as the name implies, is the resistance to a sharp object as it moves against the material's surface. Soft materials will readily deform, and a gouge or scratch will be left behind. The size and depth of the scratch, the appearance of the scratch (smooth or rough), are all elements of scratch resistance.

Indentation hardness involves taking an object, often a hardened steel ball, and pressing it against the material with a defined force, and then measuring the depth of the resulting indentation after the ball is removed.

In general, most thermoplastics are softer than your typical metal materials. Elastomers and foams also have very different behavior when it comes to hardness, since they inherently have a high amount of elasticity, and can be easily compressed without having any permanent deformation. Foam hardness is often measured based on the amount of compression during a given load. Known as indentation load deflection, this measures the ability of a foam to support a given weight.

Selecting thermoplastic materials based on their surface properties typically needs to be done in context of the system that the materials are going to be used in.

As an example, thermoplastics are frequently used in rotating applications, either as pulleys or bearings or cams. The performance of a specific thermoplastic for a given application will be heavily dependent on the speed of rotation, and the forces involved. It will also depend on the material used for the shaft, how hard that material is, and what surface finish it has. Rather than trying to find the perfect thermoplastic for that bearing, it may be simpler to focus efforts on the shaft itself.

5.9 Key Electrical Properties

When we think of the electrical properties of a thermoplastic, we often think of their ability to work as electrical insulators. That is, they are *not* expected to conduct an electric current, rather, they are expected to *prevent* any current flow.

5.9.1 Insulating Plastics

Most thermoplastic materials are inherently nonconductive and work well as electrical insulators. There are numerous test methods for evaluating the insulating properties thermoplastics, including dielectric strength, arc resistance, surface resistivity, volume resistivity, and dissipation factor.

Dielectric strength is the ability of an insulating material to withstand electric stress without breaking down. It is dependent on not just the material, but the thickness, the rate at which voltage is applied, along with a number of other factors. Just like other measurements of strength, the dielectric strength of a given thermoplastic is affected by temperature, exposure to radiation and chemicals (including water and humidity), and time.

Selecting thermoplastic materials for insulation purposes is a complex endeavor, and well beyond the scope of this book. A list of suggested references is provided at the end of this chapter for readers seeking more detailed information.

5.9.2 Conductive Plastics

At the opposite end of the spectrum is the issue of electrical conductivity. While most thermoplastics are inherently nonconductive, there are a number of additives that can be used to modify the base resin and enhance the electrical conductivity. While these modified resins will never achieve the level of electrical conductivity of most metals, they can provide *some* conductivity, making them useful for applications requiring antistatic performance (to prevent dust buildup and/or static cling), control over static discharge, and sometimes even for electronic shielding.

The selection of the thermoplastic material itself is usually driven by structural requirements first, and then the type and amount of conductivity required will dictate what additives are to be used. The use of conductive plastics is a specialty field, but is growing rapidly. Often times, a specialty compounder can provide in-depth technical guidance.

5.10 Properties of Form

One of the unique characteristics of thermoplastic materials is that they can used in a wide variety of manufacturing processes. Each of these processes is unique, with advantages and disadvantages, along with a unique set of constraints.

In a similar manner, every thermoplastic material is also unique. Not just in terms of its measured physical properties, but also in how it responds to each manufacturing process. The ability of a material to be shaped and formed into a final product that satisfies (and hopefully delights) the needs of the end user is sometimes even more important than the properties of the material itself. Unfortunately, this aspect of thermoplastic material selection is often overlooked.

5.10.1 Size

Products come in all shapes and sizes, as do plastic parts. Selecting a thermoplastic material based on the part size may involve evaluating several properties, as well assessing whether a material can be used in a specific manufacturing process.

At one end of the scale is the question, *How big can we make the part?* This is not only a question of part volume, but for many processes, there is a related question, *How thick can it be?*

At first glance, one would think that the maximum size of a plastic part is only limited by the size of the processing equipment being used. If you want bigger parts, you just get bigger machines. However, every process has practical limits. One of the responsibilities of a good part supplier is to understand these limits. While performance is always important, quite often the selection a thermoplastic material for use in very large parts is based on the experience a supplier has in working with that material.

One general guideline is to select materials that have good thermal stability at the processing temperatures involved. Since you have large parts, you will have a large volume of material, and the cycle times will be longer. So, the material will probably be at elevated temperature for a longer period of time than if you were making smaller parts (Figure 5.20).

In terms of how thick one can make a plastic part, it is highly dependent on the manufacturing processes. Parts made via the structural foam process can be significantly thicker than parts made via injection molding or rotational molding. But even with injection molding, it is possible to mold parts that are ½″–¾″ thick (12–18 mm).

Figure 5.20 Herman Miller Equa chair shell, injection molded in one piece from 30% glass-reinforced PET.

As a general rule, it is often easier to injection mold very thick parts using amorphous resins. This is not because of fill, but because of differential shrinkage. With semicrystalline materials in thick cross-sections, the rate of crystallization and the total amount of crystallization can vary significantly from skin to core. As a result, the total amount of mold shrinkage can vary through the part. This can lead to distortions (warping and/or sink marks).

At the opposite end of the scale the question becomes, *How small of a part can we make?* Also, *How thin can it be?* It is possible to injection mold very small parts, sometimes as small as the head of a pin. Known as micromolding, material selection for this technology is highly specialized. References are provided at the end of this chapter for readers interested in this technology.

In terms of how thin one can make a plastic part, the question usually involves ratios, as in how thick the part is when compared to how long and wide the part is. In injection molding applications, we are often concerned with the minimum wall thickness of part. This wall thickness is a limiting factor in the fill of the cavity during injection. In other processes, the limiting factor in lower thicknesses is structural integrity, both during processing and in the final part.

In the Equa chair shell shown earlier, the ratio of part thickness to part length is not unusual. Part fill typically only becomes a problem when

Figure 5.21 Micromolding.

the ratio gets very small—either because the part is very thin, or the part is very long. One useful property in evaluating this is spiral flow data, which involves injecting the resin into a cavity in the shape of a spiral. The length of the amount of material that will flow before cooling, along with the overall volume of material injected, is an excellent indicator of how well the material flows. This property is much more useful than Melt Flow Index (MFI), which is a popular (and often inaccurate) way of measuring resin viscosity.

In general, materials with low viscosity have a high MFI. Often, resins are specifically formulated for high flow. These version are frequently designated HF (for high flow). However, in molding very thin parts, there is a practical limit, even with a HF resin. A good part supplier will understand these limits (Figure 5.21).

One general guideline is that semicrystalline materials can typically be used in thinner wall thicknesses than amorphous materials. Since they have a distinct melting point, they easily transform into a low viscosity liquid for the injection phase, and then rapidly solidify in the mold.

5.10.2 Shape

The performance of many products is based on their overall shape, not just in terms of appearance, but in terms of function as well. The shape and form of the plastic parts in that product play an important role. While some shapes are a function of the processing technology used, such as a blow molded beverage container, sometimes shapes are based on the unique characteristics of a given material. However, this information is rarely captured in material data sheets.

As an example, with many processes it is a standard practice to maintain a uniform wall thickness. There are many reasons for this, including a desire to have uniform shrinkage over the entire part. However, there are some processes, such as structural foam and gas-assist injection molding, that allow for high variations in the wall thickness of the final part. This capability of molding both thick and thin sections in the same part can provide performance advantages in regards to shape. There are also some thermoplastic materials that defy convention and can be injection molded with both thick and thin sections in the same part, for example, some of the polyester block copolymer elastomers (known by the trade names Hytrel® and Lomod®).

Another aspect of shape involves tolerances, specifically dimensional tolerances on the final shape. Fit and function are almost always dependent on dimensional tolerances, and controlling them in the final part can be an important criteria for performance. Quite often the part supplier is responsible for dimensional tolerances, however, part design and material selection play a critical role.

Dimensional tolerances for plastic parts include not only flatness and straightness, but dimensions on features of size and positional tolerances as well. In order to achieve high precision, it is common practice to utilize low-shrinkage materials (amorphous resins). The line of thinking is that with less shrinkage, there will be less variation. There is some validity to this. There are others that argue dimensional variation in the parts is due to variation in the manufacturing process itself, and with proper process control the dimensional variations can be minimized. There is some validity to this argument as well.

As a general guideline, it always makes sense to select a material that is process friendly, that is, one that allows for less than perfect processing conditions. This may mean using an amorphous material instead of semicrystalline material, or a material that is a blend of both. It may mean using a mineral-filled material instead of glass fiber-reinforced material (in general, mineral-filled materials shrink more evenly, which can help reduce warpage and other dimensional variations).

5.10.3 Appearance

Quite often, the appearance of a plastic part is a critical performance factor. While this often involves color, it also involves texture and gloss.

When we think of the texture of a plastic part, we often think of the texture that was on the surface of the mold, which has been transferred to the surface of the part. We often forget that the textured surfaces in the part are NOT a perfect copy of the texture that was in the mold. There will be surface imperfections, minor deviations here and there, etc. Even if the mold was polished to the highest standards for smoothness, the molded plastic part will NOT have that level of smoothness. Furthermore, I would postulate that every thermoplastic material will have its own unique signature in how it replicates the mold surface. I think of this as the material texture. Unlike metal fabrication, which often involves secondary finishing processes, thermoplastic materials are rarely buffed and polished and honed. So the surface texture on the final product is typically an "as fabricated" texture, and it is dependent on the material as much as the manufacturing process. As far as I know there is no published data on this, and very few people are even concerned with it.

On the other hand, in many applications, the gloss level of the material is an important parameter and materials are often screened for gloss. Some materials, like ABS and polycarbonate, just seem to have an intrinsically high gloss level, and they come out of the mold with very high gloss, looking shiny and bright. Other materials, like polypropylene, seem to have a lower gloss level, more like eggshell. They come out of the mold looking a bit flat. However, unlike the paint industry, which has measurement data on gloss levels every which way can you can think of, resin suppliers rarely provide information on the gloss level of thermoplastics. This kind of information is loosely held, mostly as a matter of tribal knowledge.

Then there is the topic of color. Color is a complex subject, and well beyond the scope of this book. However, at a basic level, we need to understand that the appearance of an object involves not only the color of the object (the wavelengths of light that are being reflected), but the gloss level and texture of the surface that is reflecting the light. Anyone who has ever held a textured plastic color chip can tell you that the appearance changes as the texture changes over the object's surface.

Every thermoplastic material has its own innate color. Some are clear, some are a milky white, others are brown, some are even black. (A thermoplastic material in its innate color is referred to as natural, regardless of the exact color.) Furthermore, every thermoplastic material responds to pigments in a different way. These pigments—whether they be dyes, powders, flakes—are what determine the final color of the fabricated part. However, how the material responds to the pigment is a critical aspect of the overall appearance. Is the color rich and vibrant? Or is it dull and muted? Is it smooth and glossy? Or rough and eggshell?

Selecting a thermoplastic material for optimal appearance should include considerations for not only color, but gloss and texture as well.

Figure 5.22 Material samples showing some standard colors.

Unfortunately, this type of information is rarely contained in property data sheets or resin brochures. Instead, it is subculture all its own, with a language and jargon that can make your head spin. Those interested in this area are encouraged to investigate the resources listed at the end of this chapter (Figure 5.22).

5.11 Some Final Guidelines

I have been working with thermoplastic materials for over 30 years now. Throughout my career I have been complaining that most people go about selecting thermoplastic materials for performance the wrong way (and I tried to cover some of those wrong ways in this chapter).

When I started writing this chapter, I thought it would provide me an opportunity to set the record straight, and tell the whole world, *Here is how it should be done.* I was going to create a flow chart, a decision matrix, and add some interesting stories on combining technical data, real-life experience, and touchy-feely stuff into a magic elixir. This elixir would provide a fool-proof methodology for material selection, a method that would work every time, for any application, no matter what. Sadly, I have not found the magic elixir.

The reality is that material selection is a complex process [6]. It is not like ordering dinner. *And for you, sir?* “I'll have the generic prime nylon, type 6 please, natural color, with just a touch of glass reinforcement.” *And how much toughness would you like with your nylon?* “Standard toughness is fine, thank you.” (Additives always give me a headache.)

The material selection process is kind of like playing a pin ball machine. You start flipping through the process, adding up the points, when all of a sudden the warning bells go off, lights start flashing and jinga-jinga-jinga-jinga, the next thing you know you've dropped the ball, and have to start all over.

Fortunately, using the information you have gained in this chapter, you can work through this process with knowledge and confidence. There are a few tools that I would recommend you utilize.

5.11.1 Conceptual Tools

On a conceptual level, approach this process not as a singular activity, but as a collective effort. While the design team often has the responsibility for material specification, the sourcing team plays a major role as well, which is not just in negotiating supply contracts with material suppliers and/or distributors, but in managing the overall logistics of the supply chain as well. One could specify the most perfect thermoplastic material in the world, but it will not improve the performance of your product one iota if that material cannot be sourced.

The manufacturing team also has an important role. This includes the tool makers, the molder, even the people on the manufacturing floor. They are the ones who are going to be working with the material, helping to convert it from a bag of plastic resin into a functional, viable product. They will often have first-hand experience with the materials and will have knowledge and insights on all kinds of things that cannot be found on property data sheets.

In your process of material selection, do everything you can to utilize the collective knowledge and experience of your team. This can be a formal or informal process, but it should involve face-to-face conversation with the members of your team. We live in a digital age, where data and information always seems to be at our fingertips, if only we know the right terms to use in a search engine. And while databases and online resources are great, nothing beats talking through the issues with your team.

Finally, use your imagination. As we have discussed throughout this book, thermoplastics are unique materials, with unique properties, and unique behaviors. Humans have been working with metals for hundreds of years, yet we have been working with plastics for less than a century. If we are to use them effectively, we need to use our imagination.

> I am enough of the artist to draw freely upon my imagination. Imagination is more important than knowledge. Knowledge is limited. Imagination encircles the world.
>
> **—Albert Einstein [7].**

5.11.2 Mathematical Tools

There are a number of mathematical tools that are used in the world of manufacturing. Statistical Process Control is used to monitor and control the process parameters that are used to manufacture parts. Tolerance Analyses are used to analyze and predict fit and function of final assemblies. Pareto Analysis techniques are used to assess the contribution of various factors in problem situations. Design of Experiments techniques are used to quantify the variables in a given process or application.

Most of these techniques are quite rigorous, and the mathematics are precise and exact. Most of them require measurement data that is based on manufactured parts. In other words, while you can discuss them in concept, to utilize the techniques you have to have actual parts.

In the world of material selection, ideally we want to select a material *before* any parts are made. In this situation we will not have any measurement data, and the mathematical tools discussed above are not applicable. While there is published data on measured properties of materials—lots of published data—there are very few mathematical tools available to evaluate this data in a comprehensive manner. One can compare the tensile strength data of different materials, or the flexural modulus, or the heat deflection temperature (HDT); it is difficult to compare all of the available data on material candidates and be certain you are making an optimal selection. However, there are mathematical tools that can help guide this process.

In the field of failure analysis, there is a methodology known as Failure Mode and Effects Analysis [8] (FMEA). FMEA involves a systematic approach to failure analysis, where individual components, subsystems, and complete systems are evaluated for possible causes of failure. The effects of each failure are then assessed and assigned a numerical value for severity. The possible causes are assigned a probability of occurrence (what percent of the time they might occur), as well as a detection rate (how often they will be detected before failure). The severity value is multiplied by the probability to give a rating of criticality. Items with a high level of severity and a high chance of probability are the most critical.

The criticality is then multiplied by the detection value to give a Risk Priority Number (RPN). The numerical value for detection is inverse to the detection rate (a detection rate of 100% has a numerical value of zero, while a detection rate of 0% has the highest numerical value). The failure modes are then ranked basked on RPN. Additional information can then be evaluated based on whether root causes are to be evaluated, what mitigating efforts should be made, etc. While FMEA primarily utilizes qualitative assessments, it provides a robust means for quantitative analysis of complex systems.

In a similar vein, I would encourage those engaged in material selection to formally document their selection process using a Material Properties Effects Analysis (MPEA). MPEA involves a systemized approach to material selection, where materials are carefully evaluated for their effect on the system. However, instead of evaluating the effect of failure, the process is used to evaluate the effect of specific material properties. The intent is to determine the critical material properties of the materials that are used in the system.

In an MPEA, we start with a list of possible properties that will be important in the end-use application. This might include tensile strength of the material in component A and the impact toughness of the material in component B. This list can be quite lengthy, depending on the complexity of the system. For each we assign an initial importance to that number, from 1 to 100. (The assumption is that we know exactly how important that property is. We will come back to this.) From there, we itemize factors that could affect that specific material property. These could be processing factors, environmental factors, etc. We then assign a probability of occurrence for that factor. The occurrence is then multiplied by the importance to give a numerical value of criticality.

From here we then begin to make subjective assessments of the factor. For instance, the effects of short-term exposure to heat are often fully reversible. The material temporarily loses strength and stiffness but will regain them once the heat is removed. It does not affect the performance as long as we are not using the part during that exposure. This subjective assessment is assigned a value and is multiplied by the criticality to give an overall assessment. Notes and comments are made to further evaluate the factor.

Often times, we may find that our assumptions about materials and the relative importance of a given property are not based on facts. As an example, we may say tensile strength is absolutely the most important property, and we assign it an importance of 100. We also intend to specify "No Regrind Allowed," because our application is so demanding. However, after performing an MPEA, we realize that a simple solution is to increase the cross sectional area of the structure.

Just like FMEA, MPEA utilizes a number of qualitative assessments, and the overall quality of the process depends on the accuracy and consistency of these assessments. Unlike FMEA, MPEA also allows for quantitative input, based on real-world data. While MPEA is relatively new, when properly applied it provides a robust means for the quantitative analysis of material property requirements in complex systems and can be a valuable tool for material selection (Table 5.3).

Table 5.3 Material Properties Effects Analysis

Property/ Importance	Factors				Assessment			Comments	
	Item	Effect	Probability of Occurrence	Criticality	Reversible/ Recoverable	RR Value	Overall Importance	Net Effect	Possible Mitigating Efforts
Tensile strength									
100	Improper drying	Loss of strength	2%	2	10%	0.90	1.8	Brittle failure	Increase cross sectional area; implement process controls
100	Chemical attack	Loss of strength	100%	100	0%	1.00	100.0	Softening, ductile failure	Change material
100	Heat exposure (ST)	Lowered strength	10%	10	100%	0.01	0.1	Temporary loss of strength	Investigate further
100	Heat exposure (LT)	Loss of strength	20%	20	0%	1.00	20.0	Permanent loss of strength	Change material

Continued

Table 5.3 Material Properties Effects Analysis—cont'd

100	Use of re-grind	Lowered strength	100%	100	0%	1.00	100.0	Lowered strength	Increase cross sec-tional area
Toughness (single impact)									
50	Improper drying	Loss of toughness	2%	1	10%	0.90	0.9	Brittle failure	Investigate further
50	Heat expo-sure (LT)	Loss of toughness	20%	10	0%	1.00	10.0	Brittle failure	Change material
Toughness (repeated impact)									
80	Heat expo-sure (LT)	Loss of toughness	20%	16	0%	1.00	16.0	Brittle failure	Change material
80	Use of re-grind	Lowered toughness	100%	80	0%	1.00	80.0	Long-term failure	Investigate further

5.11.3 Determining Critical Material Properties

One of the major challenges in thermoplastic material selection is in determining which material properties are most important. As stated earlier, in most applications, it is a combination of properties which, when integrated together in a specific design, result in the desired performance. Most plastic parts perform multiple functions as well. It is unusual for a plastic part to perform a single function, such as acting only as a stiffening brace. If this were the case, we would select a material with adequate strength and stiffness and be done with it. However, more often than not a plastic part will not only act as a stiffening brace, but it will also provide a mounting interface to another part, a handle to grab onto, along with a hard stop for a mechanism to engage and disengage. So now we have multiple requirements, each with different evaluation criteria, and each with different demands on the material itself. How do we determine the critical material properties? While an MPEA can provide guidance in this regard, one of the most effective means of answering this question is to evaluate the performance of materials in actual real-life applications.

There is an old adage in the world of financial investment: "Past performance is no guarantee of future results." In the United States, the Securities and Exchanges Commission has even mandated that this statement be included in any marketing document that contains financial performance data. However, in regards to thermoplastic materials, past performance of a real-life product is an excellent indicator of future results. Whenever possible, look at commercial applications of thermoplastic materials and analyze them from a material perspective.

In addition to asking basic performance questions (Does it work? Does it last? Is the product reliable and safe?), investigate the performance limits. If there have been failures, what are the failure modes? Were they due to an unexpected loading condition? A loss of properties due to environmental factors (e.g., chemical attack)? Or due to abuse? These questions need to account for the performance category of the product. For example, a power tool for the industrial/professional market is expected to have significantly higher performance than a power tool for the consumer market. But at the end of this process, you should have a very good indication of the critical properties required in your application.

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