

Engineering Materials

Introduction

As we begin the 21st century, advances in materials research and technology offer great promise. Materials Science forms the foundation for engineers in product development because the structures, components, and devices that engineers design are limited by the properties of the materials that are available and the techniques that can be used for fabrication.

Selecting the "best" material is usually a difficult task, requiring tradeoffs between different material properties including:

1. **General Physical Properties**
2. **Mechanical Properties**
3. **Thermal Properties**

General Physical Properties

Density

Density is one of the most fundamental physical properties of any material. It is defined as the ratio of an objects mass to its volume. Because most designs are limited by either size and or weight density is an important consideration in many calculations.

Density is a function of the mass of the atoms making up the materials and the distance between them. Massive, closely packed atoms characterize high density materials such as Tungsten or Neptunium. In contrast light, relatively distant atoms compose low density materials such as Beryllium or Aluminum. Density on a macroscopic level is also a function of the microscopic structure of a material. A relatively dense material may be capable of forming a cellular structure such as a foam which can be nearly as strong and much less dense than the bulk material. Composites including natural constituents such as wood and bone, for example, generally rely on microscopic structure to achieve densities far lower than common monolithic materials.

Availability/Manufacturability

Availability and manufacturability requirements are often unseen limiting factors in materials selection. The importance of a material being available is obvious. Materials which are not available cannot be used. The importance of processibility is not always so obvious.

Any other desirable qualities are useless if a material cannot be processed into the shape required to perform its function. Most engineering materials in use today have well known substitutes which would perform better and often at lower cost but processes for forming, cutting, machining, joining, etc. are not available or commercially viable. There is often a period of time after a new material is introduced during which its application is severely limited while processing techniques are developed which facilitate its use.

Cost

A materials cost is also generally a limiting factor. While cost is universally recognized and perhaps the easiest of all properties to understand there are specific cost considerations for materials selection. Just as materials and their processing go hand in hand so do material costs and processing costs. Understanding the entire processing sequence is critical to accurately evaluating the true cost of a material.

Appearance

Because the appearance of many mechanical components seems fairly trivial it is also easy to overlook its importance in the marketing and commercial success of a product.

Mechanical Properties

The mechanical properties of a material describe how it will react to physical forces. Mechanical properties occur as a result of the physical properties inherent to each material, and are determined through a series of standardized mechanical tests.

Strength

Strength has several definitions depending on the material type and application. Before choosing a material based on its published or measured strength it is important to understand the manner in which strength is defined and how it is measured. When designing for strength, material class and mode of loading are important considerations.

For metals the most common measure of strength is the yield strength. For most polymers it is more convenient to measure the failure strength, the stress at the point where the stress strain curve becomes obviously non-linear. Strength, for ceramics however, is more difficult to define. Failure in ceramics is highly dependent on the mode of loading. The typical failure strength in compression is fifteen times the failure strength in tension. The more common reported value is the compressive failure strength.

Elastic limit

The elastic limit is the highest stress at which all deformation strains are fully recoverable. For most materials and applications this can be considered the practical limit to the maximum stress a component can withstand and still function as designed. Beyond the elastic limit permanent strains are likely to deform the material to the point where its function is impaired.

Proportional limit

The proportional limit is the highest stress at which stress is linearly proportional to strain. This is the same as the elastic limit for most materials. Some materials may show a slight deviation from proportionality while still under recoverable strain. In these cases the proportional limit is preferred as a maximum stress level because deformation becomes less predictable above it.

Yield Strength

The yield strength is the minimum stress which produces permanent plastic deformation. This is perhaps the most common material property reported for structural materials because of the ease and relative accuracy of its measurement. The yield strength is usually defined at a specific amount of plastic strain, or offset, which may vary by material and or specification. The offset is the amount that the stress-strain curve deviates from the linear elastic line. The most common offset for structural metals is 0.2%.

Ultimate Tensile Strength

The ultimate tensile strength is an engineering value calculated by dividing the maximum load on a material experienced during a tensile test by the initial cross section of the test sample. When viewed in light of the other tensile test data the ultimate tensile strength helps to provide a good indication of a material's toughness but is not by itself a useful design limit. Conversely this can be construed as the minimum stress that is necessary to ensure the failure of a material.

True Fracture Strength

The true fracture strength is the load at fracture divided by the cross sectional area of the sample. Like the ultimate tensile strength the true fracture strength can help an engineer to predict the behavior of the material but is not itself a practical strength limit. Because the tensile test seeks to standardize variables such as specimen geometry, strain rate and uniformity of stress it can be considered a kind of best case scenario of failure.

Ductility

Ductility is a measure of how much deformation or strain a material can withstand before breaking. The most common measure of ductility is the percentage of change in length of a tensile sample after breaking. This is generally reported as % El or percent elongation. The R.A. or reduction of area of the sample also gives some indication of ductility.

Toughness

Toughness describes a material's resistance to fracture. It is often expressed in terms of the amount of energy a material can absorb before fracture. Tough materials can absorb a considerable amount of energy before fracture while brittle materials absorb very little. Neither strong materials such as glass or very ductile materials such as taffy can absorb large amounts of energy before failure. Toughness is not a single property but rather a combination of strength and ductility.

The toughness of a material can be related to the total area under its stress-strain curve. A comparison of the relative magnitudes of the yield strength, ultimate tensile strength and percent elongation of different material will give a good indication of their relative toughness. Materials with high yield strength and high ductility have high toughness. Integrated stress-strain data is not readily available for most materials so other test methods have been devised to help quantify toughness. The most common test for toughness is the Charpy impact test.

In crystalline materials the toughness is strongly dependent on crystal structure. Face centered cubic materials are typically ductile while hexagonal close packed materials tend to be brittle. Body centered cubic materials often display dramatic variation in the mode of failure with temperature. In many materials the toughness is temperature dependent. Generally materials are more brittle at lower temperatures and more ductile at higher temperatures.

The temperature at which the transition takes place is known as the DBTT, or ductile to brittle transition temperature. The DBTT is measured by performing a series of Charpy impact tests at various temperatures to determine the ranges of brittle and ductile behavior. Use of alloys below their transition temperature is avoided due to the risk of catastrophic failure.

Fatigue ratio

The dimensionless fatigue ratio f is the ratio of the stress required to cause failure after a specific number of cycles to the yield stress of a material. Fatigue tests are generally run through 10^7 or 10^8 cycles. A high fatigue ratio indicates materials which are more susceptible to crack growth during cyclic loading.

Loss coefficient

The loss coefficient is an other important material parameter in cyclic loading. It is the fraction of mechanical energy lost in a stress strain cycle. The loss coefficient for each material is a function of the frequency of the cycle. A high loss coefficient can be desirable for damping vibrations while a low loss coefficient transmits energy more efficiently. The loss coefficient is also an important factor in resisting fatigue failure. If the loss coefficient is too high, cyclic loading will dissipate energy into the material leading to fatigue failure.

Thermal Properties

Thermal conductivity

The thermal conductivity is the rate of heat transfer through a material in steady state. It is not easily measured, especially for materials with low conductivity but reliable data is readily available for most common materials.

Thermal diffusivity

The thermal diffusivity is a measure of the transient heat flow through a material.

Specific heat

The specific heat is a measure of the amount of energy required to change the temperature of a given mass of material. Specific heat is measured by calorimetry techniques and is usually reported both as C_V , the specific heat measured at constant pressure, or C_P , the specific heat measured at constant pressure.

Melting point

The melting point is the temperature at which a material goes from the solid to the liquid state at one atmosphere. The melting temperature is not usually a design criteria but it offers important clues to other material properties.

Glass transition temp

The glass transition temperature, or T_g is an important property of polymers. The glass transition temperature is a temperature range which marks a change in mechanical behavior. Above the glass transition temperature a polymer will behave like a ductile solid or highly viscous liquid. Below T_g the material will behave as a brittle solid. Depending on the desired properties materials may be used both above and below their glass transition temperature.

Thermal expansion coefficient

The thermal expansion coefficient is the amount a material will change in dimension with a change in temperature. It is the amount of strain due to thermal expansion per degree Kelvin expressed in units of K^{-1} . For isotropic materials α is the same in all directions, anisotropic materials have separate α 's reported for each direction which is different.

Thermal shock resistance

Thermal shock resistance is a measure of how large a change in temperature a material can withstand without damage. Thermal shock resistance is very important to most high temperature designs. Measurements of thermal shock resistance are highly subjective because it is extremely process dependent. Thermal shock resistance is a complicated function of heat transfer, geometry and material properties. The temperature range and the shape of the part play a key role in the material's ability to withstand thermal shock. Tests must be carefully designed to mimic anticipated service conditions to accurately assess the thermal shock resistance of a material.

Creep resistance

Creep is slow, temperature aided, time dependent deformation. Creep is typically a factor in materials above one third of their absolute melting temperature or two thirds of their glass transition temperature. Creep resistance is an important material property in high temperature design, but it is difficult to quantify with a single value. Creep response is a function of many material and external variables, including stress and temperature. Often other environmental factors such as oxidation or corrosion play a role in the fracture process.

Creep is plotted as strain vs. time. A typical creep curve shows three basic regimes. During stage I, the primary or transient stage, the curve begins at the initial strain, with a relatively high slope or strain rate which decreased throughout stage I until a steady state is reached. Stage II, the steady state stage, is generally the longest stage and represents most of the response. The strain rate again begins to increase in stage III and rupture at t_R generally follows quickly.

Different applications call for different creep responses. In situations where long life is desired minimum creep rate is the most important material consideration. Testing through stage II should be sufficient for determining minimum creep rate. It is not necessary to proceed all the way to rupture. For this type of test the longer the test the more accurate the creep rate will be. Unfortunately practicality limits most creep tests to times shorter than would be desirable for high accuracy.

For short lived applications such as rocket nozzles the time to failure may be the only consideration. The main issue is whether or not the component fails, not the amount of deformation it may undergo. For this application creep tests may be run to completion but without recording any data but the time to rupture. In this case temperatures may be elevated above expected conditions to provide a margin of safety.

The main objective of a creep test is to study the effects of temperature and stress on the minimum creep rate and the time to rupture. Creep testing is usually run by placing a sample under a constant load at a fixed temperature. The data provided from a complete creep test at a specific temperature, T , and stress includes three creep constants: the dimensionless creep exponent, n , the activation energy Q , and A , a kinetic factor.