Module 1

BASIC MATERIAL PROPERTIES AND HOW THEY CAN BE ALTERED

OBJECTIVES:

After completing this module you will be able to:

1.1 Explain the following material properties:

Page 2 ⇔ a) strength,

Page 6 ⇔ b) ductility,

Page 7 ⇔ c) toughness,

Page 8 ⇔ d) hardness.

Pages 4, 5 ⇔ 1.2 State what happens to a material when the yield stress (or elastic limit) and the ultimate stress are exceeded.

1.3 State how the strength, ductility and hardness of metal components may be affected by:

Page 11 ⇔ a) plastic (or permanent) deformation,

Page 11 ⇔ b) alloying,

Page 12 ⇔ c) exposure to high operating temperatures.

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INSTRUCTIONAL TEXT

INTRODUCTION

Why learn about material properties, their relationships to each other, and some of the conditions which alter these properties? At some time in your career with Ontario Hydro, you will read and use some, or possibly all, of the following references:

a) Ontario Hydro Operating Manuals,

b) Ontario Hydro Training Manuals,

c) Ontario Hydro Design Manuals.

In these manuals, materials, or the reasons for selection of specific materials, for a given application may be described using basic properties such as yield and ultimate tensile strengths, hardness, ductility and toughness. Understanding the basic material properties leads to a better understanding and application of these important references. In addition, a basic knowledge of how metals behave under the application of stress, and how certain operating conditions may alter their mechanical properties will enable you to understand their influence on station operations and possible component failure.

Let us consider strength first. What is strength? How do we determine whether or not a material is strong and suitable for the proposed application? These questions are best answered by looking briefly at the science of strength of materials.

Strength And Its Relationship To Stress And Strain

Strength of materials basically considers the relationship between the external loads applied to a material and the resulting deformation or change in material dimensions. In designing structures and machines, it is important to consider these factors, in order that the material selected will have adequate strength to resist applied loads or forces and retain its original shape. These forces may be simply the effect of gravity on the structure, or may be produced by such effects as fluid pressure, impact of moving parts or transmission of mechanical power.

A simple example to illustrate what may happen if a material of insufficient strength is selected could occur with the return spring on the carburetor–throttle linkage of your car. This spring returns the engine speed to idling on releasing the pressure on the throttle cable. If this return spring had insufficient strength, then the first time engine speed was increased by using the throttle cable, we would stretch the spring permanently. However, with the spring stretched there is no return action and the engine speed will not slow but continue at the accelerated throttle setting. If the spring was made of very weak material, it would probably break when we tried to increase engine speed.

Obj. 1.1 a) ⇔

Strength can be considered a measure of the external load required to deform a material. However, you will appreciate that the load to deform a small component will be less than the load to deform a larger component of the same material. Load is therefore not a suitable term to describe strength.

NOTES & REFERENCES

Instead, we use Force(Load)/Unit Area, called **stress**, which is constant (until deformation occurs) for a given material regardless of size of the component part. Stress is, therefore, a measure of the resistance of a material to external forces which may cause deformation.

Basically, most loads or stresses can be classified as compressive or tensile. Compressive stress tends to shorten or compress a material. Tensile stress tends to lengthen or stretch a material. Both of these stresses act at right angles to the area under consideration. There is also a third type of stress (which we won't consider further at this point) known as shear which acts in the plane of the area under consideration. Refer to Figure 1.1.

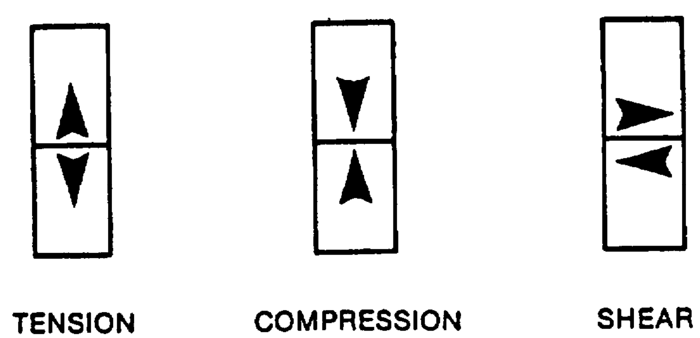

Figure 1.1: Types of Stress

As we have seen, materials subjected to external loads or stresses will deform. This deformation may or may not be permanent. Up to a limiting load, a body will be able to recover its original dimensions on removal of the load. This is known as **elastic behaviour**, and does not lead to permanent deformation. If the limiting load is exceeded then the body will experience some permanent deformation on removal of the load. This is known as **plastic behaviour** and the limiting load is called the **elastic limit**.

The measure of deformation (elastic or plastic) is known as **strain**. For a body subjected to tensile stress, strain would be the increase in length divided by the original length.

Now, let us consider the relationship between stress and strain for a material under tensile loading. There are two distinct stress–strain curves which may result and they are illustrated in Figure 1.2. These curves are sometimes called engineering stress–strain curves and are produced from a tensile test of specimens of different materials.

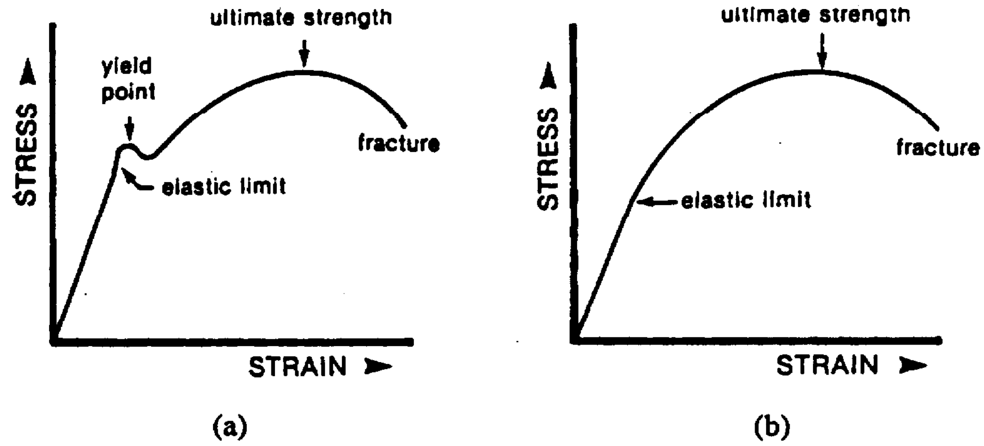

Figure 1.2: Stress–Strain Curves

Obj. 1.2 ⇔

From the stress–strain curves in Figure 1.2 we can see that the **ultimate tensile strength** is the maximum load a material can withstand before fracture. If the material is **stressed beyond its ultimate stress, failure will occur**. However, in most applications, we consider a component failed if there is *any* plastic deformation. Ultimate tensile strength does not represent a valid design criterion, but is useful as a material specification or quality control measure. Since plastic deformation constitutes failure, then exceeding the elastic limit or yielding of the material is undesirable.

Figure 1.2 (a) typically represents the behaviour of mild steel. We note a "yield point" where the stress suddenly drops before rising and this occurs very close to the elastic limit. The stress at this point is the maximum load a material can withstand before yielding or deforming plastically and is called the **yield strength.**

Figure 1.2 (b) represents the behaviour of most metals under tension. There is no obvious yield point. How do we define yield strength in this case? It is difficult to determine the elastic limit accurately, so an offset method illustrated in Figure 1.3 is used to define yield strength.

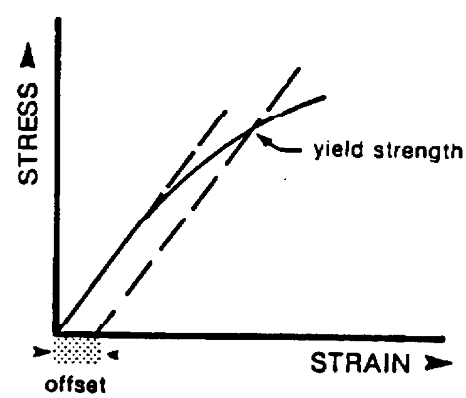

Figure 1.3: Offset Method of Yield Strength Determination

The offset represents a small amount of permanent strain, usually 0.1 or 0.2 percent of the original length. The yield strength (more correctly designated proof stress here) is the load or stress required to obtain that offset.

Yield strength can be considered a valid design criterion, provided we use a maximum design load less than the material's yield strength, ie, incorporate a *factor of safety*. Normally, we design to approximately one third of the yield strength.

Obj. 1.2 ⇔

To conclude this discussion, let us consider the effect of plastic deformation on yield strength. Refer to the stress strain curve in Figure 1.4. If we stress a material beyond the yield point or elastic limit and release that stress, what happens? Stress is now zero, and the curve returns to the strain axis on a line parallel to the original line of elastic behaviour (similar to Figure 1.3, where we illustrated the principle of offset). There is recovery of the elastic deformation, but because we exceeded the elastic limit, there is residual permanent deformation. If this material which has experienced yielding is re–stressed, we will have to exceed the previously applied stress to cause further yielding or plastic deformation. The material has a higher yield strength in this deformed state and, therefore, it appears that plastic deformation has made it stronger. We will return to this point later.

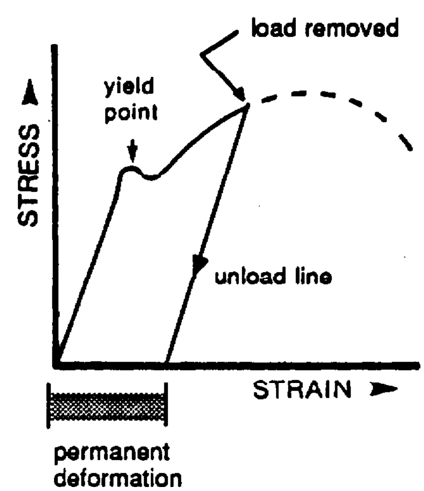

Figure 1.4: Permanent Deformation Due to Stressing Beyond Yield Point

The Relationship Between Ductility And Toughness

Besides strength, what other material properties determine how a component will behave under applied loads? Also, with respect to manufacturing components, how do we determine whether it is easy to shape or form the component?

Obj. 1.1 b) ⇔

The key required to answer these questions is the property known as **ductility**. Ductility is simply the ability of a material to deform plastically in tension (or shear) without fracture. The compression equivalent of ductility, ie, ability to deform plastically in compression, is known as **malleability**. Often ductility and malleability are used interchangeably, ductility generally substituting for malleability.

How do we measure ductility? There are no true quantitative measures for ductility. However, if we consider a stress–strain diagram, we can readily see a *representative* measurement for ductility.

In Figure 1.5, the region of plastic deformation in both curves is indicated by the marker arrows. It begins at the elastic limit and of course, ends when the material fractures, or ruptures. To measure the extent of this region, we use the unit strain at rupture (Change in Length/Original Length, ie, [Δ L/L]) or more commonly, **percent elongation** (Δ L/L x 100 %).

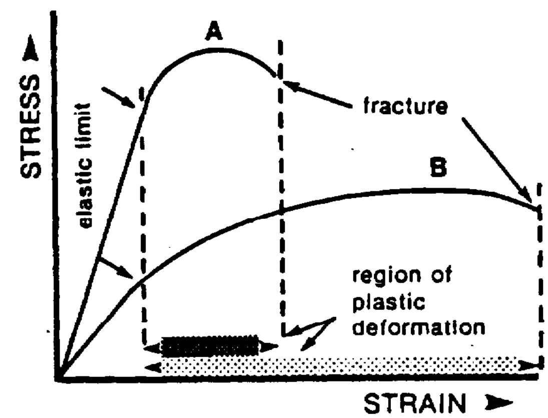

Figure 1.5: Plastic Deformation Regions

The amount of elastic strain (deformation) is included in percent elongation because it is small compared to total strain. A ductile metal has a large percent elongation and a material represented by curve "B" would be considered ductile. A material represented by curve "A" would be considered less ductile, or more brittle.

Deformation up to the ultimate strength, or maximum load, is uniform, ie, the material elongates uniformly along its length. Beyond the maximum load, a phenomenon known as "necking" occurs; elongation is no longer uniform.

"Necking" is localized deformation when a certain section of the material elongates more than the rest. During a tensile test of a metal, the onset of "necking" is indicated by a visible decrease in the cross–sectional area of the specimen at the point where fracture will occur.

How is this information used? As already noted, a ductile metal has a large percent elongation. We would expect a component of a ductile metal to take a considerable amount of local deformation without damage to the entire component. For predicting the ability to form or shape metals by rolling, forging, drawing, etc, percent elongation may be used.

Obj. 1.1 c) ⇔

Ductility also contributes to another material property called **toughness.** Toughness combines strength and ductility in a single measurable property. The specific property, **modulus of toughness** is actually a measure of the maximum energy a unit volume of material will absorb without fracture. It can be measured by an impact test or estimated from the engineering stress–strain curve. The impact test measures toughness under conditions of sudden loading and the presence of flaws such as notches or cracks which will concentrate stress at weak points.

The stress–strain curve measures toughness under gradually increasing load. To calculate the area under the curve we could approximate it by a rectangle and then multiply length by width. Effectively, we would be multiplying stress by strain which is Load/Unit Area x Δ L/L or (Work or Energy)/ Unit Volume.

These are the units of modulus of toughness and therefore we can consider the area under the stress–strain curve as a measure of toughness. With reference to Figure 1.6, we can see that the metal represented by curve "B" would be considered tough, whereas the metal represented by curve "A" would be somewhat brittle. Therefore, we can generally state that a ductile metal will be a tough metal. Brittleness indicates a lack of either ductility or toughness.

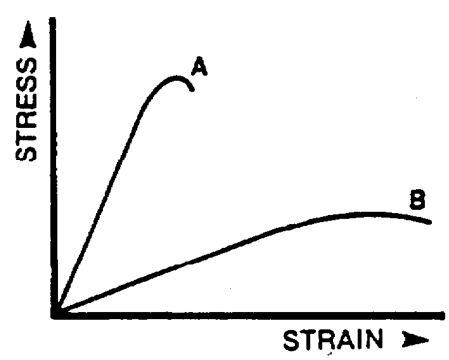

Figure 1.6: Stress–Strain Curves for Toughness Estimates

However, a word of caution is necessary. It is possible to have a material with high tensile strength and low ductility possessing comparable toughness to a material with low tensile strength and high ductility.

Hardness

Hardness is probably the most poorly defined material property because it means different things, depending on the background of the person involved. It may indicate resistance to abrasion, resistance to scratching, resistance to indentation or even resistance to shaping or plastic deformation. For a person concerned with materials testing, hardness will indicate resistance to indentation but, to a design engineer, it will indicate something about strength, ductility and heat treatment of the metal.

Obj. 1.1 d) ⇔

Many techniques have been developed for obtaining a quantitative measure of hardness and among the most popular are percentage wear and hardness number as determined by indentation tests. Percentage wear measures the quantity of material abraded or worn away from a surface under standard conditions and is used for materials such as brick, stone, or concrete where resistance to abrasion is important. **Hardness** in metals is invariably measured as the resistance to forcible penetration (plastic deformation) by an indentor under standard loads and controlled conditions. The hardness is generally quoted as a dimensionless number relative to the particular test method used.

There are a variety of test methods in common use; eg, Brinell, Knoop, Vickers and Rockwell. Tables are available correlating the hardness numbers from the different test methods where correlation is applicable (Table 1.1 illustrates this). In all scales, a high hardness number represents a hard metal.

Besides the correlation between different hardness numbers, there are also some correlations possible with other material properties. For example, for heat-treated plain carbon steels and medium alloy steels, the ultimate tensile strength (in psi) approximately equals the Brinell Hardness Number multiplied by 500. Generally, a high hardness will indicate a relatively high strength and low ductility in the material under consideration.

In industry, hardness tests on metals are used mainly as a check on the quality and uniformity of metals, especially during heat treatment operations. The tests can generally be applied to the finished product without significant damage. During analysis of failed components, a hardness test is a useful and quick check on the original quality of the component.

			Rockwell	
	Brinell	Vickers	R_B	R_C
Pure Lead	5	10		
Pure Aluminum (annealed)	16	21		
(cold worked)	44	49		
Pure Copper (annealed)	30	35		
Brass 70:30 (annealed)	75	80	35	
(cold worked)	200	210	93	
0.2% C Steel (annealed)	130		72	
Austenitic Stainless Steel				
18.8 (annealed)	162	170	85	
(cold worked)	370	391		40
0.8% C Steel (annealed)	324	342		35
0.6% C Steel (quenched)	767	880		70

Table 1.1: Hardness Numbers

SUMMARY OF THE KEY CONCEPTS

- The strength of a material is a measure of the external load required to deform the material.
- The yield strength, or elastic limit, of a material represents the maximum stress that can be withstood before undergoing permanent deformation. Stress beyond this point leads to plastic (permanent) deformation.
- The ultimate strength of a material is the highest stress that can be withstood before fracture occurs.
- Ductility is the ability of a material to deform plastically, under tensile (or shear) loading, without fracture.
- Toughness is the ability of a material to absorb energy under load prior to fracture. It is a measure of strength and ductility combined.
- Hardness, in metals, is a measure of the resistance to forcible penetration (plastic deformation) by a known indentor under controlled conditions.

NOTES & REFERENCES

CONDITIONS WHICH AFFECT MATERIAL PROPERTIES

So far, we have looked at a few of the more important material properties, with regard to what they mean, how they are measured, and how they are related. Now, we will consider how these properties are changed. They may be altered purposely to produce a component with the desired characteristics for the job, or they may be altered in error due to poor control of operating conditions. This latter situation often produces undesirable changes in properties leading to early component failure.

To understand how changes in mechanical properties are effected (whether purposely or accidentally) we must consider which factors determine a given materials properties. Is it just the chemical nature; is copper very ductile because it is copper, or steel strong and tough because it is steel? No, the common structural element influencing properties such as strength, ductility and toughness is crystal structure.

Metals are crystalline materials composed of a large number of crystals (ie, they are polycrystalline). The crystals may be all alike, in which case the metal is known as single phase, or may be of two different kinds in which case the metal is known as two phase. What does crystalline mean?

A crystalline solid has atoms packed into a regular geometric array which gives the most economical packing of atoms in a given space. The density of packing is limited by the repulsive forces between the atoms. Actually, a specific crystal structure is effectively a balance between the cohesive forces of bonding and these repulsive forces.

Most metals exist in one of three types of crystal structure representing different packing arrangements for atoms. This arrangement of atoms or crystalline lattice structure has a significant effect on the mechanical properties of metals. For example, one type of lattice is the body–centered cubic. Metals with this crystal structure (eg, steel) generally exhibit high strength and limited ductility. A second type of lattice is the face–centered cubic structure. Metals with this crystal structure (eg, copper) are generally lower in strength and higher in ductility than body centered cubic metals. The third lattice type, hexagonal close–packed, gives a more brittle nature to the metal than the face–centered cubic lattice, but without the strength generally found with the body–centered cubic lattice. An important hexagonal close–packed material for our purposes is zirconium.

Crystal structures are not ideal or perfect arrangements of atoms but, in reality, contain various defects or imperfections. These defects may be created when the crystal is forming, or may be created by the action of stress on the material. In either case, the defects disrupt the regularity of the crystal structure, and as such, influence the mechanical properties of the crystal.

NOTES & REFERENCES

Recall the discussion on strength. We noted that the yield strength of a material was raised by plastically deforming it. Permanent deformation destroys the normal regularity of the crystal structure and introduces large numbers of imperfections. These imperfections create internal stress in the crystal because the atoms have been dislocated from equilibrium, or more stable positions. The internal stress will, of course, oppose any external stress due to applied loads and, therefore, the level of external stress (or load) will have to increase to cause further deformation.

Obj. 1.3 a) ⇔

Plastic deformation increases the strength of a material. Our natural response to this phenomenon is that it is good. But, is it? What happens to ductility, toughness and hardness as strength increases? Hardness increases, ductility and toughness decrease and the material becomes more brittle. Although the material will be able to withstand higher applied loads, it will be much less flexible in its response to the applied load. Sudden failure of machine components without warning becomes a distinct possibility.

Alloying is a process used deliberately to change or improve the mechanical properties of metals. An **alloy** is a mixture of two or more metals. Most metals are soluble in one another in the liquid state and alloying generally involves melting of one or all the constituents before mixing. On cooling, the alloy melt may remain a solution or may separate into an intimate mechanical mixture of the constituent metals.

In a solid solution, the dissolved metal atoms may substitute for the regular metal atoms in the parent crystal lattice, or they may fit into sites between the regular metal atoms. In either case, there will be only one type of crystal present and the alloy will be single phase. Because the dissolved alloy atoms are a different size from the regular atoms (recall from Nuclear Theory that atomic size is a fundamental property of each element), a degree of irregularity is introduced into the crystal structure. Internal stresses are set up and, as in the case of plastic deformation, they oppose applied stress and effectively raise the strength of the alloy metal.

Where alloy solidification produces a mixture of the constituent metals, we will have a mixture of two or more different types of crystal. Since mechanical properties such as strength, ductility and hardness are directly dependent on crystal type, a two phase alloy (mixture of two crystal types) will have different material properties than either constituent metal. In fact, the formation of two phase alloys produces a greater strengthening effect than achieved through formation of single phase alloys.

Obj. 1.3 b) ⇔

Thus, alloying will increase the strength of a metal and, correspondingly, will increase hardness and decrease ductility.

NOTES & REFERENCES

Obj. 1.3 c) ⇔

Finally, let us consider the effect of temperature on mechanical properties. Most of us are familiar with the fact that as we heat a metal it expands and, if sufficient heat is added, the metal will melt. Crystallinity implies rigidity of structure and, therefore, liquids can not be crystalline because they conform to the shape of their containment vessel. As we apply heat to a metal, the crystal structure expands and becomes less rigid, ie, it is approaching a more fluid structure. Obviously, the more open nature of the crystal lattice at higher temperatures means it will deform more readily under applied stress. Therefore, metals operating at elevated temperatures will show increased ductility and lower strength and hardness than the same metal operating at room temperature or lower.

What is the significance to you, as an operator, of factors which change material properties? All the components in our nuclear stations have been designed to perform particular tasks. The material of the component will be supplied to given specifications conforming to the expected operating conditions. Strength, hardness, ductility as well as a host of other properties will be specified. We now realize these properties are not constant, but dependent on such variables as temperature and load, both of which can be operator influenced. Provided you operate equipment within the specified operating limits, the material will give the desired service. Going beyond specified operating limits, eg, pressure or temperature excursions, may lead to changes in material properties which are detrimental and limit service life.

SUMMARY OF THE KEY CONCEPTS

- Plastic deformation of a metal affects its mechanical properties by creating internal stresses in the crystal lattice which oppose externally applied stresses. This increases the strength and hardness of the material and decreases its ductility.
- The alloying of metals is used to increase strength and hardness but a decrease in ductility results.
- Subjecting a metal to an elevated operating temperature increases its ductility and decreases its strength and hardness.

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You can now work on **assignment questions 1 – 9.**

ASSIGNMENT

1. Define strength.
2. State what happens to a material when its yield stress is exceeded.
3. State what happens to a material when its ultimate stress is exceeded.
4. A material may be described as ductile or brittle. Explain what these terms mean.
5. We normally describe a ductile metal as tough. Define toughness, and explain how toughness is related to ductility and strength?
6. Explain hardness as it applies to metals, and state how strength and ductility are generally related to hardness.
7. State how strength, ductility and hardness are affected by plastic deformation.
8. State how strength, ductility and hardness are affected by alloying.
9. State how strength, ductility and hardness are affected by elevated temperature.

Before you move on to the next module, **review the objectives** and make sure that you can meet their requirements.

Original by: A. Wadham, ENTD

Revised by: P. Bird, WNTD

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