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Applied Physics

Lecture-9 & 10

Unit II-Mechanical Properties of solids

Topics to be discussed in this lecture:

- Material property
 - ✓ Hardness
 - ✓ Toughness
 - ✓ Strength
- Strengthening mechanisms

By analyzing the relationship between stress and strain, scientists and engineers have been able to predict how materials will react when subjected to forces at different levels. This has also allowed for the classification of materials based on their material properties, leading to qualifiers such as brittle, ductile, elasticity, hardness, toughness, and strength.

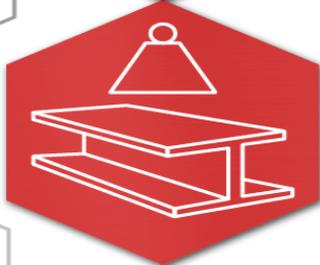
Previous lectures dealt with brittle and ductile materials, in this lecture we will come across Hardness, toughness and strength in detail.

The terms hardness, strength, and toughness are often used interchangeably. But in reality, they have three distinct definitions — at least, when it comes to metals. For example, a tough substance doesn't have to be hard or strong.

Here are the key differences.



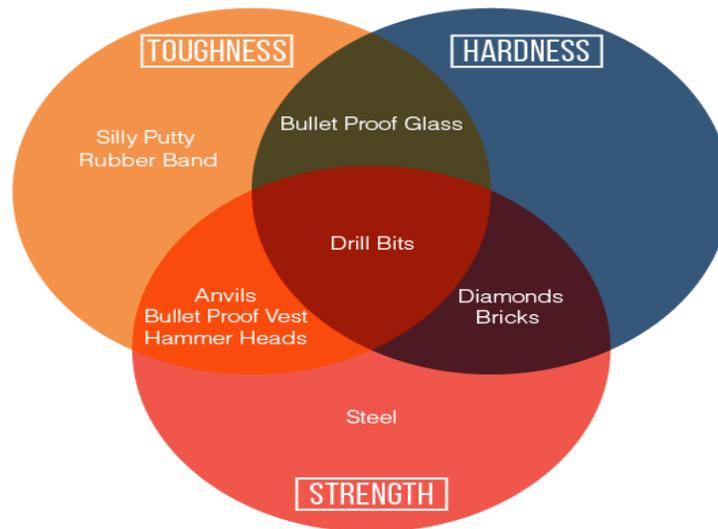
HARDNESS is how well a material holds together when friction is applied. Common hard substances include diamonds, drill bits, and grinding discs.



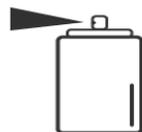
STRENGTH is how much force needs to be applied before the material deforms. Silly putty has low strength, but steel has high strength and is extremely difficult to pull apart.



TOUGHNESS is the ability of a material to resist breaking when force is applied. It takes a combination of strength and ductility, which is a material's ability to deform under physical stress, rather than fracturing.



ENHANCE MATERIALS



A metal that inherently has the strength and toughness of steel can be boosted by a ceramic coating, which would lend it the hardness of ceramic.



Infusing carbon into steel through carburization diffuses carbon into the edges, but allows the core to retain its original properties.

What is hardness?

Simply put, the hardness of a material is a measure of its resistance to localized deformation. In most cases, this deformation is brought about by abrasion (due to friction forces) or indentation (due to a constant lateral mechanical force). On a subatomic level, hardness is determined by the strength of intermolecular bonds, although there are also a couple of minor details that come into play.

The unique characteristic of hardness is elegantly displayed by diamond, a substance known to be one of the hardest in the planet. Due to the hardness of diamond, it is practically impervious to getting scratched. In the world of infrastructure, it is not rare to find diamond used in some important applications that require hardness. Diamond-tipped drill bits are incredibly common, whether it's for handheld drills or industrial-sized drills for drilling in solid rock.

However, hardness does not determine how a material will react to sudden application of a large amount of force. For instance, diamond can be easily shattered with a single smash from a sledgehammer, despite being one of the hardest materials. This ties right into the next material property – toughness.

What is toughness?

Toughness is a measure of the amount of force that a material can absorb without fracturing. Take note that the key word here is fracture, which constitutes a total failure

of the material. This means that a material can undergo elastic deformation, or a deformation that allows it to return to its original form, without fracturing.

The condition that allows a material to deform before fracturing means that ductile materials can also be considered tough. Therefore, the toughness of a material depends on both its strength (which we shall get to shortly) and its ductility.

To understand this in more practical terms, metals and foams are just about equal in terms of toughness. In terms of stress and strain, these two materials exhibit very different behaviors but have similar yield points. Metals can only withstand a very small amount of deformation before they fracture, but even getting it to deform will require a huge amount of force. On the other hand, foams deform with a minimal amount of compression force but will only fail at almost the same amount of force as metals.

Rubber reigns supreme in terms of toughness. It has enough strength to withstand a good amount of force before it deforms but does not fail right away upon deformation. It is this combination of strength and ductility which makes rubber a uniquely tough material.

What is strength?

Of the three material properties we have discussed here, strength is probably the most complex. Strength is a measure of the amount of force that an object can withstand before it undergoes plastic deformation or the kind of deformation that is non-reversible. Also

known as unrecoverable strain, an object that has undergone plastic deformation will no longer return to its original form even after the stress has been removed.

Take note of the distinction between strength and toughness: while toughness measures the force needed for the complete failure of the material, strength is only a measure of the force it takes to reach plastic deformation. In some cases, such as very brittle material such as ceramics, strength, and toughness practically overlap.

There are different types of material strength, which ties right back to the types of stress that an object can experience. Thus, a material can have unique values compressive strength and tensile strength, depending on whether it measures the material's ability to withstand compressive stress or tensile stress. All materials also have a shear strength, which measures its ability to withstand shear stress before undergoing a sliding failure.

Which characteristic should we prioritize?

Now that we have the definitions out of the way, it's time to use this knowledge to make smarter decisions when buying products. When is hardness important? In which products should I prioritize tensile strength or toughness?

1. Prioritize toughness for rigid prints

Rigid prints, or prints designed to be durable, will benefit from having high toughness. These can include replacement machinery parts, toys, hinges, or outdoor signs. A high

toughness means that these parts can withstand a great deal of stress before complete failure. Take note that an object can undergo plastic deformation before it fails, which you should take as a sign to create another replacement part. Still, having a wide plastic deformation window gives you a wide margin before the object breaks or fractures.

2. Prioritize tensile or compressive strength for flexible items

If you want to print using a flexible filament, such as TPE (thermoplastic elastomers), then you're better off choosing a filament with a high tensile or compressive strength rating. This means that the object has a wider elastic deformation region, allowing it to deform under stress but return to its original form once the stress has been relieved. For flexible items, plastic deformation is practically tantamount to failure – after all, you wouldn't want your custom-made phone case or bracelet to be in a perpetually stretched form.

Strengthening mechanisms

Methods have been devised to modify the yield strength, ductility, and toughness of both crystalline and amorphous materials. These strengthening mechanisms give engineers the ability to tailor the mechanical properties of materials to suit a variety of different applications. For example, the favorable properties of steel result from interstitial incorporation of carbon into the iron lattice. Brass, a binary alloy of copper and zinc, has superior mechanical properties compared to its

constituent metals due to solution strengthening. Work hardening (such as beating a red-hot piece of metal on anvil) has also been used for centuries by blacksmiths to introduce dislocations into materials, increasing their yield strengths.

Plastic deformation occurs when large numbers of dislocations move and multiply so as to result in macroscopic deformation. In other words, it is the movement of dislocations in the material which allows for deformation. If we want to enhance a material's mechanical properties (i.e. increase the yield and tensile strength), we simply need to introduce a mechanism which prohibits the mobility of these dislocations. Whatever the mechanism may be, (work hardening, grain size reduction, etc.) they all hinder dislocation motion and render the material stronger than previously.

The stress required to cause dislocation motion is orders of magnitude lower than the theoretical stress required shifting an entire plane of atoms, so this mode of stress relief is energetically favorable. Hence, the hardness and strength (both yield and tensile) critically depend on the ease with which dislocations move. Pinning points, or locations in the crystal that oppose the motion of dislocations can be introduced into the lattice to reduce dislocation mobility, thereby increasing mechanical strength. Dislocations may be pinned due to stress field interactions with other dislocations and solute particles, creating physical barriers from second phase precipitates forming along grain boundaries. There are few main strengthening mechanisms for metals, each is a method to prevent dislocation motion and propagation, or make it energetically unfavorable for the dislocation to move. For a material that has been strengthened, by some processing

method, the amount of force required to start irreversible (plastic) deformation is greater than it was for the original material.

There are several ways to hinder dislocation motion/Strengthening mechanisms in metals and some of them are mentioned below:

- Work hardening
- Grain boundary strengthening
- Precipitation hardening
- Solid solution hardening

For understanding these strengthening mechanisms in detail:

Click on: (a) https://www.youtube.com/watch?v=7BBldSkL_k8

(b) <https://www.youtube.com/watch?v=-k034vrwHY>