6. Getting More Technical With Mechanical Behaviour

LEARNING GOALS

Learning Objectives

1. Identify on the stress-strain curve for a typical metal the following points or regions:
    1. yield strength
    2. ultimate tensile strength
    3. fracture strength
    4. linear elastic region
2. Explain the rationale for the use of the 0.2% offset yield strength
3. Identify on the stress-strain curve for a typical metal the following points or regions:
    1. uniform elastic deformation
    2. uniform plastic deformation
    3. non-uniform plastic deformation
    4. onset of necking
4. Explain why the engineering stress decreases following the onset of necking
5. Compare and contrast uniform and non-uniform deformation
6. Demonstrate how plastic deformation in metals occurs through the movement of linear crystalline defects
7. Compare and contrast between elastic and plastic deformation in terms of the movement of atoms in a lattice

Revisiting the Stress-Strain Behaviour of Metals

You may wonder why, at this point, we need to look at stress-strain curves for metals again. Well, I often find that students start asking really good questions around this point in the course.

> *"Why exactly does the engineering stress decrease after the peak?"*

> *"Can we just use the end of the straight part of the curve as the point when plastic deformation begins?"*

> *"Is the behaviour always linear elastic until the yield strength?" "How, exactly do we determine the yield strength?"*

All excellent questions. And, now is the time to address these questions. Now we have some microstructure under our belts and we can dive deeper into the mechanism for plastic deformation in metals. I'm so excited!

Q6.3.1
Review

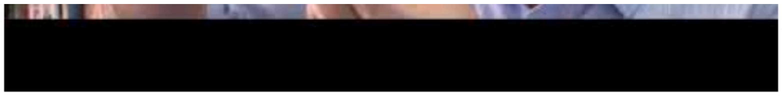
Mark as: None

Which of the following are possible definitions of elastic deformation? Choose all correct options.

Multiple answers: Multiple answers are accepted for this question

Select one or more answers and submit. For keyboard navigation... Show more

a	Atoms do not move to new equilibrium positions
b	Atoms move to new equilibrium positions
c	The sample does not return to its original dimensions upon unloading
d	The sample returns to its original dimensions upon unloading



Let's start by looking at the generalized stress-strain curve for a metal, as shown in Figure 1.

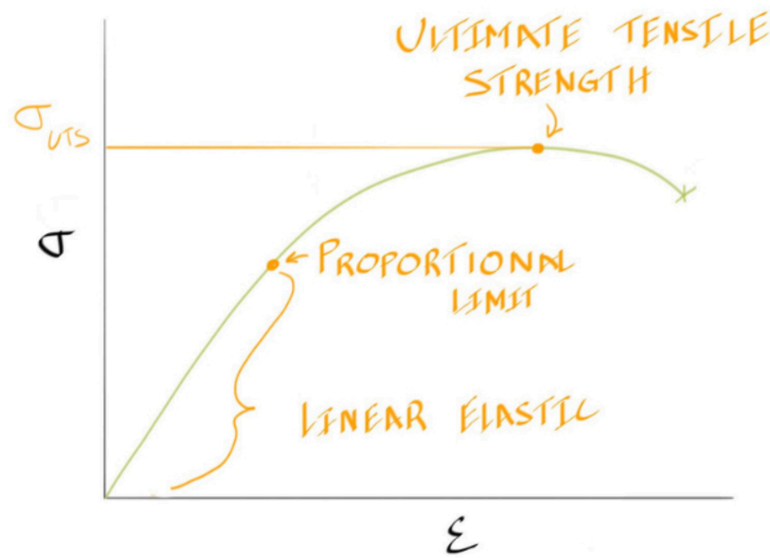


Figure 1: The generalized stress-strain behaviour for a metallic sample loaded in tension with a few important points identified.

There are a few points that can be easily identified. The peak of the curve, for example, is pretty clear. We haven't discussed yet why the curve comes to a maximum and then decreases, but we can certainly identify it. This was one of my favorite material properties when I was an undergraduate engineering student. What's better than the *ultimate* tensile strength. In fact, on the engineering stress-strain curve, there is no value higher than the ultimate tensile strength. That's how *ULTIMATE* it is. Often, hip engineers will call it the UTS, or slightly less cool, but perhaps more technical sounding, σ_{UTS}.

The presence of an initial linear elastic region is likely very familiar to you by this point. However, what is not necessarily immediately obvious is where the linear region ends, or the *proportional limit*. Of course, if you look at Figure 1 you may be inclined to say, "come on, Ramsay, the straight line clearly ends where you drew that big orange dot!" You wouldn't be incorrect in saying that, however, what if I had not drawn that dot and labeled the region below it as *linear elastic*? You could likely eyeball the approximate point where the stress stopped being directly proportional to the strain, but with experimental data it would be essentially impossible to define the end of the straight line by any objective measure. It is conceptually useful, however, to think of the proportional limit as being approximately where plastic deformation begins, and again, this is generally correct.

Q6.1.1
Review

Mark as: None

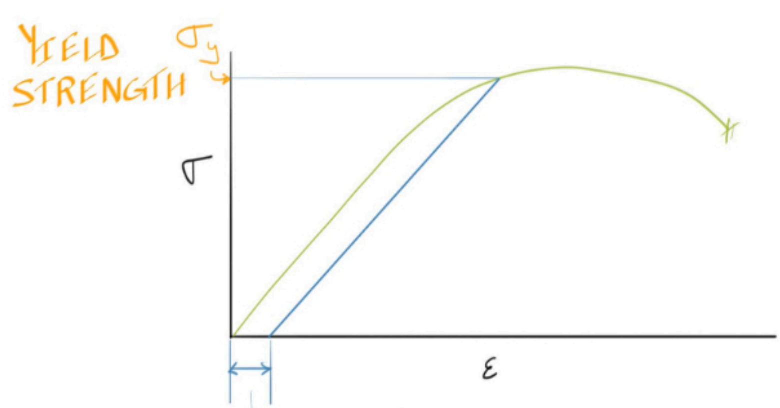
The proportional limit on a tensile stress-strain curve represents which of the following?

Select an answer and submit. For keyboard navigation, use the up/down arrow keys to select an answer.

a	The onset of necking
b	The end of the non-linear elastic region
c	The onset of plastic deformation
d	The end of the linear elastic region

Defining the Start of Plastic Deformation

So how do we define the *yield strength* - the point where, in practice, we assume plastic deformation begins and also, again in practice, is where on a metallic stress-strain curve the stress-strain behaviour stops being linearly proportional. For much the same reason as we just discussed that the proportional limit is hard to determine objectively, it is hard to determine the yield strength without adopting some convention. It would even be difficult if we carefully measured the sample dimensions at infinitesimally small in- creases in stress and tried to observe when the sample dimensions changed; that is, when deformation started to become permanent. Aside from being *infinitesimally* tedious, this approach would also depend on the way that we measured the sample. Do we use a ruler? How about a micrometer? Maybe a scanning electron microscope? So we need a convention. We pick some- thing convenient that will allow us to define a value of stress that will be close to the start of plastic deformation for most metals. That convenient convention is the *0.2% offset yield strength*.



$\varepsilon = 0.002$

Figure 2: The generalized stress-strain behaviour for a metallic sample loaded in tension showing how the 0.2% offset yield strength is determined.

To determine the 0.2% offset yield strength we begin from a strain of 0.002 (note: (0.002)(100%) = 0.2%) and draw a line parallel to the original curve, or with the same slope as the Young's modulus of the metal being tested. Where this line intercepts the curve is where we define the yield strength, as shown in Figure 2.

Q6.1.2
Review

Mark as: None

For a certain steel alloy, the yield strength is 560 MPa and the Young's modulus is 200 GPa. What is the maximum load that may be applied to a specimen with a cross sectional area of $100mm^2$ without plastic deformation?

Select an answer and submit. For keyboard navigation, use the up/down arrow keys to select an answer.

a	26 kN
b	36 kN
c	46 kN
d	56 kN

Q6.1.3
Review

Mark as: None

A hypothetical metal has a 0.2% offset yield strength of 358 MPa, an ultimate tensile strength of 522 MPa, and a fracture strength of 460 MPa. A sample of this metal, originally 1 m in length with a cross section of 2 mm × 2 mm is loaded along its long axis. Just before fracture, while the load is still applied, the length is 1.3 m and when the load is released, the length is 1.18 m. Calculate the modulus of elasticity in GPa.

Type your numeric answer and submit

Q6.2.1
Review

Mark as: None

When a sample of a typical metal has been loaded exactly to the 0.2% offset yield strength would you expect that any atoms within the sample had moved to new equilibrium positions?

Select an answer and submit. For keyboard navigation, use the up/down arrow keys to select an answer.

a	No, since this reflects the exact transition between elastic and plastic behaviour
b	No, since any non-linear behaviour up to this load will be entirely non-linear elastic
c	Yes, since 0.2% strain is selected to be large enough to cause a small amount of plastic deformation in most metals
d	None of these

Uniform and Non-Uniform Deformation

> *Uniform deformation: when you forget to press your school uniform.*

Horrible! Sorry. That's what happens when a prof tries too hard to be funny. Quick, let's look at a serious figure. Figure 3 should do the trick!

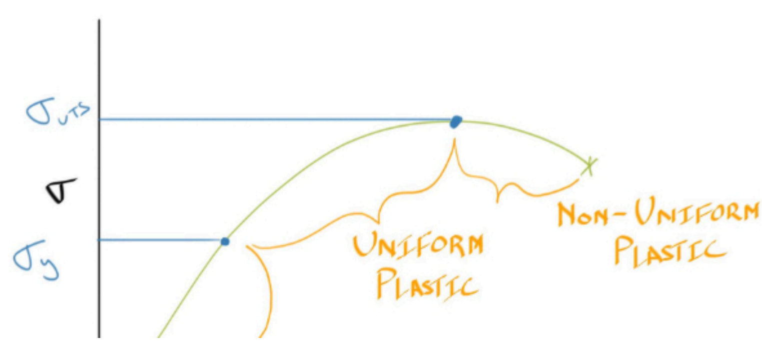


Figure 3: The generalized stress-strain behaviour for a metallic sample loaded in tension showing the regions of uniform elastic, uniform plastic, and non-uniform plastic deformation.

This figure shows a few things. First, it shows that deformation is uniform until the ultimate tensile strength, after which point the deformation becomes non-uniform. It also shows what we already know, that deformation is elastic until the yield strength and then plastic deformation begins. This is all well and good, but you are probably asking yourself, "this still doesn't explain what *uniform* refers to." Good point. To address this, we need another figure. Figure 4 attempts to show what is meant by uniform and non-uniform. The term *uniform* in this context refers to the uniformity of the deformation.

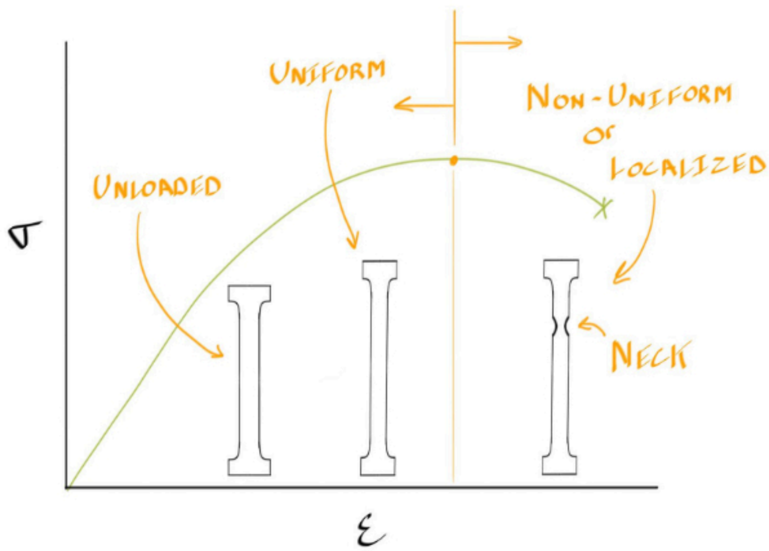


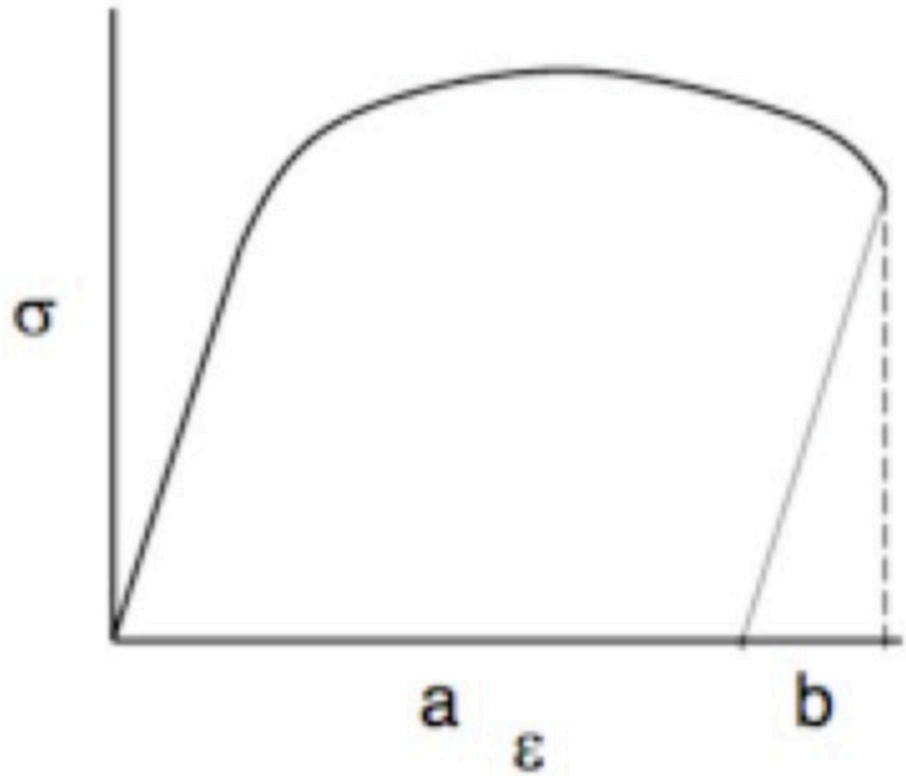
Figure 4: The generalized stress-strain behaviour for a metallic sample loaded in tension showing the sample geometry in the regions of uniform elastic, uniform plastic, and non-uniform plastic deformation.

That is, whether the deformation is distributed evenly and equally through- out the sample (uniform) or if the deformation is isolated to a particular region (non-uniform). Now we can discuss why the engineering stress-strain curve decreases after the ultimate tensile strength. As a metal sample is loaded to progressively higher values of stress, eventually it will begin to fail. In tension, this begins when a few bond break between metal atoms. In a theoretically perfect sample, this would occur randomly anywhere within the reduced section. In practice it likely occurs around some small defect like a scratch on the surface or a tiny pore or oxide inclusion. Several regions of these few broken bonds will eventually come together and form a larger crack that eventually progresses to a larger crack leading to the final fracture event when the sample breaks into two pieces. Microscopically we observe that somewhere within the reduced section we see a sudden narrowing of the cross-sectional area. We call this the neck and refer to this process as necking. The cross-sectional area in the neck is reduced and although the metal itself does continue to get stronger within the neck, it does not strengthen as rapidly as the cross-sectional area is decreasing. Remember that we are plotting and discussing the *engineering stress* at this point and the engineering stress is defined as the force applied divided by the *initial* cross-sectional area. The initial cross-sectional area is a constant and as the actual cross- sectional area decreases rapidly the force required to continue elongating the sample decreases and so we observe the engineering stress decreasing after the onset of necking, at the UTS.

Q6.3.2
Review

Mark as: None

Identify the strain quantity labelled “a” in the figure below.



Select an answer and submit. For keyboard navigation, use the up/down arrow keys to select an answer.

a	Electrostatic strain
b	Elastic strain
c	Plastic strain
d	Total strain

Q6.3.3
Review

Mark as: None

A stapler is used to fasten two pieces of paper together. Assuming that the papers are pressed together by the staple, what type of deformation is present in the staple at the end of the fastening operation?

Select an answer and submit. For keyboard navigation, use the up/down arrow keys to select an answer.

a	Elastic and plastic
b	Elastic only
c	Plastic only
d	The staple remains un-deformed

How Do I Get to Work? Plastic Deformation

Alright, the title of this section is *massively* misleading. My hope is that if you continue reading you'll see where I was going with the title. If you're just confused and plan to give up, well, don't give up, but I'm sorry for confusing you. The idea here is that we need to understand how plastic deformation occurs, that is, the *mechanism* for plastic deformation. Once we understand the mechanism we can design and understand ways to make plastic deformation more difficult.

Making plastic deformation more difficult means increasing the strength. So what about this business of me getting to work? Well, let's say for some reason that you wanted to make it more difficult for me to get to work.

What could you do? Some common responses are:

> *"Make a big traffic jam!"*

> *"... a big snow storm."*

> *"Hide your car keys."*

> *"Steal your shoes!"*

Would it surprise you if I told you that only the second of the above ideas would be likely to slow me down on my trip to work? You see, if you didn't know that I ride my bike to work you would not understand what would make that trip more difficult. Now that you know the *mechanism* for my trip to work you would know to steal my cycling shoes, not my walking shoes.

The mechanism for plastic deformation involves rows of bonds breaking in a step-by-step fashion. But how can the bonds break only a few at a time you ask? Well, this is all because crystals are not actually as perfect as I've been having you believe up to now. Crystals are amazingly perfect and the symmetry in ordered solids is truly beautiful, but so are the various imperfections that are always present within crystals. Think of that wonderful John Legend song, *All of Me*. My favourite lines in that song are about imperfections:

> *'Cause all of me*
> *Loves all of you*
> *Love your curves and all your edges*
> *All your perfect imperfections*

I'm singing it now.

Much like the unusual features and quirky habits that make the people in your life so uniquely special, it is the crystalline imperfections that determine so many of the properties of materials.

Q6.3.4
Review

Mark as: None

Considering a stress-strain curve, which of the following statements is TRUE?

Select an answer and submit. For keyboard navigation, use the up/down arrow keys to select an answer.

a	There is linear plastic deformation before the proportional limit
b	The yield strength is representative of the resistance of a material to elastic deformation
c	All of these options

d	There is non-uniform plastic deformation after necking

Q6.4.1
Review

Mark as: None

Which of the following best describes the reason that the neck formed in a metal sample loaded in tension will always progress to fracture?

Select an answer and submit. For keyboard navigation, use the up/down arrow keys to select an answer.

a	The strain hardening of the metal does not decrease as rapidly as the stress increases within the neck due to the decrease in cross-sectional area
b	The strain hardening of the metal does not increase as rapidly as the stress within the neck decreases due to the increase in cross-sectional area
c	The strain hardening of the metal does not increase as rapidly as the stress increases within the neck due to the decrease in cross-sectional area
d	The strain hardening of the metal does not increase as rapidly as the stress within the neck increases due to the increase in cross-sectional area

Q6.4.2
Review

Mark as: None

A metal specimen is loaded in tension beyond the yield strength, but without necking. Upon unloading, it is found that the Young's modulus is which of the following?

Select an answer and submit. For keyboard navigation, use the up/down arrow keys to select an answer.

a	Greater than it was on initial loading
b	Less than it was on initial loading

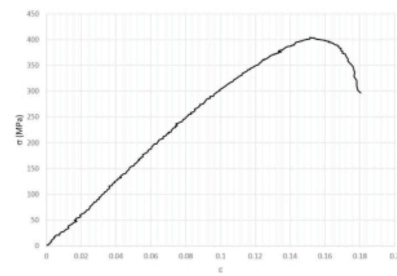
c	The same as it was on initial loading
d	The Young's modulus cannot be determined upon unloading.

Q6.5.1a

Review

Mark as: None

The following figure illustrates the stress-stain behaviour for a hypothetical metallic specimen that has a diameter of 1 cm and an initial (unloaded) length of 10 cm.
(a) Calculate the length of the specimen an instant prior to fracture (while the load is still applied), in cm.



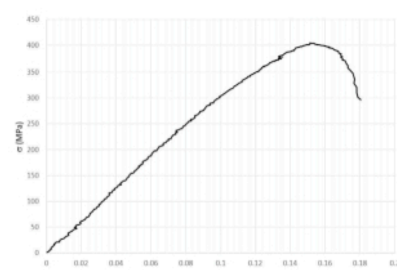
Type your numeric answer and submit

Q6.5.1b

Review

Mark as: None

The following figure illustrates the stress-stain behaviour for a hypothetical metallic specimen that has a diameter of 1 cm and an initial (unloaded) length of 10 cm.
(b) What is the maximum force, in kN, that this specimen can support before necking begins?



Type your numeric answer and submit

Q6.6.1
Review

Mark as: None

Plastic deformation in metals occurs through which of the following mechanisms?

Select an answer and submit. For keyboard navigation, use the up/down arrow keys to select an answer.

a	The simultaneous breaking of all bonds along a crystallographic plane
b	The step-by-step movement of point defects
c	The simultaneous breaking of all bonds along a grain boundary
d	The step-by-step movement of linear imperfections

Q6.7.1
Review

Mark as: None

When a metal undergoes plastic deformation you would expect that atoms will move to new equilibrium positions.

Select an answer and submit. For keyboard navigation, use the up/down arrow keys to select an answer.

a	True
b	False

Q6.8.1

Review

Mark as: None

Ceramics do not plastically deform at room temperature for which of the following reasons?

Select an answer and submit. For keyboard navigation, use the up/down arrow keys to select an answer.

a	Ceramics do not have dislocations
b	Ceramics have too high density
c	The bond strength in ceramic materials is too high to permit plastic deformation

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