Modern Construction Materials
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Module - 3
Lecture - 7
Part 02 of 03
Response to Stress – Part 02

Will continue now with the lecture on the responsive materials to stress, until now we look that how we reach failure passing through the phases of elastic and plastic behavior. Now, will go and to see different types of stress strain curves, and then start discussing brittle failure. And, in the last part this lecture we look at failure that is occurring due to fatigue creep and swan.

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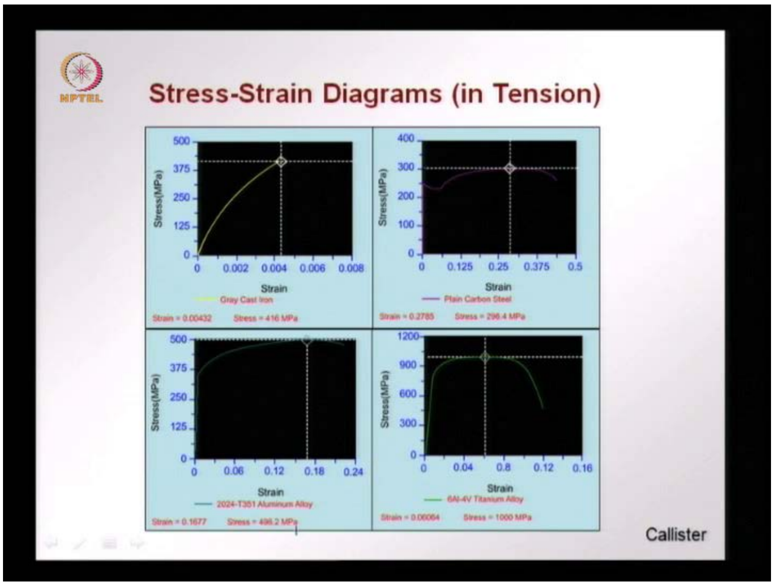

Stress-Strain Diagrams (in Tension)

Callister

So, let us start by looking at some different types of stress strain curves. These are taken from the software that comes along with the book of callister, and we see here on the top left the stress strain curves for cast iron which is a relatively brittle material. We have hardly any linear elastic part in the stress strain curve. It is non-linear up to failure which occurs in a brittle manner. So, cast iron is a metal which fails in a brittle manner and, we looked the reasons for this when we talked about defects in the microstructure.

We saw that flakes of graphite form in cast iron, and these can propagate as cracks and cast failure. On the other hand when we look at plain carbon steel on the top right, we see a curve where you have a sharp increase that is the linear elastic part the stress increases which strain, and then we have a flat part which is denoting the yielding. And, then we have strain hardening with an increase of stress as strain, increases this would be the peak load on the peak stress of which there is a drop in the stress and finely failure.

These crosses mark the peak stress in each of these cases just to given indication of what are the stress values and strain values that we have for the different materials, and the uni-axial tension. At the bottom we have aluminum and titanium alloys, both these cases you see that there is no definite yield plateau that we saw in the case of plain carbon a mild steel. But, we have a smoothly increasing curve there is a transition from the linear elastic to the final strain hardening and failure through a curved region.

There is no definite yield point followed by a flat region, and then strain hardening. But, there is a smoothly increasing curve until the peak is reached. In this case of at 500 mega paschal, and then we have failure. This is for an aluminum alloy for a titanium alloy again the curves seems very similar except that the peak stress the maximum stress. That the titanium alloy can take is about 1000 mega paschal the strain is also a different it is now 0.06 instead of what we saw in aluminum 0.17 was this strain at the peak stress.

So, we see that metals generally have a ductile behavior in the sense. That there is a lot of elongation lot of strain before failure occurs w e see also that in alloys we do not have a very definite yield point. This is true for all polycrystalline materials, because different crystal grains will start yielding different points. We also saw that a metal such as gray cast iron can have brittle failure, and that is the reason why cast-iron is used in applications where we do not require a lot of ductility in civil engineering application we used for casting grills fence pose and so on.

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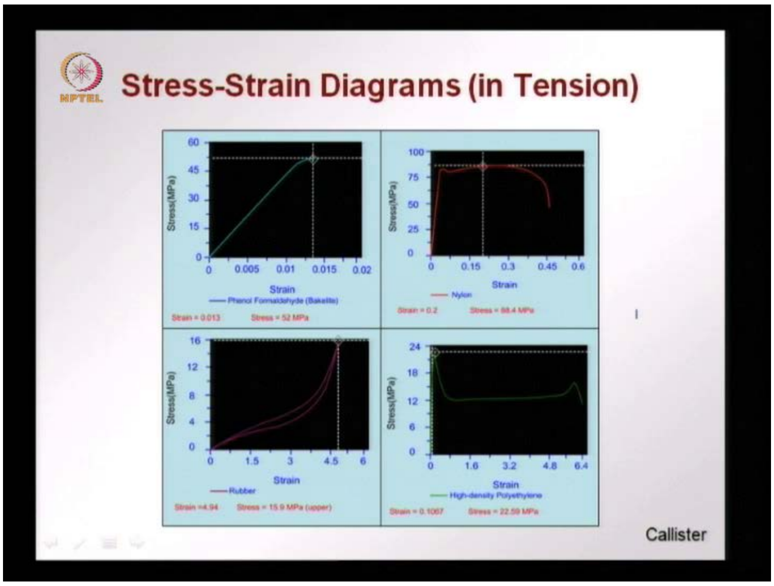
Stress-Strain Diagrams (in Tension)

Callister

Polymers also have the range of a behavior patterns, at the top left we see a case of linear elastic and almost ideal brittle failure. This is in the case of Bakelite or phenol formaldehyde, which was one of the first plastics to be used in large scale applications. And, we see here the this stress at failure is about 50 mega paschal strain is 0. 013. And, I repeat that you see here a linear elastic response over a large part of this stress strain behavior followed by certain failure.

You do not have any substantial curve beyond the peak. On the other hand when we look at the case of nylon on the top right, we see that there is a linear response followed by something like yielding of flat part slightly increasing, we reached peak at a strain of about 0.2. And, then there is as gradual decrease and failure occurring. This is the stress is a peaks at around 88 mega paschal. This was very similar in shape to what we saw in mild steel.

Rubber on the other hand does not have a yielding response that we saw in nylon, but what we have is a non-linear elastic response. In the sense that as we keep pulling as we keep applying tension to rubber, there is a very high strain that rubber can take in the order of about 5 strains. And, when we release the stress the rubber returns to which original position that is there is no permanent deformation even though this strain values are very high. However, we also see that there is not a very large linear response. The linear response is very short and after that we have a non-linear elastic behavior, it is still elastic because it returns to 0. When this stress is release we return to the 0 point. So, it is still elastic, but it is non-linear elastic.

In the case of high-density polyethylene would be a material which has some amount of crystallization that increase the density and this crystallization comes because of the ordering of the polymer chains. And, what we have here is now a situation of there is an elastic part shown by this increase we have a peaks stress of about 23 mega paschal. This is now where all the chains start being aligned in a certain section, and this is followed by a drop and some amount of plastic behavior.

Where the chains now start resisting low, to you have a elastic part a peak occurring some amount of drop this could be called softening, and then we have a plastic response over a large strain. So, we see that metals and polymers and many other materials have a range of stress strain behavior, and this has to be characterized and understood in order to be used in design.

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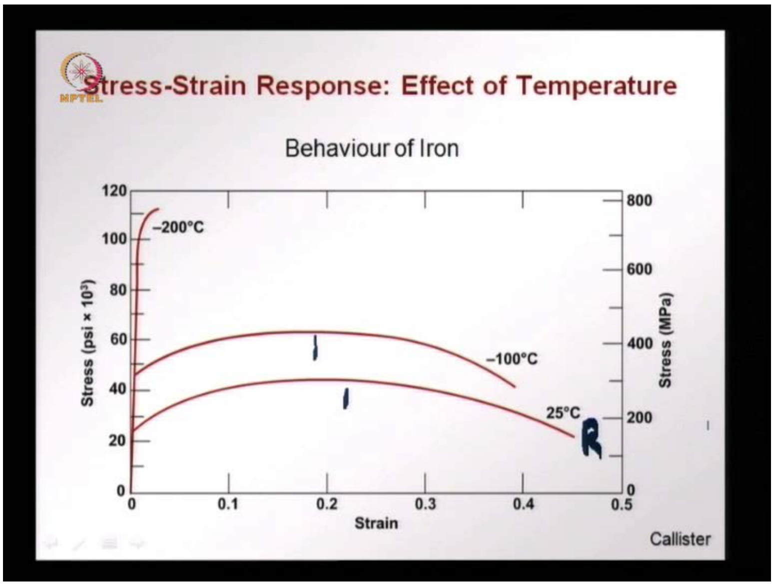

Stress-Strain Response: Effect of Temperature

Behaviour of Iron

Callister

This stress train response also changes his with temperature. In this case we have the diagrams for iron the bottom curve is what we see for room temperature, so this would be at normal temperature. So, we fine that there is a certain yield stress at around 200 mega paschal, then after wise there is substantial elongation with hard hardening the reached peak around here. And, then there is what is called necking, and then we have failure.

So, the neck would form around where the peak values at a lower temperature say minus 100 degrees. We find now that the yielding occurs at a higher value around 300 mega paschal. And, then again we have the strain hardening the peak now occurs may be somewhere around here. And, then we have failure occurring at a strain of 0.4, which is less than what happened at room temperature.

Now, if you decrease the temperature even further when we go to minus 200 degree centigrade. Now, we have a much higher the yield value close to around 700 mega paschal. But, there is not much of elongation after that failure occurs abruptly at a very small strain. So, what we see here for iron is typical of many materials as temperature decreases. We find that strength goes up, but the elongation or ductility severely decreases.

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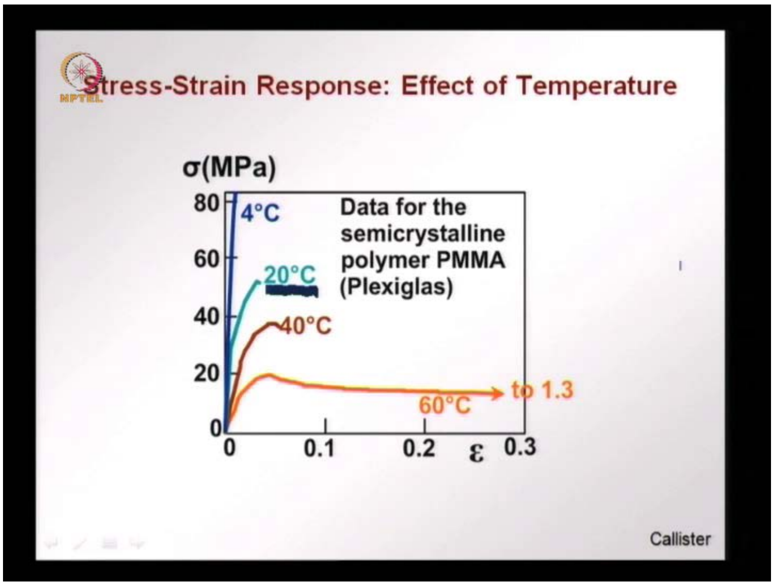

Stress-Strain Response: Effect of Temperature

Data for the semicrystalline polymer PMMA (Plexiglas)

Callister

This is also seen in the case of flexi glass or a semi-crystalline polymethyl methacrylate PMMA for short. And, we find here this graph given by callister showing the stress and strain behavior again and under tension over a temperature range of 4 degrees to 60 degrees. So, here the room temperature would be this case of 20 degrees, we find that PMMA brittle behavior, you have a linear elastic part followed by slightly non-linear behavior, and then PMMA fails in a brittle manner.

However, if the temperature is a higher see 40 degrees. Now, you see that there is more nonlinearity there is a decrease in strength from around 50 mega paschal, it is come down to about 40 mega paschal. The ductility or the elongation before failure as however, increased you have more strain until failure occurs compare to the 20 degree case at 60 degrees you have a significantly plastic behavior.

That is you have an increase it reaches a peak value, and then there is a large plastic plateau which can go up to 1.3 strains. On the other hand when temperature decreased if you look at 4 degrees Celsius we find that the strength is higher it exceeds 80 mega paschal. But, then after that the failure is very brittle. So, just like we saw in the case of iron, we see here that as temperature decrease is strength increases, but ductility or elongation to failure decreases.

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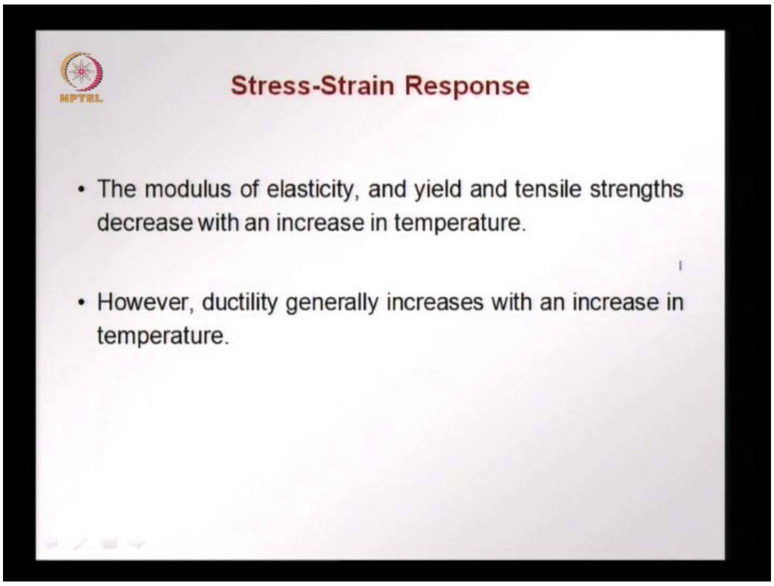

Stress-Strain Response

- The modulus of elasticity, and yield and tensile strengths decrease with an increase in temperature.
- However, ductility generally increases with an increase in temperature.

So, general we find that module is of elasticity, and yield and tensile strength decreases with an increase in temperature. Significantly ductility increases with an increase in temperature or it decreases when the temperature drops. That is the material becomes more brittle as the temperature drops.

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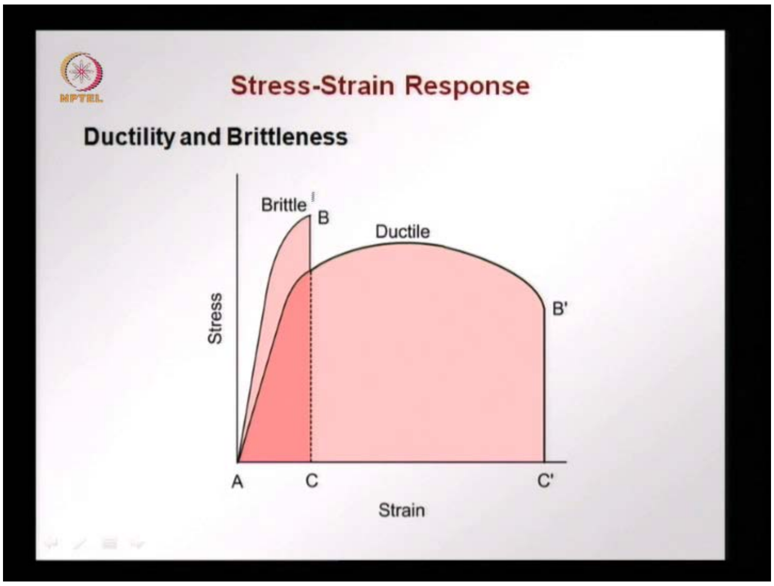
Stress-Strain Response

Ductility and Brittleness

Now, we talked about ductility and brittleness, how do we quantify these concepts? we can do, so based on the stress train diagram that we look that, and we can say that a material is ductile is there is a higher energy absorbed until failure occurs given by the area under the stress strain curve. So, this curve A C prime B prime can be an indication of how ductile the materialist. If the material is not ductile like we saw in the case of a grey cast iron Bakelite the material fails in a brittle manner, this area now A B C is much lower than what we saw for A B prime C prime.

And, the four we can say that this material which fails like, in this case which has a stress strain diagram A B instead of A B prime is more brittle than this one. And, the area under the curve is an indication of ductility unable indication could be the elongation up to failure you can see very clearly that A C prime is much more than A C A C prime being that of a ductile material A C being the elongation up to failure for a brittle material.

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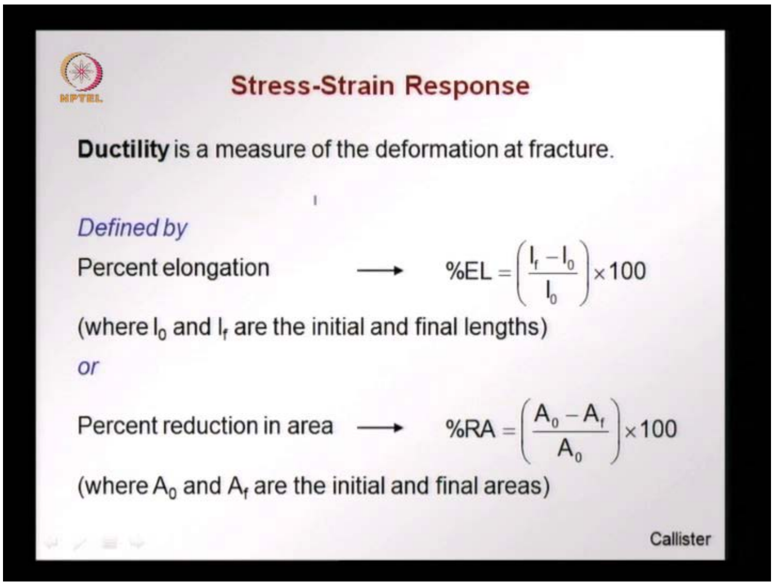

Stress-Strain Response

Ductility is a measure of the deformation at fracture.

Defined by

Percent elongation ⟶ $\%EL = \left(\frac{l_f - l_0}{l_0}\right) \times 100$

(where l_0 and l_f are the initial and final lengths)

or

Percent reduction in area ⟶ $\%RA = \left(\frac{A_0 - A_f}{A_0}\right) \times 100$

(where A_0 and A_f are the initial and final areas)

Callister

So, ductility can be defined as a measure of the deformation at failure, it represents how much a material can deform before failure occurs? The energy can be dissipated observes by the material during failure it can be defined in two ways, Percentage elongation given by the difference between the initial and final lengths divided by the initial length.

That would give the elongation can be put, in terms of the percentage or we can look at percentage reduction in area. That is we see look at the cross-section change in cross-section area divided by the initial cross-section area is given as a percentage reduction in area, which also represents ductility other than this we saw in the previous figure that the area under the curve can also be treated as a measure of ductility.

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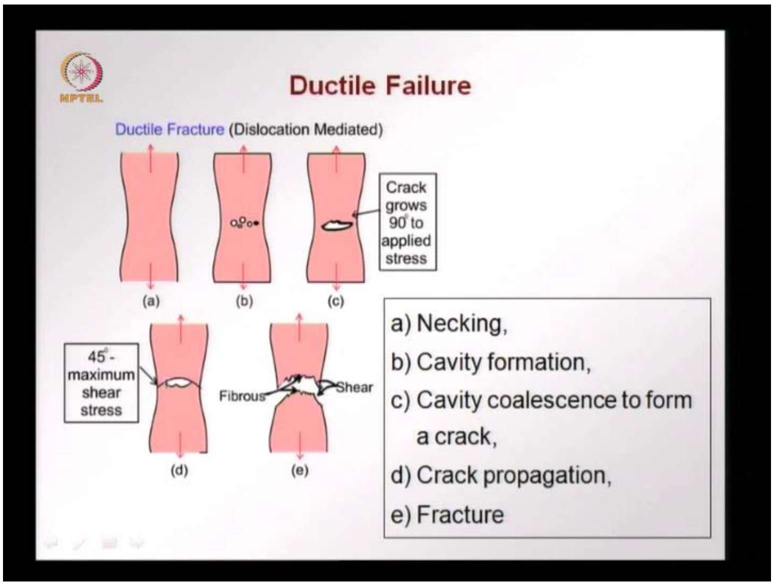

Ductile Failure

Ductile Fracture (Dislocation Mediated)

a) Necking,
b) Cavity formation,
c) Cavity coalescence to form a crack,
d) Crack propagation,
e) Fracture

So, how does ductile failure occur? What happens of the strain hardening phases and the ductile phases? How does the material actually fail? We take a specimen under tension of save a metal, and we look at failure that is dominated by dislocation moment. We would have a specimen like this subjected to tension. This is what is usually called a dog bone specimen, where there is a section with a lower with where failure would occurs, so that became monitor more easily,

And, which is also for away from where the specimen is gripped. So, here cavities form as the dislocations start moving these cavities link to form a crack this crack, now grows 90 degrees to the applied stress this crack now grown laterally in this case. And, then as the crack reaches the hence we have slip occurring at 45 degrees, which is the direction of the maximum shear stress. And, we have now a curved failure occurring like what is shown here. We have the crack joining together with an inclined slip plane around this a conference if it is a circular specimen.

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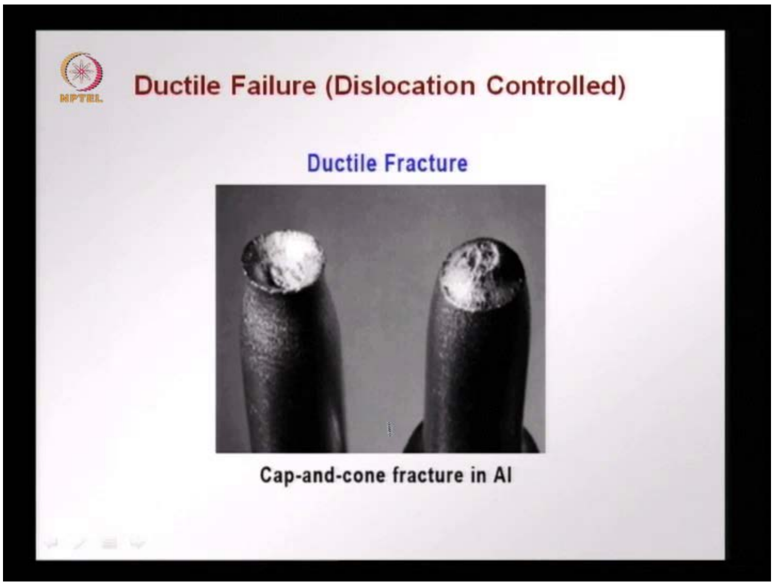

Ductile Failure (Dislocation Controlled)

Ductile Fracture

Cap-and-cone fracture in Al

So, when we look at a photo we see something like this. So, this is in the case of aluminum this part is where we had the flat crack propagating and then we have the slip zone over the edges. So, you see that there will be jagged edge around the hence instead of a smooth surface that were finally, we have the slip ending and fracture completing. This is called the cap and cone fracture, this being the cone and this being the cup So, this is very typical of ductile failure in metals.

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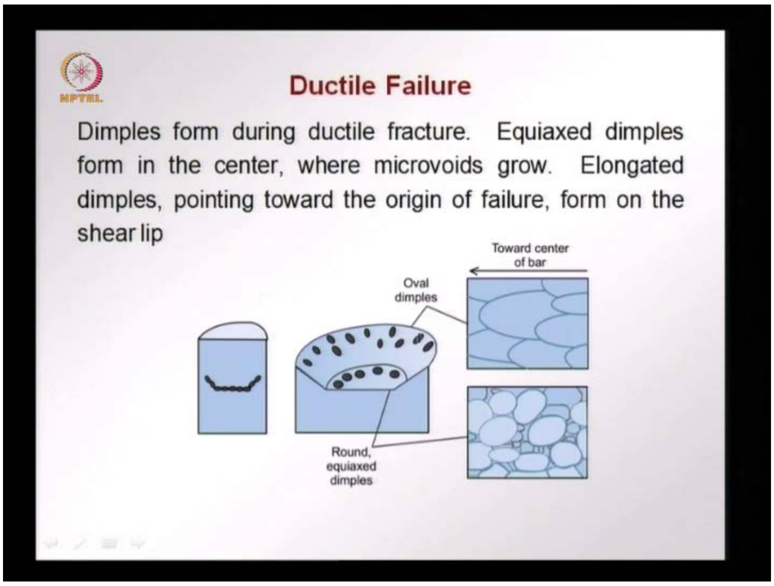

Ductile Failure

Dimples form during ductile fracture. Equiaxed dimples form in the center, where microvoids grow. Elongated dimples, pointing toward the origin of failure, form on the shear lip

If we take a close a look at the failure surface, we will see dimples that have form during the ductile failure dimples are depressions that form on the failure surface. Now, the dimples or cavities initially start the flat crack, and then you have propagation this is the slip zone and we have sharing occurring and finally fracture. In the flat crack part we will have round equiaxed dimples, and in the slip zone we have these dimples more oval. That is if we look towards the centre of the bar will see a dimple like this. And, the dimples point towards the origin of failure. So, this is the centre of the bar where the failure started and the dimples form with this orientation. And this is now what is call the shear lip, where shearing occurred and this is by the overall dimples.

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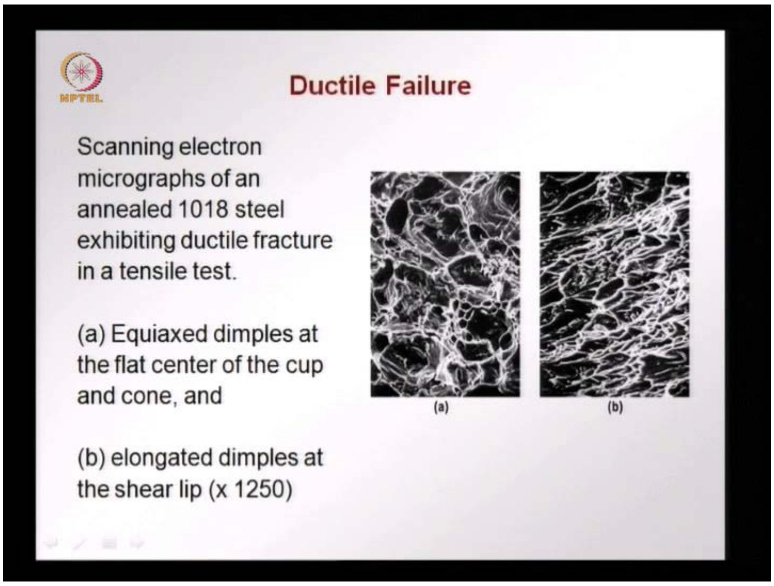

Ductile Failure

Scanning electron micrographs of an annealed 1018 steel exhibiting ductile fracture in a tensile test.

(a) Equiaxed dimples at the flat center of the cup and cone, and

(b) elongated dimples at the shear lip (x 1250)

If we look closure in a scanning electron micrographs see a in the case shown here, which is annealed 1018 steel we find in the flat centre, we have equiaxed dimples. So, these are all equiaxed almost circular dimples this is now in the flat area. And, here in the shear lip we find elongated dimples the dimples are now elongated. So, these are depressions which form, and this cavitation leads to the propagation of the crack and ultimately fail, so this is what happens during the ductile failure of a material such as steel and. We ultimately have a lot of strain that the material can undergo until this final failure occurs.

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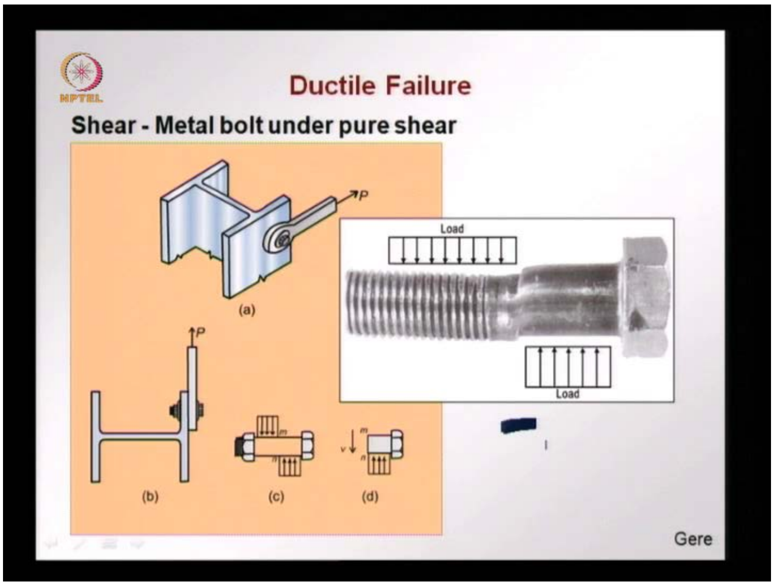

Ductile Failure

Shear - Metal bolt under pure shear

Gere

Failure in a ductile manner does not have to occur only under tension. We can have even materials failing in a ductile manner under shear if we take the case of a bolt that is holding together the flange of an eye section and see a tie. I suppose we have tie pulling on this bolt and this bolt transferring the load to the flange of this eye section. We have this force, now pulling and this is transferred a sheer stress to the bolt. The bolt now undergoes a sheer stress, and if the stress is very high. If the load is very high and consequentially this stress is very high the material can shear, and here you see this picture from the book of gear that you have a very high strain. Here cast by the sheer force and you have yielding occurring here, so this would be the yielding zone in sheer.

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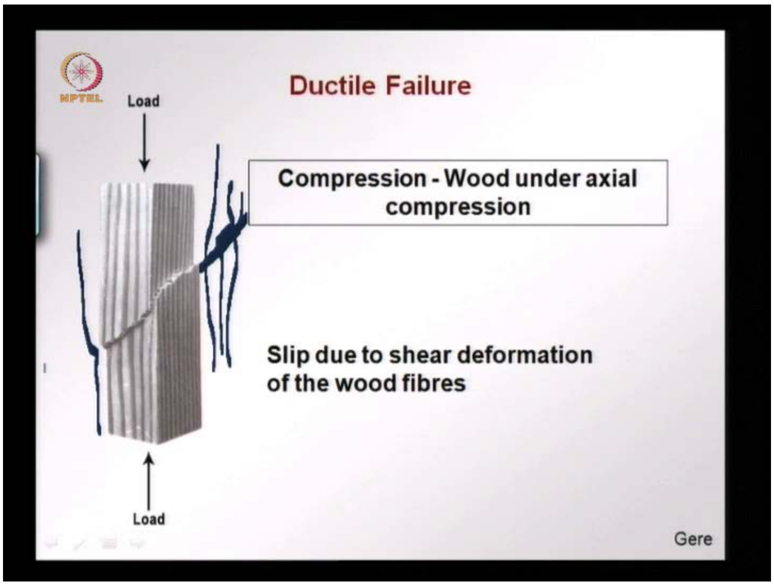

Ductile Failure

Compression - Wood under axial compression

Slip due to shear deformation of the wood fibres

Some other material also exhibit ductile that is the failure is not sudden, but it is a gradual type of failure. And, one example is the compression failure of wood say in a strut if you have a piece of wood like this vertical lines that you see other grains for the fibers material. And, what happens is when you have very high compressive stresses peace fibers are at a certain point kink, and you have something like a shear zone forming.

Across, this zone if you look at it closely you will see that the fibers of the wood are kinking or bending like this. And, you have ultimately a zone of sheer forming, so along this line the fibers are bending. The wood fibers are bending and when adjacent fibers all bend together, because of this high shear occurring in compression you have this slip zones forming in wood, and this gives rise to a ductile failure. The failure is not sudden.

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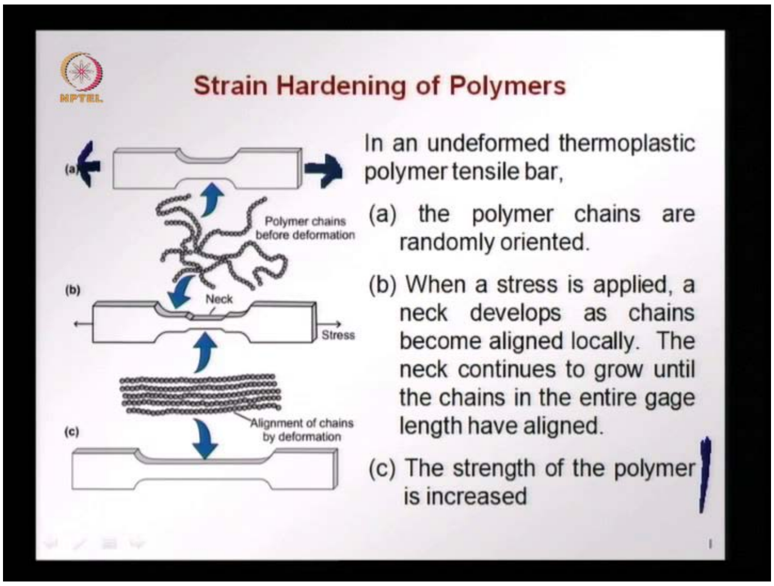

Strain Hardening of Polymers

In an undeformed thermoplastic polymer tensile bar,

(a) the polymer chains are randomly oriented.

(b) When a stress is applied, a neck develops as chains become aligned locally. The neck continues to grow until the chains in the entire gage length have aligned.

(c) The strength of the polymer is increased

In the case of polymers are very interesting phenomena occurs which causes something like strain hardening in the polymer. Suppose we take a thermoplastic polymer. This would have long chains entangled, and if we take a coupon made out of this was the dog bones specimen that I mentioned earlier. So, imagine that we apply as tensile force here. We are going to pull on this, and failure is going to occur here, because this is where we have a reduce section. And, in this section if we were to look very close we would see the polymer chains all entangle long polymer chains say in a linear polymer.

There is random orientation of the polymer change, and when we apply stress necking occur as we saw. In the case of metals now here when a connecting occurs is polymer change, now all along it they are all stretched leading to the decrease of the cross-section. And, when they all stretch, now we can see very clearly that they would take much more stress than in the case of a polymer system, which as change all entangle. So, this system now will take most stress then this and therefore, it shows strain hardening type of behavior or we see an increase in the polymer strength as this strain increases.

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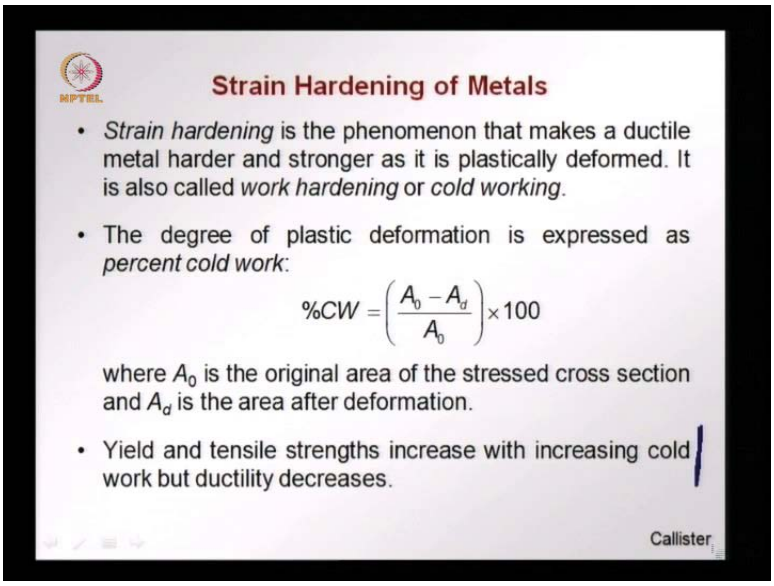

Strain Hardening of Metals

- *Strain hardening* is the phenomenon that makes a ductile metal harder and stronger as it is plastically deformed. It is also called *work hardening* or *cold working*.
- The degree of plastic deformation is expressed as *percent cold work*:

$$\%CW = \left(\frac{A_0 - A_d}{A_0}\right) \times 100$$

where A_0 is the original area of the stressed cross section and A_d is the area after deformation.

- Yield and tensile strengths increase with increasing cold work but ductility decreases.

Callister

So, we talked about strain hardening. Strain hardening now is the phenomenon that makes a ductile metal harder and stronger. Will talk about basically even though, we saw guessed this slider earlier that polymer can also strain harden. However, strain hardening is a phenomenon that is very important in the behavior of metals in how metals can be used effectively, and how we can make metals stronger through strain hardening or cold working.

So, strain hardening as I say is as phenomena or a procedure which makes a ductile metal harder and stronger as it undergoes plastic deformation. This is called work hardening also or cold working. Cold working because it is carried out these occur when temperature increase thus in accompanied. That is it is occurring a room temperature or ambient temperature. So, that is why it is called cold working. And the degree of plastic deformation or the percentage cold work can be expressed as the change in area of the section divided by the original area as a percentage.

So, this is called the percentage cold work. So, if we take an abort under tension and we look at how the cross-section area changes the change in area divided by the original area is expressed as the percentage cold work and indication of how much strain hardening the material undergoes. What we find is? When we called work material as the cold work increases the yield and the tensile strain increase, however the ductility decreases.

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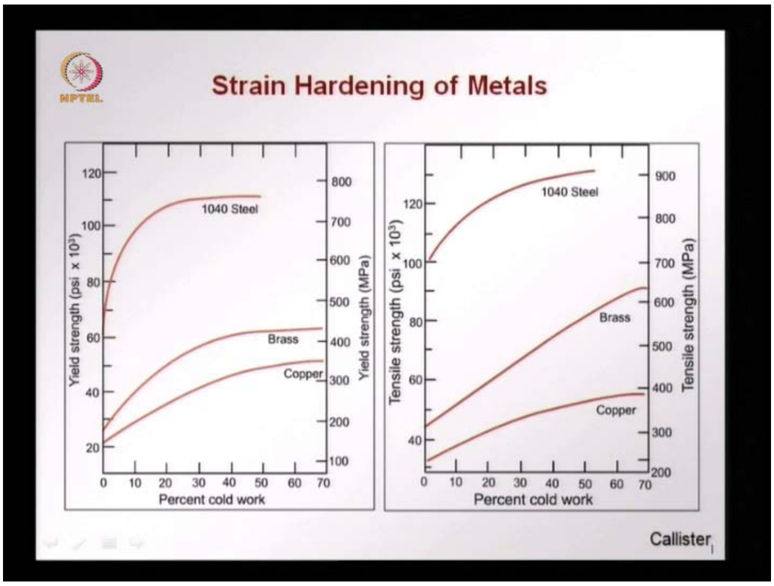

Strain Hardening of Metals

Callister

So, we have in the next two slides curve showing what I have just told you about the effect of the cold work on the x axis we have the percentage cold work. This you remember is defined as the ratio between the change in cross-section area and the original area. In the plot on the left we have yield strength as a function of the percentage cold work for copper brass and steel.

And, we find in all the cases we have an increase in yield strength as the cold work increases. That is you to strain hardening we have an increase in the yield strength. Now on the right we have the tensile strength that is the strength at failure. This obviously is higher in all cases then the yield strength, but we also see the same trends, where the tensile strength. Now, increases as the percentage cold work of the effect of the strain hardening increases more strain hardening higher or the yield strength and the tensile strength.

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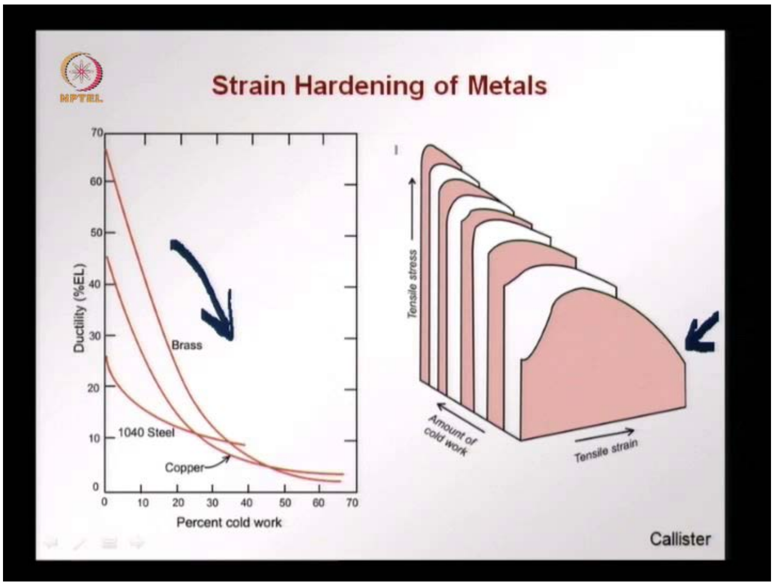

Strain Hardening of Metals

Callister

On the other hand what we see is the ductility decreases. On this graph on the left, we find that as the percentage cold work on the x axis increases. We see that ductility now decreases as we strain hard in the material. We cold work the material the material becomes less and less ductile and more brittle. Now, callister as an interesting diagram which I have shown on the right which explains what happens in terms of cold work and the stress strain behavior.

Now, let us look at this first graph which would be the stress strain behavior without any cold working. So, if we take a material such as mild steel we have an elastic part, and yielding part, then we have a strain hardening necking occurring and failure. Now, suppose I was to increase this strain until I reach the this point, and then I unload now if I considered.

This as a new material and I was going to do as tensile test again the stress strain diagram, which start from this point I would have an elastic response up to this. Yielding would occur hear followed by necking and failure. This is this curve what I just describe is what will happen in this curve this is a cold work material, whereas certain amount of cold work has been done. And, now when this cold work material is loaded it as an elastic response yielding and it continues with the previous stress in diagram.

However, this elongation is now less, because we have used up some of the plastic deformation when we did the cold work. Now, suppose I where to do this again with the original material, but I stopped at a later point. I go up to here, and then I unload though this you material if I test it again will start from here. Go up here, this would be the yield point, then it would reach a peak, and so that would be say something like.This that would be something like this here I would have large elastic regime followed by yielding and immediately I have necking occurring and failure.

So, we see that the higher up I go before unloading more cold working I will have higher will be the yield strength. Because, I am taking the material to higher stress before unloading, but the elongation starts decreasing drastically, because, I am using of the plastic deformation capability of the material. So, when we look at cold work as the cold work increases, the strain capacity will decrease. But, the tensile stress capacity will increase. This is the reason why we have the phenomena that we discussed earlier.

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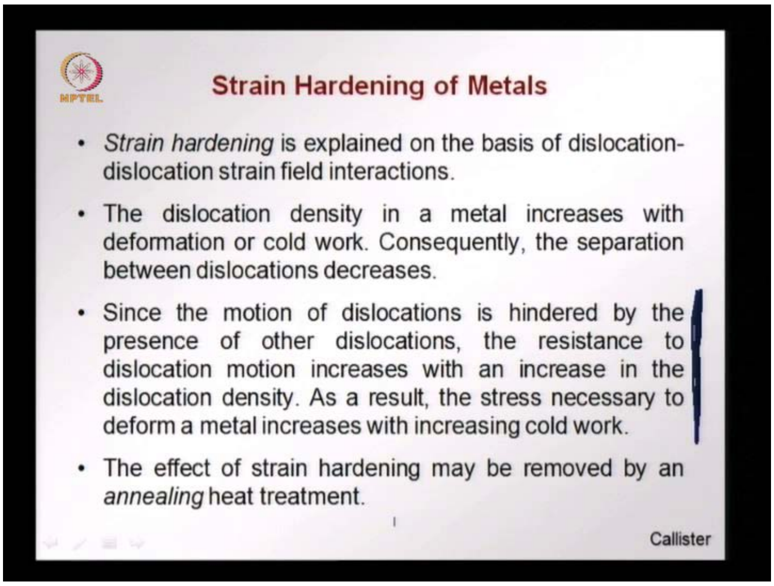

Strain Hardening of Metals

- *Strain hardening* is explained on the basis of dislocation-dislocation strain field interactions.
- The dislocation density in a metal increases with deformation or cold work. Consequently, the separation between dislocations decreases.
- Since the motion of dislocations is hindered by the presence of other dislocations, the resistance to dislocation motion increases with an increase in the dislocation density. As a result, the stress necessary to deform a metal increases with increasing cold work.
- The effect of strain hardening may be removed by an *annealing* heat treatment.

Callister

So, strain hardening in the microstructure can be explain as occurring due to the interactions between dislocations or dislocation-dislocation strain feel interactions. Dislocation density increases when the deformation of cold work increases dislocations start moving and coming closer to each other, and there is more interference between the dislocations. And, this will cause the hindrance of the motion of the dislocation. We are seen that when grain boundaries hinder dislocation moment we have an increase in the strength in the yield strength.

Similarly, here now as dislocations start moving an interfering with each other we have an increase in the dislocation density and therefore, we have strain hardening are an effective increase in the strength. The stress needed to deform the material, now increases because of this higher density of dislocations, which comes about by the increase of cold work. We can remove this effect of strain hardening by a process call annealing, which is heat treatment will discuss this in a moment.

So, we can have a material which is initially not strain harden, we can strain harden it and through a heating process we can anneal it. So, this means that when we apply heat to a strain harden material, we can reverse the effect of strain hardening to some extent this is annealing this is the reason why we should be careful and applications, where we use strain harden materials. We should not subject them to heating through welding and so on. Because, this can bring down the strength that we have achieved by strain harden.

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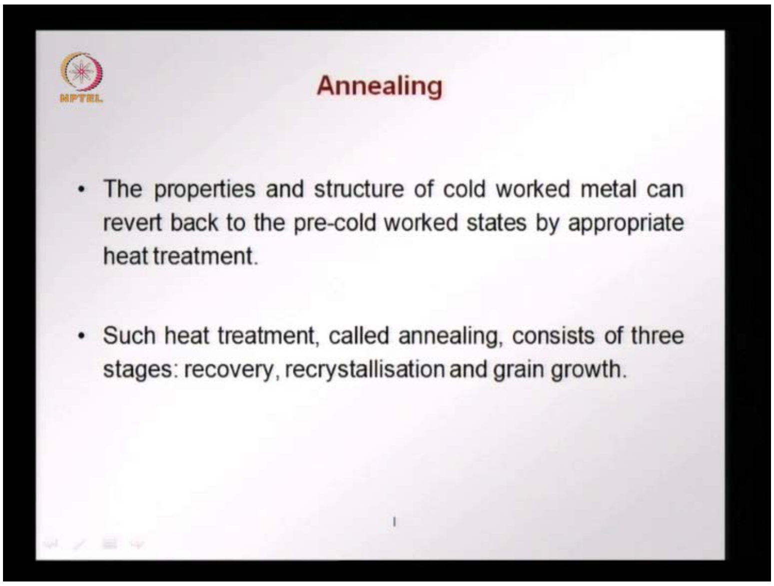

Annealing

- The properties and structure of cold worked metal can revert back to the pre-cold worked states by appropriate heat treatment.
- Such heat treatment, called annealing, consists of three stages: recovery, recrystallisation and grain growth.

So, annealing is a process by which the properties and structure of a cold worked metal can revert back to the pre- cold worked states. That is the original state by using heated treatment, remember that strain hardening is done at ambient temperature, now when we anneal it higher temperatures we bring the material back to the original state. Annealing consists of three stages recovery, re-crystallization and grain growth. Recovery is where most of the residual stressors are may 0 they are compensated. Re-crystallization is where new crystals are forming and grain growth as the name implies means that larger grains are forming.

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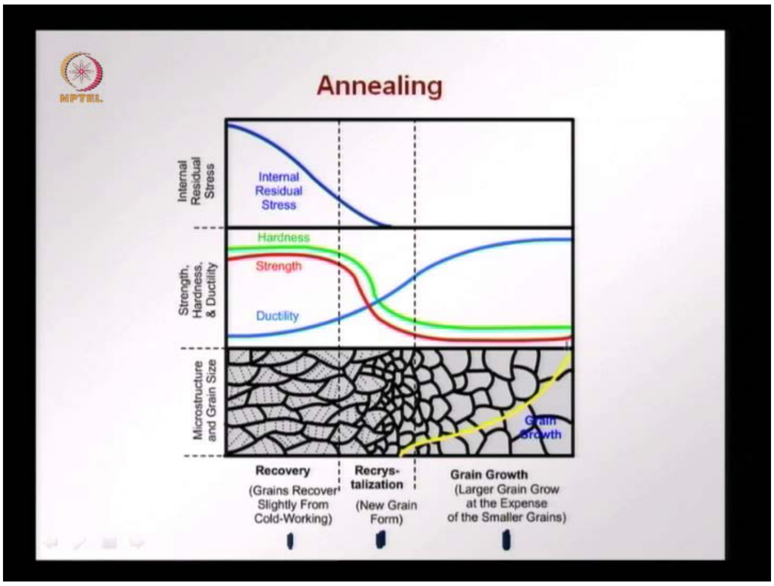

So, this is a nice diagram shows all the different phenomena in one graph, where we have along the x direction they effect of temperature applied going through the three phases that we look that in text recovery, re-crystallization and grain growth. First let us, look at the top what happens due to the temperature during anneal. First we see that in the recovery phase the internal residual stresses that where brought about by the cold working decreases drastically, initially during the recovery stage.

The hard nesses strength do not change merge ductility starts to increase and mainly what happens in the grain structure is now we are releasing some of the residual stresses the grain start recovering from cold working. In the next phase more sustain temperature, we find new grains starting to form the residual stress is now completely gone, there is hardly any residual stress remaining in the material. And, this coincides with a drastic drop of hardness and strength, so hardness and strength of come down significantly where as ductility continues to increase.

In the microstructure we find now that the residual stress is gone, and the new small crystals start to grow within the structure. In the phase the grain growth phase, we have now no residual stressors ductility has come back to with the original pre-cold work state as well as hardness in strength grains. Now, start to grow that is instead of small grains we have larger grains this yellow lines shows the grain growth. So, the larger grains now form less grain boundaries and larger grains now occur.

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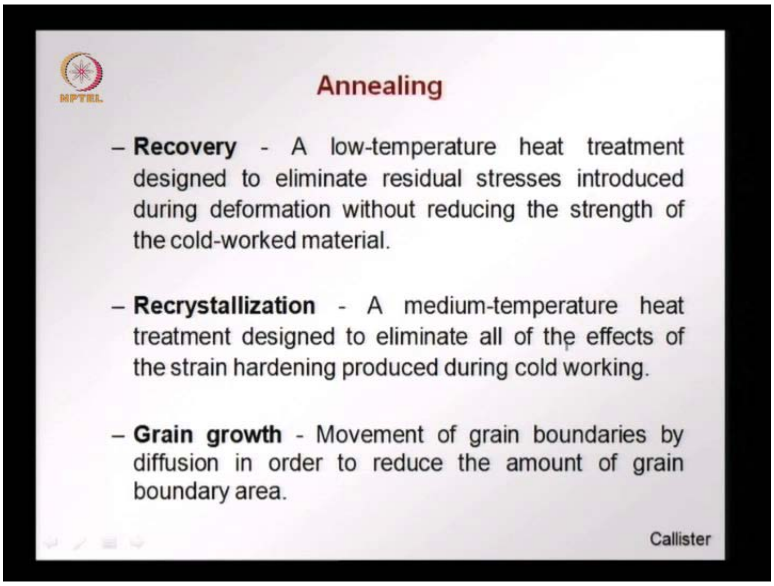

Annealing

- **Recovery** - A low-temperature heat treatment designed to eliminate residual stresses introduced during deformation without reducing the strength of the cold-worked material.
- **Recrystallization** - A medium-temperature heat treatment designed to eliminate all of the effects of the strain hardening produced during cold working.
- **Grain growth** - Movement of grain boundaries by diffusion in order to reduce the amount of grain boundary area.

Callister

So, to look at again, recovery is a low-temperature heat temperature needed to eliminate residual stresses that we have introduced during deformation during the cold working. Re-crystallization is a medium temperature heat treatment, which eliminates all the effects of strain hardening that were produced during cold working. Grain growth is where through diffusion, we make the grains larger we move out the grain boundaries. And, therefore there is a reduction in the amount of grain boundary area and the system also decreases. The energy and becomes more states.

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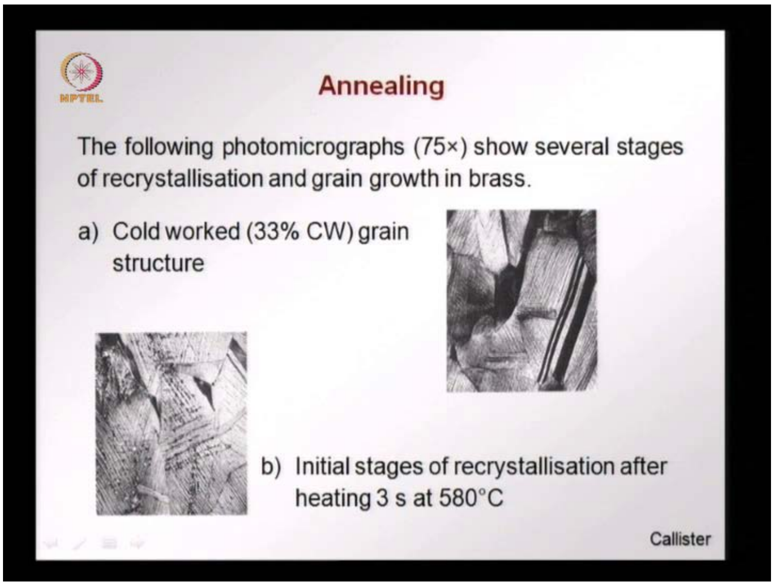
Annealing

The following photomicrographs (75×) show several stages of recrystallisation and grain growth in brass.

a) Cold worked (33% CW) grain structure

b) Initial stages of recrystallisation after heating 3 s at 580°C

Callister

These are some pictures some photomicrographs taken from callister showing different stages of re-crystallization higher temperature grain growth in brass. In this diagram we have a cold worked brass 33 percent cold working and you see here many of the slip planes in the different crystal, we have all the slip planes that have occurred due to cold working.

This is now just after cold working when we start annealing see three seconds of heating and 500 degree Celsius. We find re-crystallization occurring this small imperfections, which are starting are actually crystal, which as starting to grow we see decrease of this slip lines being prominent. And, we have the small crystals now growing this is the initial stage of re-crystallization.

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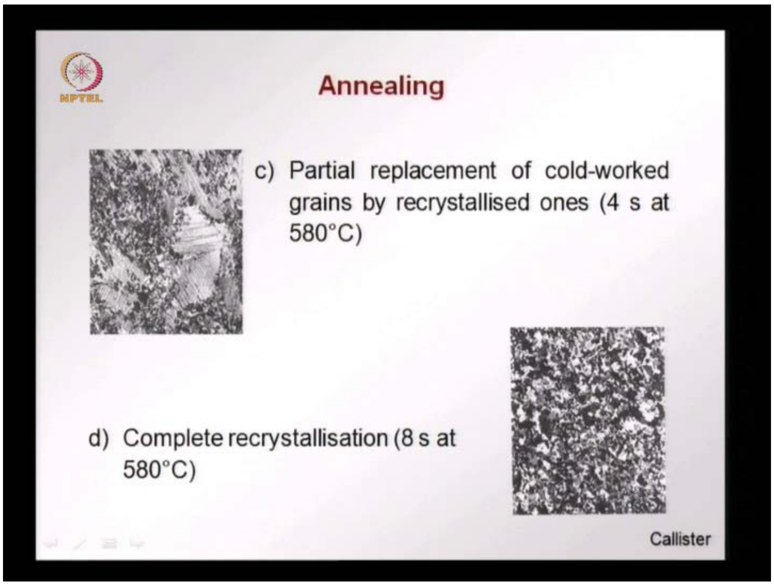

Annealing

c) Partial replacement of cold-worked grains by recrystallised ones (4 s at 580°C)

d) Complete recrystallisation (8 s at 580°C)

Callister

Now, we continue now after four seconds at 500 degrees centigrade we have the cold work grain being replaced by re-crystallize smaller grains. Re-crystallization completes at 8 seconds that the same temperature of 580 degrees. So, we have we hardly see any planes and we see a lot of small crystals in the picture.

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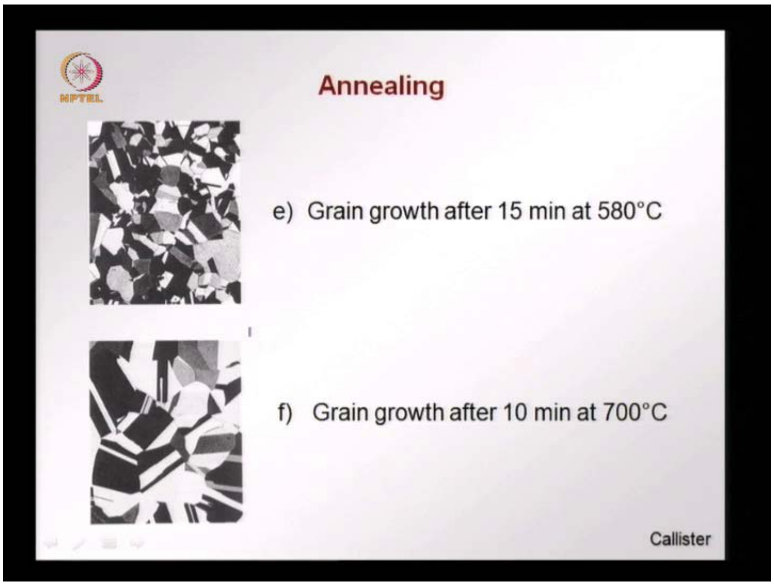

Annealing

e) Grain growth after 15 min at 580°C

f) Grain growth after 10 min at 700°C

Callister

After, 15 minutes now the grains have grown. There are larger grains this different colored areas are individual crystals are grain. Now after 15 minutes we have a different grain structure then what we saw before. Now, finally we have third stage where we have grain growth at a higher temperature 700 degrees 10 minutes. And, we find now the grains now are larger that we saw before grain growth is significantly a more we have larger grains fewer grain boundaries. And therefore, we have a system with less potential energy or lattice energy. So, these are the different stages of anneal.

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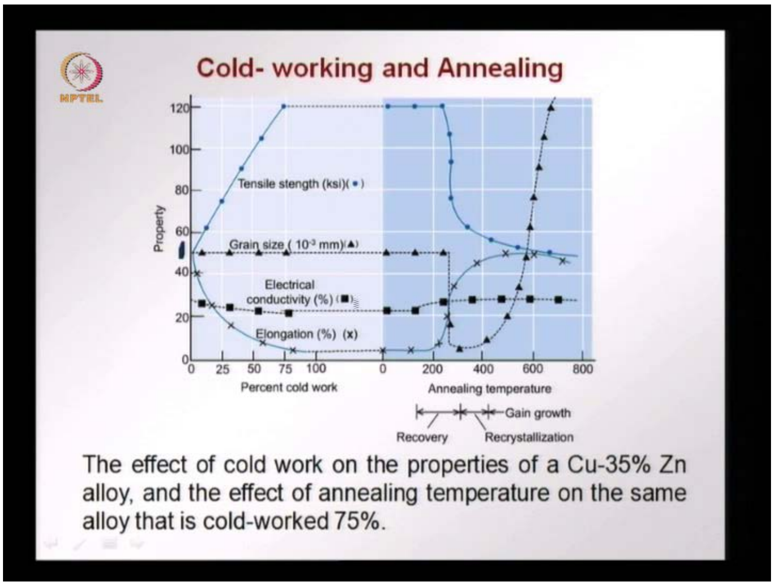

Cold- working and Annealing

The effect of cold work on the properties of a Cu-35% Zn alloy, and the effect of annealing temperature on the same alloy that is cold-worked 75%.

We can put both the phenomena that we recently discussed together cold working and annealing in the same picture. We take the case of an alloy of copper with 35 percent zinc and will see what happens during cold working to the different properties. and then what happens when the anneal the same after it has been cold work to 75 percent. So, on the left side we see the cold working part on the y axis are the different properties on the x axis.

Initially, we have the percentage cold work. So, this would be the starting point where we start of from no cold working, and we see that first as we could work this is now the cold working as we could work up to 75 percent there is almost linear increase in the tensile strength. If, now we start annealing it in the recovery phase we hardly have any change in the tensile strength, and then there is a drastic drop in the re-crystallization and grain growth phase.

Elongation on the other hand as we increase the percentage cold work decreased. Elongation decreases as we saw before the material becomes less ductile and more brittle. Then, we start annealing again initially in the recovery phase we do not see much change, but then after wise we see the ductility and elongation increase. This graph is that of grain size we found that in the process of cold working there is no change in the grain size. Neither, do we find anything happening in the recovery phase of annealing.

But, then after wise we have in the re-crystallization the formation of tiny crystals this is sudden drop in grain size and then we have larger grains growing. In this plot we also have electrical conductivity which decreases slightly due to cold working and we recovered that as well during annealing. So, these are the different processes that occur during cold working and annealing.

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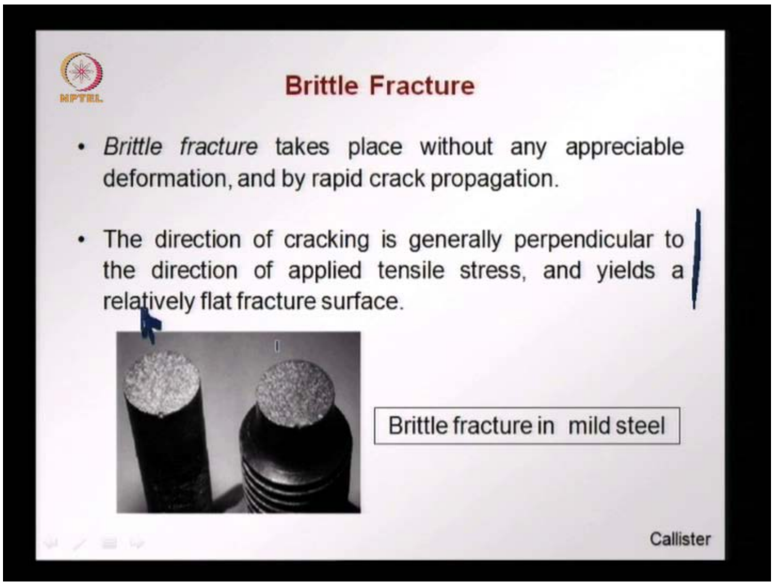

Brittle Fracture

- *Brittle fracture* takes place without any appreciable deformation, and by rapid crack propagation.
- The direction of cracking is generally perpendicular to the direction of applied tensile stress, and yields a relatively flat fracture surface.

Brittle fracture in mild steel

Callister

Now, what happens when we have brittle fracture? We had looked until now its failure that is ductile dominated by dislocation movements and yielding in metals. We can also have cases where the failure other fracture is brittle. Brittle means sudden without any large deformation occurring and the crack propagation is very fast. Here, we do not have cup and cone type of failure suppose we look at the failure of a rod Of material failing in brittle manner.

But, we have a crack that is flat the crack runs across enough flat manner and we have now the sudden failure. So, if you have brittle failure these are pictures showing brittle fracture in mild steel we will have a crack running perpendicular to the direction of the tensile stress. In this case the tensile stress is applied in this direction. We will find that the crack occurring perpendicular to it and finally, flat fracture surface.

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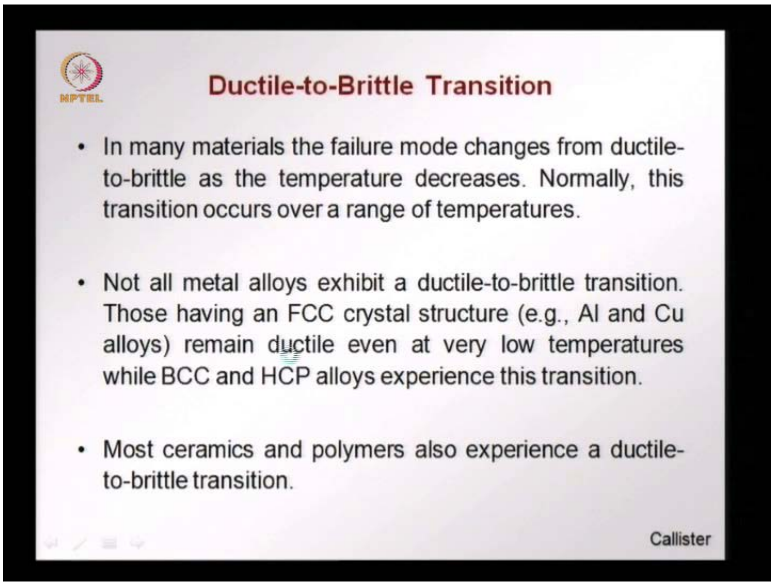

Ductile-to-Brittle Transition

- In many materials the failure mode changes from ductile-to-brittle as the temperature decreases. Normally, this transition occurs over a range of temperatures.
- Not all metal alloys exhibit a ductile-to-brittle transition. Those having an FCC crystal structure (e.g., Al and Cu alloys) remain ductile even at very low temperatures while BCC and HCP alloys experience this transition.
- Most ceramics and polymers also experience a ductile-to-brittle transition.

Callister

What is interesting is the some materials have a ductile to brittle transition? That is the same material under some conditions fails in a ductile manner and in at the conditions fail in a brittle manner. And, generally this is dominated by temperature effects. So, as temperature decreases, we find that many materials change their failure mode from ductile to brittle. This transition occurs over a range of temperatures does not occur at a fix definite temperature, but there is a gradual change over a range of temperatures in metals.

What we find is that FCC crystal structure metals for example aluminum and copper. Remain ductile even at low temperatures that is there is no ductile to brittle transition overall very large range for FCC metals. While, BCC and HCP alloys experience this transition from ductile to brittle transition. So, it also occurs different ways and different metals not all of them are the same this is the reason by we have two study and examine when the ductile to brittle transition occurs. We also find that some ceramics polymers also experience a ductile to brittle transition.

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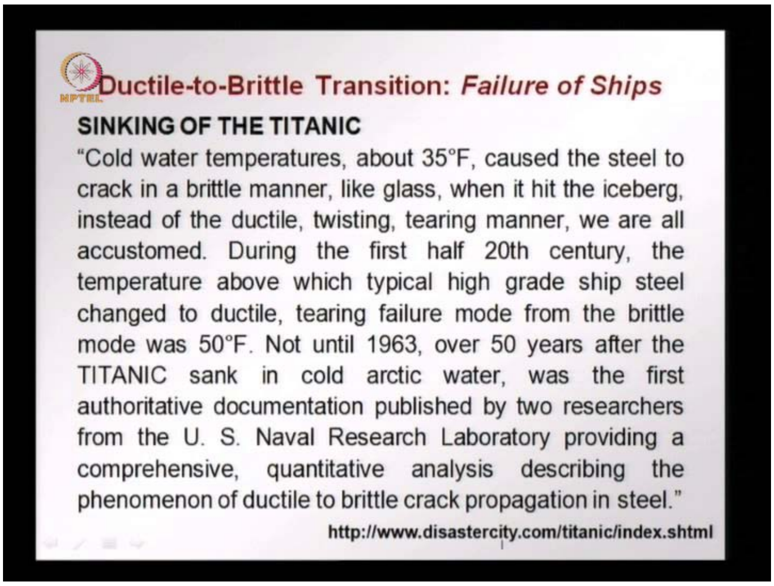

Ductile-to-Brittle Transition: *Failure of Ships*

SINKING OF THE TITANIC

"Cold water temperatures, about 35°F, caused the steel to crack in a brittle manner, like glass, when it hit the iceberg, instead of the ductile, twisting, tearing manner, we are all accustomed. During the first half 20th century, the temperature above which typical high grade ship steel changed to ductile, tearing failure mode from the brittle mode was 50°F. Not until 1963, over 50 years after the TITANIC sank in cold arctic water, was the first authoritative documentation published by two researchers from the U. S. Naval Research Laboratory providing a comprehensive, quantitative analysis describing the phenomenon of ductile to brittle crack propagation in steel."

http://www.disastercity.com/titanic/index.shtml

Now, these are some codes regarding famous failures that can be attributed to ductile to brittle transition. This is a code from this link given here disastercity.com on the sinking of the titanic. I let you read through it basically what it says is that when the titanic failed there was not enough knowledge about this ductile to brittle transition.

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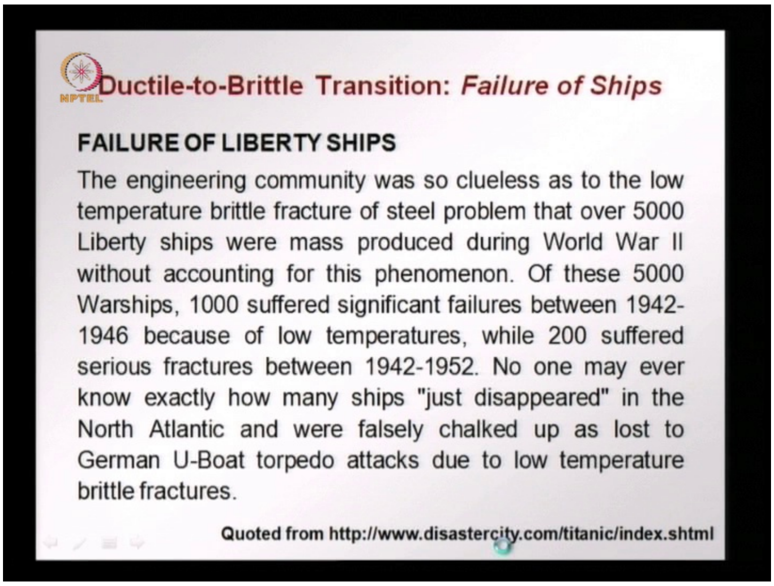

Ductile-to-Brittle Transition: *Failure of Ships*

FAILURE OF LIBERTY SHIPS

The engineering community was so clueless as to the low temperature brittle fracture of steel problem that over 5000 Liberty ships were mass produced during World War II without accounting for this phenomenon. Of these 5000 Warships, 1000 suffered significant failures between 1942-1946 because of low temperatures, while 200 suffered serious fractures between 1942-1952. No one may ever know exactly how many ships "just disappeared" in the North Atlantic and were falsely chalked up as lost to German U-Boat torpedo attacks due to low temperature brittle fractures.

Quoted from http://www.disastercity.com/titanic/index.shtml

Similar ductile to brittle transition also occurred in the failure of the liberty ships over 5000 liberty ships where produced during world war 2 without taking into account this phenomena ductile to brittle transition. About, 1000 of these failed between 1942 and

1946, because of low temperatures and 200 had serious fracture again between the periods of 42 to 52.

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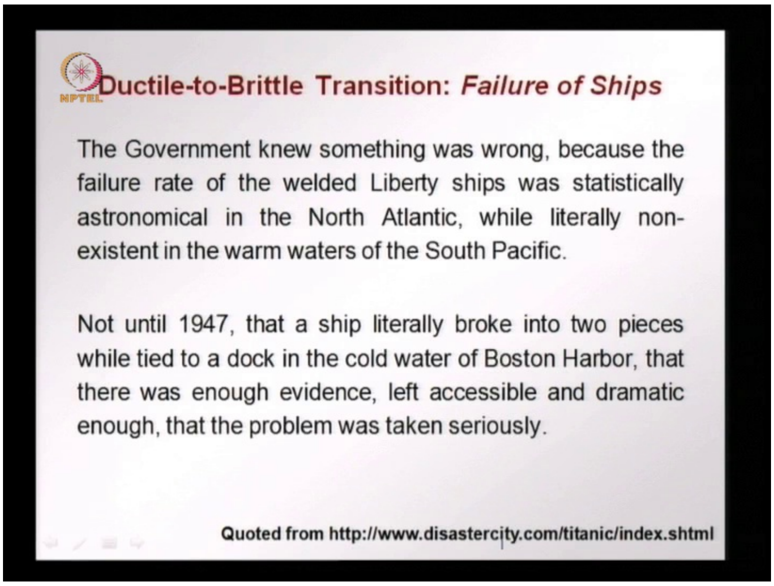

Ductile-to-Brittle Transition: *Failure of Ships*

The Government knew something was wrong, because the failure rate of the welded Liberty ships was statistically astronomical in the North Atlantic, while literally non-existent in the warm waters of the South Pacific.

Not until 1947, that a ship literally broke into two pieces while tied to a dock in the cold water of Boston Harbor, that there was enough evidence, left accessible and dramatic enough, that the problem was taken seriously.

Quoted from http://www.disastercity.com/titanic/index.shtml

The government thought that something was wrong because in the colder north Atlantic there was more failure than in the warm or south pacific. Until, 1947 this remain the mystery. Then, and 1947 a ship broke into two in the Boston harbor in the cold conditions and this was evidence that it was temperature that was breaking the ships and it was not necessarily the German submarines.

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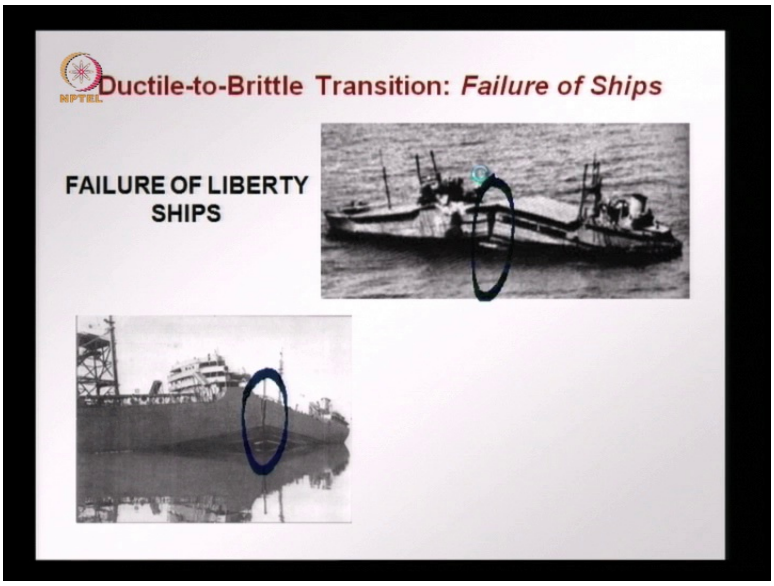

Ductile-to-Brittle Transition: *Failure of Ships*

FAILURE OF LIBERTY SHIPS

These are pictures where we see the ship breaking into half this you see is the crack occurring. So, this gave rise to this major study on ductile to brittle transition and change in design of ships and other elements.

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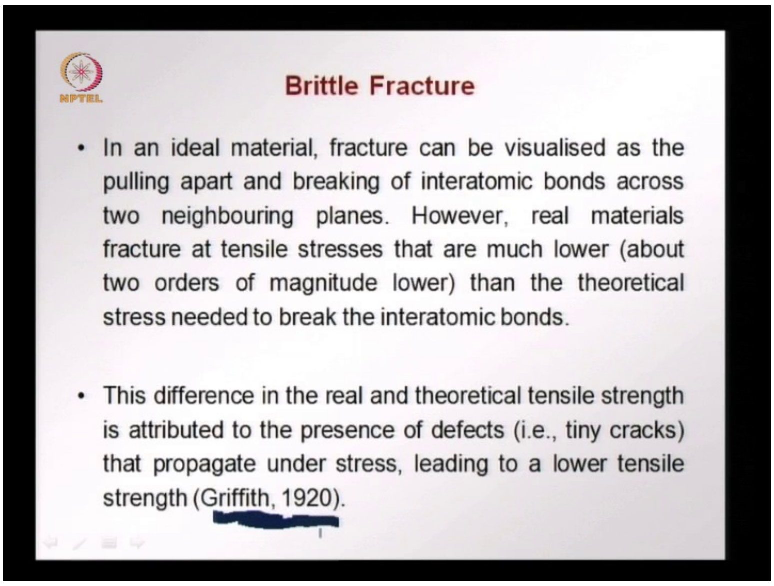

Brittle Fracture

- In an ideal material, fracture can be visualised as the pulling apart and breaking of interatomic bonds across two neighbouring planes. However, real materials fracture at tensile stresses that are much lower (about two orders of magnitude lower) than the theoretical stress needed to break the interatomic bonds.
- This difference in the real and theoretical tensile strength is attributed to the presence of defects (i.e., tiny cracks) that propagate under stress, leading to a lower tensile strength (Griffith, 1920).

Ideally, we have fracture occurring with the pulling apart of bonds in neighboring planes. However, will see later on with more detail that real material fracture at the tensile stresses that are much lower this is the problem. The failure under fracture occurs at strengths that a much lower than the theoretical tensile stress that should occur when inter atomic bonds are broken. The theoretical stress is about two orders higher than the actual failure under fracture. This difference was attributed by Griffith in the1920’s to the presence of defects. Now, tiny cracks which always occur in different materials.

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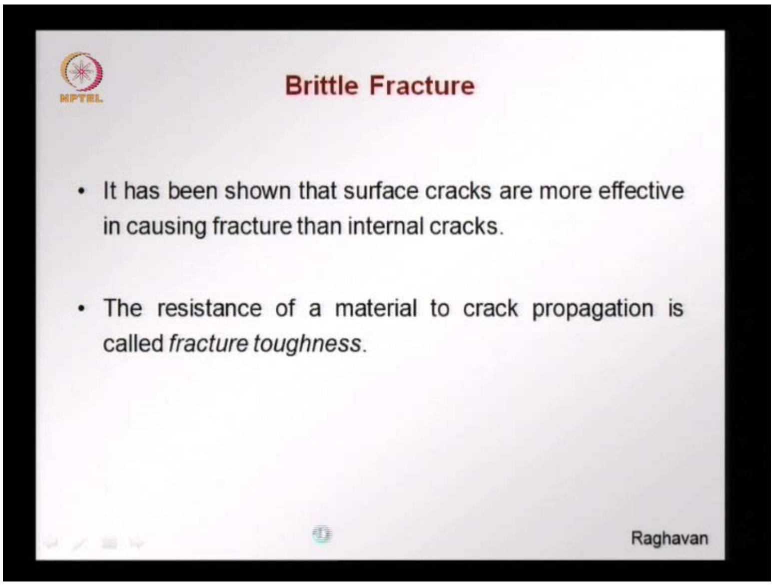

Brittle Fracture

- It has been shown that surface cracks are more effective in causing fracture than internal cracks.
- The resistance of a material to crack propagation is called *fracture toughness*.

Raghavan

We also find that surface cracks are more effective in causing fracture than internal cracks. So, surface cracks if they are eliminated will help bring down the brittle fracture. The property that governs this resistance to crack propagation is called fracture toughness. These are concept that will examine in later lecture.

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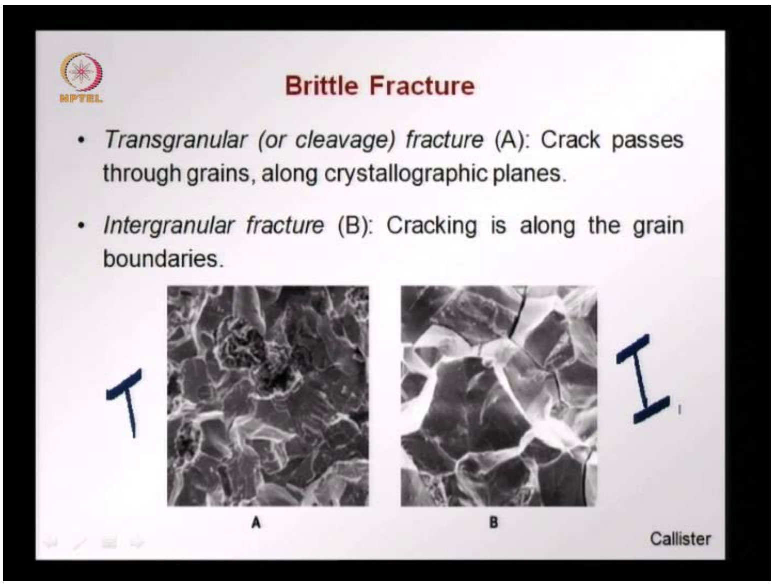

Brittle Fracture

- *Transgranular (or cleavage) fracture* (A): Crack passes through grains, along crystallographic planes.
- *Intergranular fracture* (B): Cracking is along the grain boundaries.

Callister

Fracture can now occur through grains or along the grain boundaries when fracture occurs across the grains it is called transgranular or cleavage fracture like we see here though they have the grains failing. This is the transgranular fracture. Then we have cracks that can pass through the interfaces this is called inter granular fracture cracking along the grain boundaries.

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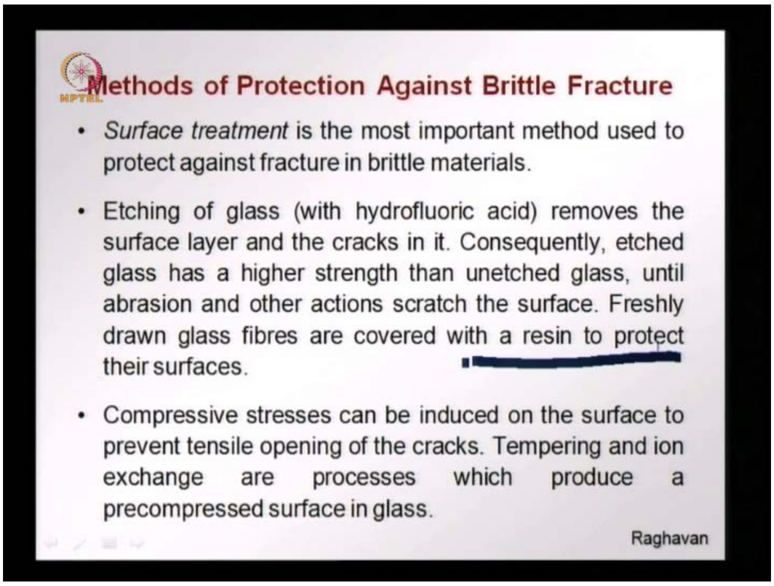

Methods of Protection Against Brittle Fracture

- *Surface treatment* is the most important method used to protect against fracture in brittle materials.
- Etching of glass (with hydrofluoric acid) removes the surface layer and the cracks in it. Consequently, etched glass has a higher strength than unetched glass, until abrasion and other actions scratch the surface. Freshly drawn glass fibres are covered with a resin to protect their surfaces.
- Compressive stresses can be induced on the surface to prevent tensile opening of the cracks. Tempering and ion exchange are processes which produce a precompressed surface in glass.

Raghavan

Finally, a comment on how to protect against such brittle fracture occurring, the most important methodology is to treat the surface if the surface. If free from defects and defects do not occur during service then the brittle material is better protected. There are two ways how surface treatment has been done in materials such as glass. One is etching see with hydrofluoric acid the surface layer is removed along with the cracks that occur in it. Consequently, the etched glass now since it does not have any defects on the surface has a higher strength then the un-etched glass.

Until, some abrasion some scratch is occur, and this can be prevented by covering with a resin on the surfaces. On the other hand again with glass and other materials, we can induce a compressive stress on the surface, which prevents the tensile opening of the cracks. that is the crack is prevented to open on the surface the defects are kept close by pre-compressing through process like tempering ion exchange. So, that the cracks to not start opening from the surface. So, this could be different methods of preventing surface defects from becoming cracks and causing brittle fracture.

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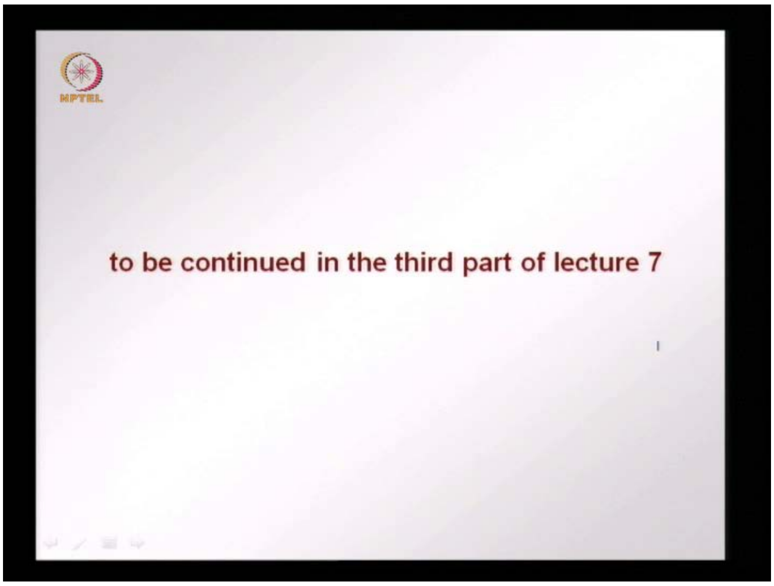

to be continued in the third part of lecture 7

So, to summarize we look that different types of stress strain behavior we look that how the cup and cone failure develops, which is typical characteristics of ductile failure under tension we also look that how brittle failure occurs with the sudden cracking. And, we have close, this part of a lecture seven by looking at surface treatments underlining the influence of the surface defect. In the next part of this lecture we look at phenomena such is fatigue and creep which lead to failure. And, here again failure occurs at stresses that a lower then the strength of the material, and the occurs sometime in a brittle manner. That is why we are concerned about such type of failure.

Thank you.