Structure of Materials
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Lecture - 45
Phase Transformations

We have studied Phase Transformations, and even when we consider a simple phase transformation for instance.

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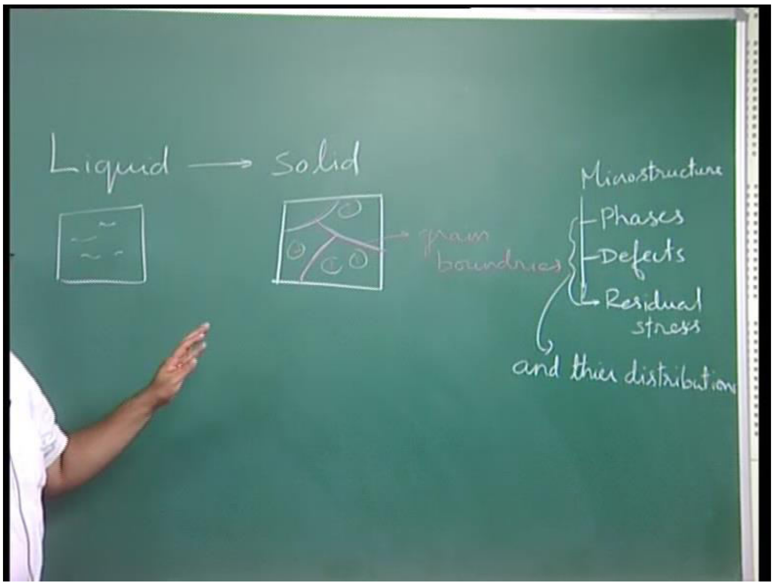

Suppose, I am talking about solidification from the liquid state to the solid states, and now for now I will assume that there is pure metal which is in the liquid state, which is getting solidified. So, the final solid typically consists of a polycrystalline microstructure; that means, there are entities like grain boundaries and within these grains themselves there are defects like dislocations present. That means, that along with this phase transformation I have a complete transformation of the microstructure, and we have already defined a microstructure as.

So, along with this phase transformation where as the simplest one we can think of a pure liquid going to a solid. We have complete change in microstructure, for instance the solid phase forms there are defects like grain boundaries and dislocations, and there are stress fields associated with these dislocations. That means that the entire or the components of the microstructure, change when there is a phase transformation, but let us now consider certain other type of transformations where in true sense there is no change in the what you might call the phases.

But, it is the circular aspects of microstructure which get transformed, so let us consider those kind of features in this.

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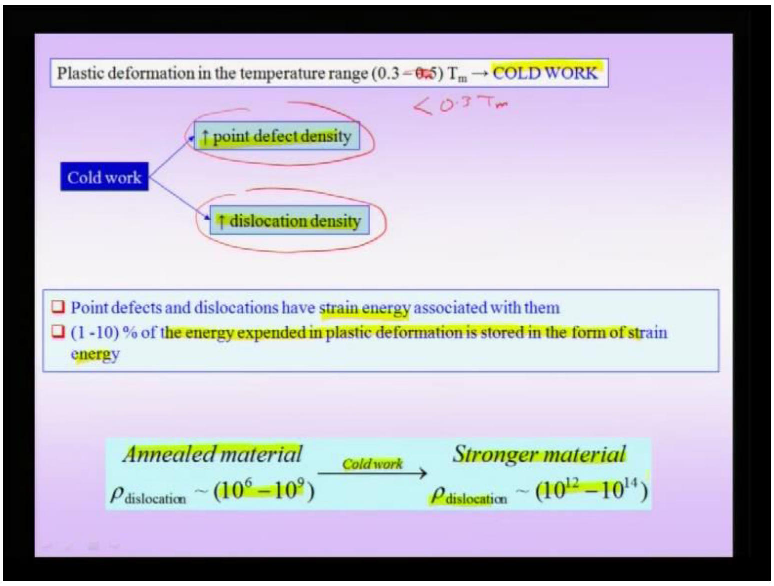

Plastic deformation in the temperature range (0.3 – ~~0.5~~) T_m → COLD WORK

$< 0.3 T_m$

Cold work

↑ point defect density

↑ dislocation density

- ☐ Point defects and dislocations have strain energy associated with them
- ☐ (1 -10) % of the energy expended in plastic deformation is stored in the form of strain energy

Annealed material $\xrightarrow{\text{Cold work}}$ *Stronger material*

$\rho_{\text{dislocation}} \sim (10^6 - 10^9)$ $\qquad$ $\rho_{\text{dislocation}} \sim (10^{12} - 10^{14})$

And we talk about three of them here, one is called recovery, other is re-crystallization and third is grain growth. Suppose we elastically deform a material, and we typically call this when we do it under cold conditions as cold work. Under such circumstances typically, the point defect density typically vacant seas etcetera are increases, and also the dislocation density increases.

Now, using at the end of these set of slides we will and try to understand that what is the correct definition of cold work, for now we will assume that it is a temperature regime. That means, we are at a low temperature regime, typically let us assume now that we are less than 0.3, let us mark out this we are less than about 0.3 T m and we are doing a working which is called cold working. And in the process we are increasing the defect density, which includes the point defect density, and the dislocation density.

So, when I am doing cold working the material becomes a store of energy, and the string energy in the material increases. Typically, if you are spending say x amount of energy about 1 to 10 percent of this energy expanded is stored in the form of strain in the material. And this strain typically we have seen is where the increase in dislocation density and other defects in the material, now that implies that suppose I have an well annealed material which is of course, well annealed polycrystalline material, like let me take copper or aluminium.

The dislocation density is of the order of about 6 to 10 power 9, and when you do cold working of this material, not only that is the material becomes stronger. Because, of this cold work, but the dislocation density increases to about 10 power 12 to 12 power 14. In fact, it is increase in this location density which is causing the increase in strength of the material. So, there is a few orders of magnitude increase in dislocation density, and as you have seen these the string fuels of these dislocations store energy.

And about say for instance about one tenth or about one hundredth of the energy expended in cold work is stored as strain energy within the material.

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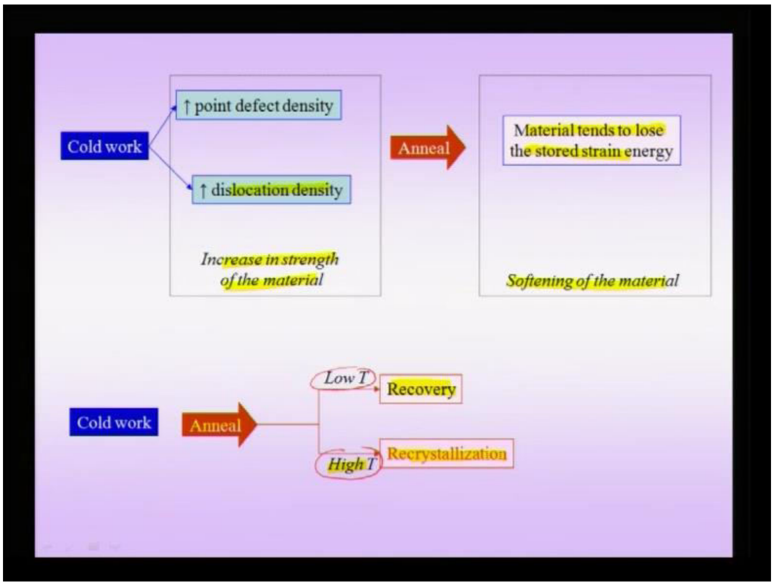

Cold work

↑ point defect density

↑ dislocation density

Increase in strength of the material

Anneal

Material tends to lose the stored strain energy

Softening of the material

Cold work

Anneal

Low T

Recovery

High T

Recrystallization

Now, when you anneal such a material; that means, heat it to an some temperature and hold it, the material tends to lose the stored energy, and tries to come back to it is original state. That means, the state wherein the defect density is small, and that implies if I am doing cold work, I have an increase in defect density leading to an increase in strength of the material. And after annealing the material becomes softer and the dislocation density would decrease.

This annealing itself can be done under two circumstances; that means, we can do an annealing under slightly lower temperatures or we can do it at a higher temperatures. At lower temperature of course, we are supplying less amount of activation energy, and the processes which take place are collectively called recovery. And at higher temperatures we have the phenomenon of re-crystallization, and we will try to understand these technical terms in little more detail in the coming slides.

So, we have a cold work material which is been plastically deformed for instance by like rolling, forging, extrusion, etcetera. And after the material has been cold worked, if you heat it to a certain high temperature and hold it, then there Rae two kinds of process taking place within the material, depending on the temperature to which you heat. One at low temperatures you have recovery, and at higher temperature you have a phenomenon known as re-crystallization.

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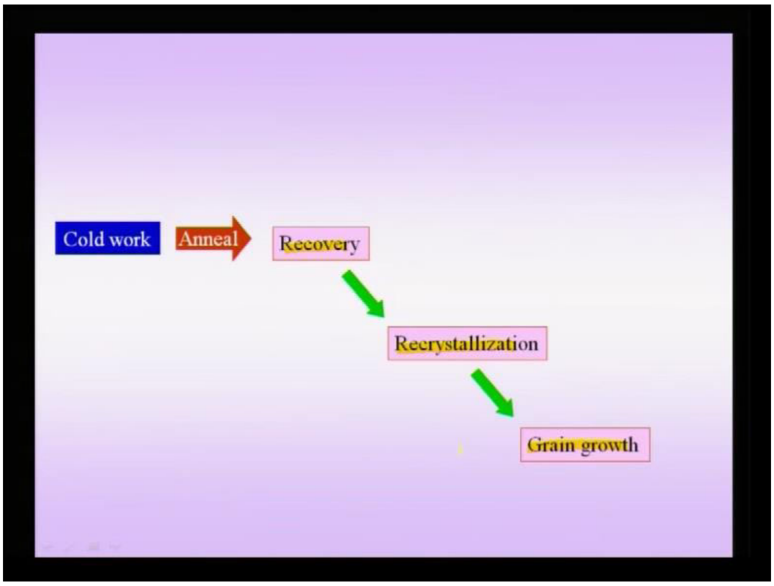

Cold work

Anneal

Recovery

Recrystallization

Grain growth

Now, therefore, during annealing you can and if you give a sufficient kinetic energy, suppose you are holding at high temperatures. You would have recovery followed by re-crystallization followed by grain growth, in the case of even high temperatures there would be recovery. But, then since the dominant process re-crystallization we have written it as re-crystallization, so in the whole process we will see that the physical properties of the material changes.

And in fact, physical and electrical properties etcetera change and in the process you would notice that with the material.

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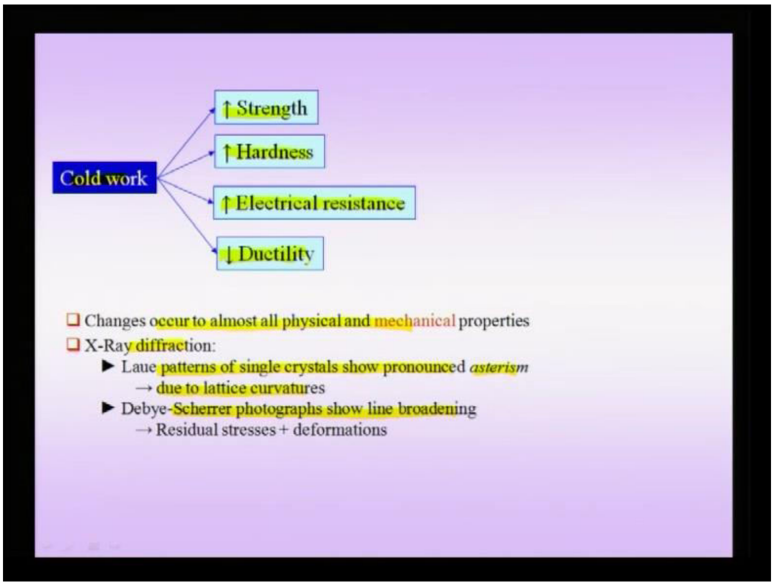

Cold work

↑ Strength

↑ Hardness

↑ Electrical resistance

↓ Ductility

❑ Changes occur to almost all physical and mechanical properties

❑ X-Ray diffraction:

- ► Laue patterns of single crystals show pronounced *asterism*
  → due to lattice curvatures
- ► Debye-Scherrer photographs show line broadening
  → Residual stresses + deformations

Exchanging it is properties due to a change in microstructure, and now as you point out there is actually no phase transformation involved in these process, it is actually what you might call micro structural transformation. So, cold work leads to an increased strength, and increased hardness it also leads to an increased electrical resistance because, of the point defect density increase, and dislocation density increase.

But, the ductility of the material comes down, and changes typically occur to all physical and mechanical properties, which are we call it structured dependent properties or the micro structured dependent properties. In X-ray diffraction you will notice that, Laue patterns or single crystals show for pronounced asterism; that means, they look like star like, and they are no longer well defined spots, and these are due to lattice curvatures. Debye-scherrer photographs use show line broadening and in fact, this line broadening can be used to characterize the strain in the material.

That means, we can compute the strain in the material, by knowing the amount of line broadening. So, cold work changes many of the physical and mechanical properties, which include the strength, the hardness, the electrical resistance and ductility, and if you do annealing the reverse. You can actually reverse and get back the material to it is original well unhealed state.

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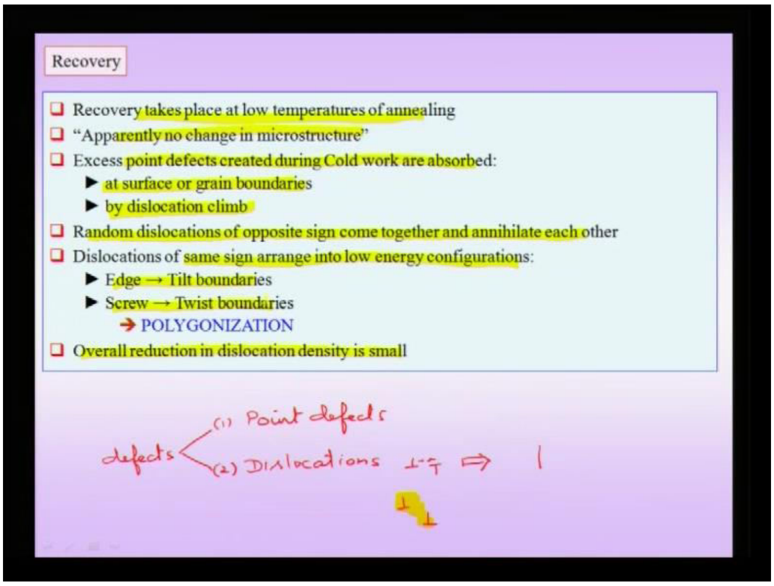

Recovery

- ❑ Recovery takes place at low temperatures of annealing
- ❑ "Apparently no change in microstructure"
- ❑ Excess point defects created during Cold work are absorbed:
  - ▶ at surface or grain boundaries
  - ▶ by dislocation climb
- ❑ Random dislocations of opposite sign come together and annihilate each other
- ❑ Dislocations of same sign arrange into low energy configurations:
  - ▶ Edge → Tilt boundaries
  - ▶ Screw → Twist boundaries
    - → POLYGONIZATION
- ❑ Overall reduction in dislocation density is small

defects (1) Point defects
(2) Dislocations ⊥ ⊤ ⇒ |
⊥ ⊥

Now, what is the storm recovery mean, recovery takes place at low temperatures of annealing. And if you look under an optical microscope, and not under for instance an higher transmission electron microscope, but in an optical microscope or even a scanning electron microscope, you would note that there is apparently no change in micro structure. And this is because, what is happening is that, the excess point defects creating during cold work are abdorbedt or absorbed at surfaces and grain boundaries, and also by dislocation client.

And as you know that, it is not possible to absorb vacancies or clusters of vacancies, using optical or scanning electron microscope. Even in a transmission electron microscope, it is actually difficult observe vacancies, and you have to use some indirect methods to find evidence for the presence of vacancies. Now, I could certain vacancy clusters can be located in an transmission electron microscope, so during recovery there is a pronouns decrease in the excess point defect density.

And for instance vacancies which are created during cold working or absorbed at grain boundaries or surfaces, and by even by dislocation claim the vacancy concentration decreases. Now, additionally one more thing happens to dislocations, the random dislocations of opposite sign come together and anneal it at each other. Now, we will see the schematic of that in the next slide, and the dislocation tend to of the same sign arrange into low energy configuration.

First thing of course, that you have two kind of defects which we are talking about, which we discussed before when we talked about cold work, one is point defects. And typically the important one being vacancies, and the second one is dislocations, so we have two kind of defects which are important, which have been altered during cold work. And when you are doing recovery, both these defects are affected more, so the vacancies and less the dislocations.

But, we talk about defects and now the pronounced effect is to the one, which is now my point defects. And of course, this may include self interstitials, and if you are talking about dislocations there is a lesser effect on dislocations, what happens is that dislocations of opposite sign come together, and anneal it each other. That means, they come towards each other and finally, you will land up with the configuration in which you have a full atomic plain; that means, no dislocation.

Additionally if you have dislocations of the same sign, which are lying on different slip lines. Then we will see in the as in the next micrograph that they can come together to form low energy configurations, like low angle grain boundaries, so we will come to the slide in a little more detail. So, but the important point note is that, though there is a small reduction dislocation density, and there are some low energy configurations which are arising during this recovery, but the overall reduction in dislocation density is small.

So, this is an important point to note, and when these dislocations of same sign come together once in the schematic here. They if they happened to be a edge character, then they can form tilt boundaries, and if they are of screw character they can form twist boundaries. And when this process in which these slow energy configurations of a dislocations arise is called polygonization. So, let us try to understand this polygonization in the next slide.

So, because of the presence of dislocations of course, first we said that if the dislocations are of opposite sign, they can come together and anneal each other. So, therefore, there is now only continuous plains and there are no dislocations, there is no atomic plains and there is no dislocation. Originally for instance we might have started off with the dislocation of one side, and a dislocation of another side lying on the same slip line. So, by this process they can anneal it at each other, but suppose I am talking about dislocations of the same sign present in a certain excess.

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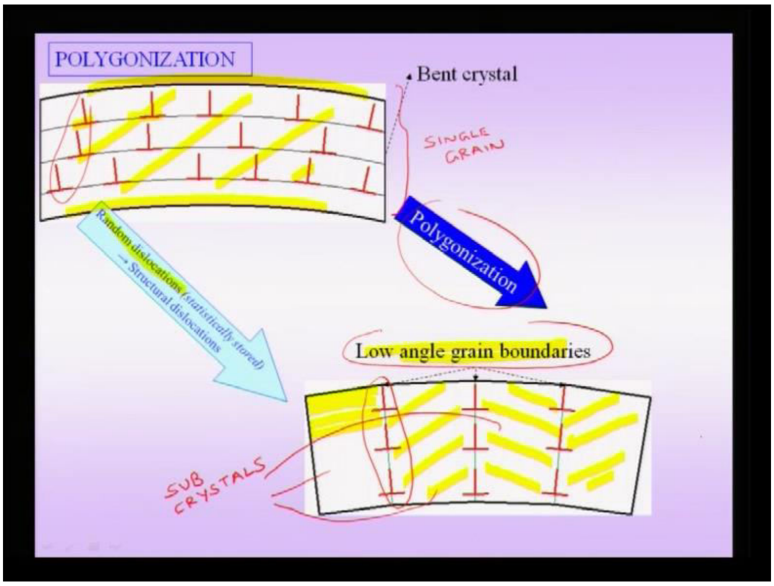

POLYGONIZATION

Bent crystal

Polygonization

Random dislocations (statistically stored) → Structural dislocations

Low angle grain boundaries

Then you can see that, so many dislocations of the same sign, give actually bent the crystals. So, we have the bending of the crystal, so there is an pronounce bending of the crystal, so they have a bending of the crystal, though this bending is small, but presence of many dislocations can give a certain amount of bending to the crystal. And this bending of the crystal has we noted before, we noted here that this due to lattice curvatures, these can lead to effects on the Laue patterns if you take them Laue diffraction patterns.

Now, during recovery of course, the thermal energy is not, so high, so these dislocations cannot move a large distances, but they can come together in close vicinities. That means, say few dislocations lying in this regime, they can all come together which are all of course, on a different slip plane. Say for in these three dislocations can all come together and form a low angle grain boundary the important of course, this phenomenon overall is called polygonization, wherein originally there was a single crystal a single bent crystal as you can see here.

So, this is my single bent crystal this is now forming sub crystals, so these are all now my sub crystals. So, this is sub crystal 1, then you may have a core sub crystal 2, and you can have a sub crystal 3, and a sub crystal 4, so these original single crystal is now split into sub crystals, which are now between them has the low angle grain boundary. So, in this process which is called polygonization, an important phenomenon which takes place is that, these random dislocations which are otherwise called statistically stored dislocations, become structural dislocations.

We know that, the role of statistically stored dislocations in plasticity is very different from those of structural dislocations. But, in this process we see that random statistically stored dislocations, by their motion and rearrangement become structural dislocations. And therefore, the now the material is split into sub grains, and there are no low angle grain boundaries between these sub grains, so this is now my. So, let me summarize what takes place during recovery.

During recovery a material partly goes down to a lower energy state, but because of thermal activation is not very large, we are not heated into a very high temperature. The major reduction is actually in the point defect density, which could include self interstitials, and vacancies. And these vacancies for instance could be absorbed at surface or grain boundaries or dislocation climb can lead to; that means, that suppose had a dislocation here.

And there are some excess vacancies here, these can come and sit at the base; that means, the atom can come here, and fill up the space. So, in that process atomic dislocation has gone up one level, so this can be the climb process by which vacancy concentration can come down of course, the opposite will takes if a self interstitial, diffuses to the core of the dislocation. And more importantly we noted that, though there is no observable change in an optical or a scanning electron micro graphs.

There could be rearrangements of dislocations etcetera, which can be seen in a transmission electron microscope. But, the overall deduction in density of dislocations is only small; that means, the material has a reasonable dislocation density, and we may end of forming this polygonized for sub grain structure.

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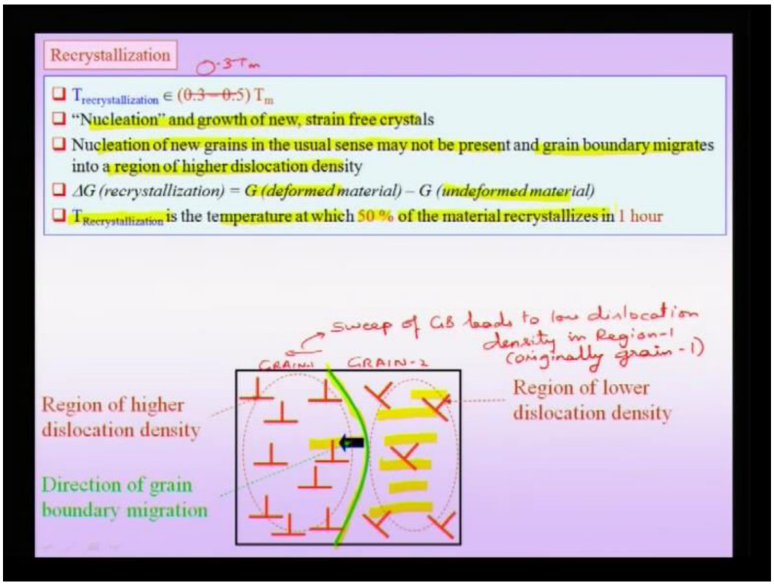

Recrystallization

0.3 T_m

- ☐ $T_{\text{recrystallization}} \in$ (~~0.3—0.5~~) T_m
- ☐ "Nucleation" and growth of new, strain free crystals
- ☐ Nucleation of new grains in the usual sense may not be present and grain boundary migrates into a region of higher dislocation density
- ☐ *ΔG (recrystallization) = G (deformed material) – G (undeformed material)*
- ☐ $T_{\text{Recrystallization}}$ is the temperature at which 50 % of the material recrystallizes in 1 hour

And now suppose I do my heat treatment at even at higher temperatures, say for instance above say for instance 0.3 T m. So, I can do my heat treatment above 0.3 T m, so then there is a possibility that now I can refresh my entire microstructure; that means, now we can have nucleation and growth of new strain free crystals. And this implies that the dislocation density and the vacancy or the point defect density in these new strain free crystals will be small, and the material would have been restored to its original annealed state, which was present before cold working started.

So, we can have nucleation and growth of strain free crystals, sometimes nucleation of new grains in the usual sense may not be present. And grain boundary migration to regions of higher dislocation density, may lead to the formation of strain free grains. So, you can see in the schematic below for instance there is a grain boundary here, and one side of the grain boundary there is a region of low dislocation density. On the other side of the grain boundary, there is region of higher dislocation density.

And this grain boundary can move sweep in to this, and we are assuming this is now an high angle grain boundary, sweeps into the region of higher dislocation density. And in the process the dislocations are absorbed with the grain boundary, and the overall dislocation density in the left hand side crystal also or the left hand side grain also decreases. So, the region which was originally grain one is will have a reduced dislocation density of course, we may have of course, formation of new, strain free crystals it may grow, which also leads to a reduced dislocation density.

And of course, the driving force for this process is a fact that, the free energy of the deformed crystal is higher than the free energy the unreformed material. And therefore, you have a free energy benefit, when that material comes down to a low energy state, there is a temperature which is defined in the context, which is called the re-crystallization temperature. Because, suppose I am using re-crystallization as an intermediate step during say for instance some kind of a mechanical working process like forging, then I need to hold my material at certain temperature.

So, that I have significant amount of soften material, which can take for the deformation without cracking. So, temperature re-crystallization unfortunately is a certainly notional term, which involves both percentages and time in it is definition, so T re-crystallization or the temperature re-crystallization, is the temperature at which 50 percent of the material re-crystallizes in 1 hour. That means, that here the definition involves both percentages and time, we are not talking about we are not waiting for infinity, we are not talking about instantaneous re-crystallization of the entire material.

But, we are saying that 50 percent of the material; that means, 50 percent of the stored energy needs to be reduced, and this needs to takes place within an hour. So, therefore, if I keep a material at the re-crystallization temperature for 1 hour, then I can assume that 50 percent of a material will be re-crystallized, and it will be good enough to be cold worked again.

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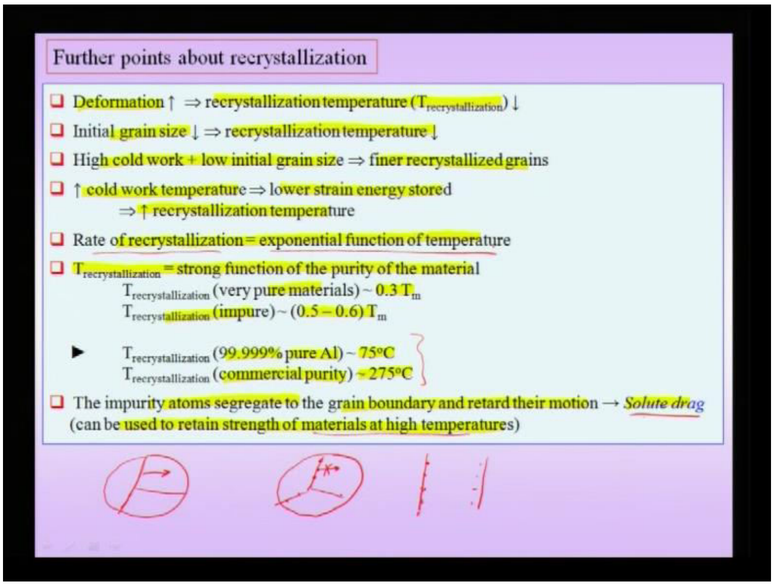

Further points about recrystallization

- ☐ Deformation ↑ $\Rightarrow$ recrystallization temperature ($T_{recrystallization}$) ↓
- ☐ Initial grain size ↓ $\Rightarrow$ recrystallization temperature ↓
- ☐ High cold work + low initial grain size $\Rightarrow$ finer recrystallized grains
- ☐ ↑ cold work temperature $\Rightarrow$ lower strain energy stored
  $\Rightarrow$ ↑ recrystallization temperature
- ☐ Rate of recrystallization = exponential function of temperature
- ☐ $T_{recrystallization}$ = strong function of the purity of the material
  $T_{recrystallization}$ (very pure materials) ~ $0.3\ T_m$
  $T_{recrystallization}$ (impure) ~ $(0.5 - 0.6)\ T_m$
  - ► $T_{recrystallization}$ (99.999% pure Al) ~ 75°C
    $T_{recrystallization}$ (commercial purity) ~ 275°C
- ☐ The impurity atoms segregate to the grain boundary and retard their motion → *Solute drag* (can be used to retain strength of materials at high temperatures)

Now, if this re-crystallization or the working itself is done at a higher temperature, wherein re-crystallization can take place, actively during working such are re-crystallization would actually be called dynamic re-crystallization. That means, that I do not have to have a separate re-crystallization step between the working steps therefore, I am doing working at hot working. And again let me one once more that these term terms like hot working, and cold working are technical terms.

And we will be defining them a in the coming slides, but the important point is that suppose I do my working at high enough temperature that re-crystallization is actively taking place. While the deformation is in progress that implies that I do not have to have a separate step, wherein I have to re-crystallize the material before I do further deformation, a few points about re-crystallization temperature. So, once again what is the definition of re-crystallization temperature, it is the temperature at which 50 percent of material re-crystallizes in 1 hour.

If you increase the amount of deformation, the re-crystallization temperature decreases; that means, more the deformation I give, the lower the temperature I have to heat to form these strain free crystals. If my initial grain size decreases, the re-crystallization temperature decreases; that means, that I have and also if you have a high amount of cold work. That means, higher amount of deformation along with low initial grain size, the finer will be the final re-crystallized grains.

Therefore, if I am interested in producing a fine crystallized size, then I need to start of course, with the lower grain size, and I have to do high amount of cold work. And if the cold work temperature increases, then the lower amount strain energy is stored in the material. Because, as I pointed out some of these process can actually of recovery etcetera can take place, while deformation is in progress and therefore, my re-crystallization temperature increases, by less amount of energy is stored.

The rate of re-crystallization is an exponential function of temperature, this is something like the Arrhenius behaviour. But, we have to note that at the heart of these re-crystallization, there are not one single process, but multiple complex process therefore, the activation energy which you calculate using this Arrhenius kind of function, is not for a single process, but for a complex set of processes. The re-crystallization temperature is a strong function of the purity of a material.

That means, that suppose I take a re-crystallization temperature for instance very pure materials of the order of 0.3 T m. But, suppose I take impure version of the same material, it is between 0.5 and 0.6 T m like for an example, if you take pure aluminum which is about 99.999 percent aluminium. The re-crystallization temperature about 75 degree Celsius, but suppose I take commercial purity aluminum which may have other impurities, then the re-crystallization temperature increases to about 275 degree Celsius.

The reason for this is that the impurity atoms, and all the impurity atoms may not always be equally soluble in the lattice or the grain boundary, many of them may not have pure solubility in aluminum for instance of the lattice. And therefore, they typically tend to segregate at grain boundaries, and these typically they start the motion of the grain boundary itself, which is called solute drag. And this can be used to retain the strength of materials at high temperatures.

So, what we are talking about here suppose I had a pure material, whose grain boundary now this is my polycrystalline material. And therefore, there are grain boundaries and this grain boundary is pure, on the other hand in a material of lower purity you would find that the at least there are some elements, which can do segregate at grain boundaries. Now, if this grain boundary has to move this implies suppose I have my grain boundary, and there are solute atoms which are segregated to this grain boundary.

If this grain boundary moves out, this implies that the solute atoms would be left inside the grain. This is an energetic un-favorable situation because, these elements are typically not very soluble in the lattice. Therefore, what would happen is that, these elements have to defuse along with the grain boundary, so then they can remain segregated at the grain boundary. And this whole process; that means, coupled processes is less free as compared to just the motion of the grain boundary.

So, these grain boundaries can move easily, these grain boundaries with segregations cannot move that easily. And therefore, these grain boundaries feel what you call a solute drag, and in the process the re-crystallization is difficult in such materials, and this solute drag can be used to retain the strength of materials at high temperature. That means, you do not have a re-crystallization taking place readily; that means, the energy has put in a cold work the stronger material, remains strong even at a higher temperatures.

So, as I pointed out just let me repeat this, the impurity atom segregate to the grain boundary, and retard their motion. This process of solute drag can be used to retain the strength of materials at high temperatures, apart from of course, solute atoms you may also have second phase particles precipitates, which set at a grain boundary which also may actually retard the motion of grain boundaries. So, let us try to understand summarize this slide that what are the factors that affect re-crystallization, we are worried about the amount of or the re-crystallization temperature in particular.

So, we are worried about the amount of deformation I have cost to the material, what temperature did I cause this deformation. In other words how much of this energy I put actually is stored in the microstructure, in the form of detects and we have noted higher the deformation or higher the energy we have stored lower will be the re-crystallization temperature. Additionally we have noted that it is the function of the purity of the material, so we have to worry about the amount of deformation you put in, the purity of the material, the lesser the purity higher will be the re-crystallization temperature.

As nicely demonstrated for the case of aluminum, where the re-crystallization temperature can drastically increase, if you take an impure material. Further we also have to worry about the grain size of the starting material which was deformed, additionally we had also noted that the rate of re-crystallization is an exponential function of temperature.

And it looks like an Arrhenius equation, but then this activation energy as we should note is a representative many, many complex process taking place and should not be interpreted in a simple term, as if it were a single term as if re-crystallization for a single fundamental process.

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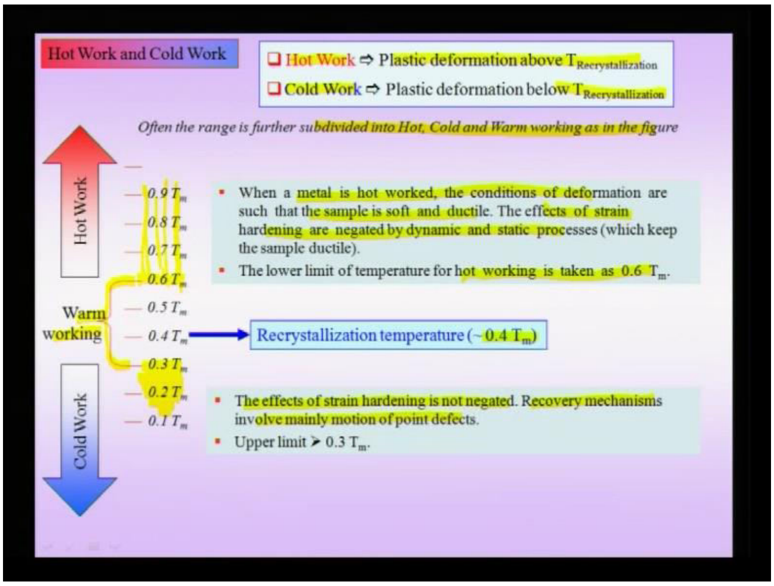

Hot Work and Cold Work

☐ Hot Work ⇨ Plastic deformation above $T_{Recrystallization}$

☐ Cold Work ⇨ Plastic deformation below $T_{Recrystallization}$

Often the range is further subdivided into Hot, Cold and Warm working as in the figure

- When a metal is hot worked, the conditions of deformation are such that the sample is soft and ductile. The effects of strain hardening are negated by dynamic and static processes (which keep the sample ductile).
- The lower limit of temperature for hot working is taken as 0.6 T_m.

Recrystallization temperature (~0.4 T_m)

- The effects of strain hardening is not negated. Recovery mechanisms involve mainly motion of point defects.
- Upper limit ➤ 0.3 T_m.

Now, we are right in a position to define, what is cold work, what is hot work or what is cold working and what is hot working, and further what we can call as warm working. So, if you because, now we have a correct platform to define these terms, if you do plastic deformation above the re-crystallization temperature, this is called hot working. And that implies that the material, can spontaneously re-crystallize as the deformation is taking place, and this implies also that the material constantly remains soft, and it is ductility is not lost while working is taking place.

On the other hands suppose you do plastic deformation below the re-crystallization temperature, it is called cold work. And this range can be further be sub divided into three regimes, as suppose I do for instance typically re-crystallization above 0.6 T m I can call it is hot working. If I do it in the low temperature regime below 0.3 T m, so this is my regime, then I call it cold working where in typically my material is becomes a battery of energy, these the defect density increases.

That means, that in the cold working regime, the effect of strain hardening are not negate it, recovery mechanisms involve mainly motion of point defects. And my material tends to accumulate these defects and it is ductility would reduce, but strength would increase.

When a material is hot worked on the other hand above this 0.6 T m this regime, so I am in this high temperature regime, then the sample remains soften ductile the effect of strain hardening are negated by dynamic and static process, which keep the material ductile; that means, that there are process taking place.

While my deformation is happening, the lower limit of hot working is typically taken as 0.6 T m. The temperature regime between the two, which is now between 0.6 and 0.3 T m is often called warm working, wherein of course, there are some amount of recovery and some amount of re-crystallization taking place. But, it is a regime between hot working and cold working, so if a person wants to increase the strength of the material, he would do cold working.

On the other hand he wants to maintain the give extended deformation of the material, without any intermediate processing steps like re-crystallization. He would actually do hot working of the material, so somewhere around between the 2 is typically coated as a re-crystallization temperature which is above 0.4 T m.

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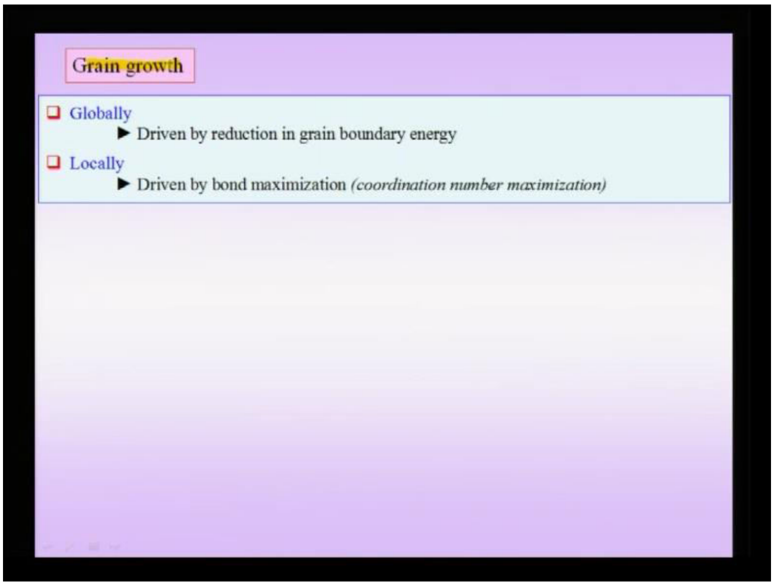

Grain growth

- ❑ Globally
  - ► Driven by reduction in grain boundary energy
- ❑ Locally
  - ► Driven by bond maximization *(coordination number maximization)*

Finally even in a re-crystallization material there is of course, the re-crystallization material is in a lower energy state as compared with the cold work material. Because, now my dislocation density is smaller, my point defect density is smaller, still we have energy stored in the form of grain boundaries, which means there is interfacial energy in the form of grain boundaries. And this energy the crystal can lower, by causing a phenomenon known as grain growth.

In grain growth, what we are noticing is that typically grain growth implies of course, all the grains cannot grow, what it implies is that, the larger grains grow at the expense of smaller grains. So, that my overall grain size decreases, so let me show this schematically on the board.

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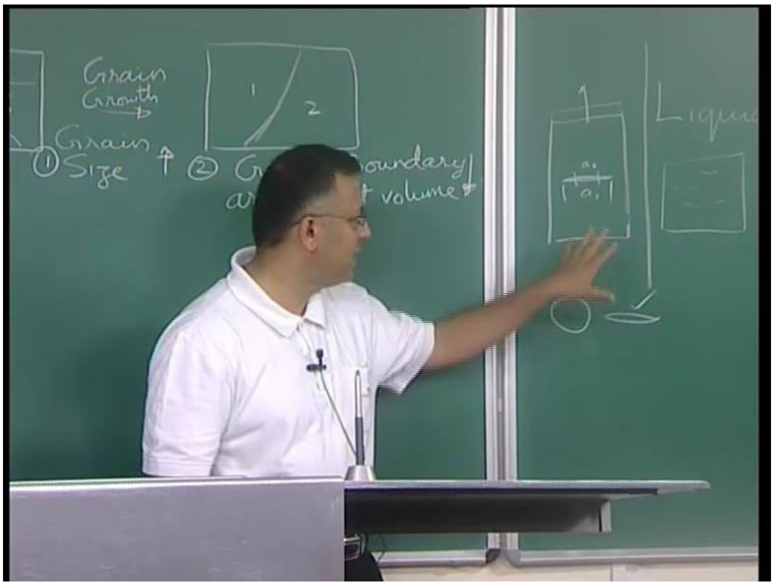

So, initially we have say for instance a fine grain material, which could be of course, re-crystallized material. So, I have my grain structure, and after grain growth I would notice typically that my grain size would have increased, so for instance they were, so many grains in this place 1, 2, 3, 4, 5, 6, and I have only 2 grains in this place. So, my I have, so grain growth implies that my average grain size increases; that means, the grain boundary area per unit volume decreases, the grain size increases number 1.

So, what is the driving force for this, the driving force for the factor the grain boundary area per unit volume in a fine grain structure is more as compared to this. That means, during grain growth my grain boundary area per unit volume decreases, which means my energy associated with the grain boundaries decreases. This is happening by an increase in grain size of course, grain size increases not means each of these grain size increasing.

Then of course, for instance in a structure like this that this could be small grains like, so when the small grain may vanish. And this will typically happen at expense of the larger grain; that means, the smaller grains vanish at the expense of the larger grains, so two important things have to note, to overall there is a reduction in interfacial energy. As I groom from a fine grain material to force grain material, my because of increase in grain size of course, further my strength decreases as compared even to a what you might call a well re-crystallized state.

Because of that the grain size goes into hall petch relationship for the determination of strength, it means the instant would decrease from when you go from here to here. That means, even though I do not have a very high dislocation density or the dislocation density does not change, much when I go from an fine grain to a coarse grain during grain growth, what happens typically is that my overall strength can drop because, of the hall petch effect.

Now, what drives this process is globally is very clear, it is a reduction in the grain boundary energy. So, globally it is actually a reduction in grain boundary energy, which drives this process, but for every process to take place we have to worry about two criteria, one is known as the global criteria which is typically a thermodynamic criteria. But, additionally we also have to about local criteria, which sometimes may behave like a stress or a stress intensity or even like a local energy density criteria.

To give an example for instance, suppose I am having a material with the crack in it, suppose I have a body allay body in which I have a crack. And I cause deformation of this body, stretch it to a little bit and hold it, then this strain energy stored in the material can drive the crack growth. But, the global I globally can understand suppose this crack grows from length to a longer length, so my original length is a 0 and it goes to a longer length a 1.

Then this strain energy is relived, and this strain energy now goes in the form a goes to the formation of the enter part of it goes to the formation of the interfacial energy or the broken bonds, and the overall strain energy of that material comes down. But, suppose for this crack growth to take place, I know that my strain energy drives this whole process. But, on the other hand if suppose I take a circular crack, visa via sharp crack like these it is clear that this stress concentration which needs to cause braking of bonds is lower in the case of circular crack as compared to a sharp crack.

That means, here I would expect better chance of my crack growth to take place; that means, even though the overall energy is stored in the body may be larger, crack growth will not takes place. Because, locally it is not satisfying the fact that, then enough energy density or enough stress is not available at the tip of the crack to break the bonds.

So, therefore, even as in the case this crack growth problem, we have also have to worry about not only about the global criteria for also about the local criteria. And locally it is bond maximization or what you might call co-ordination number maximization, which drives my grain growth.

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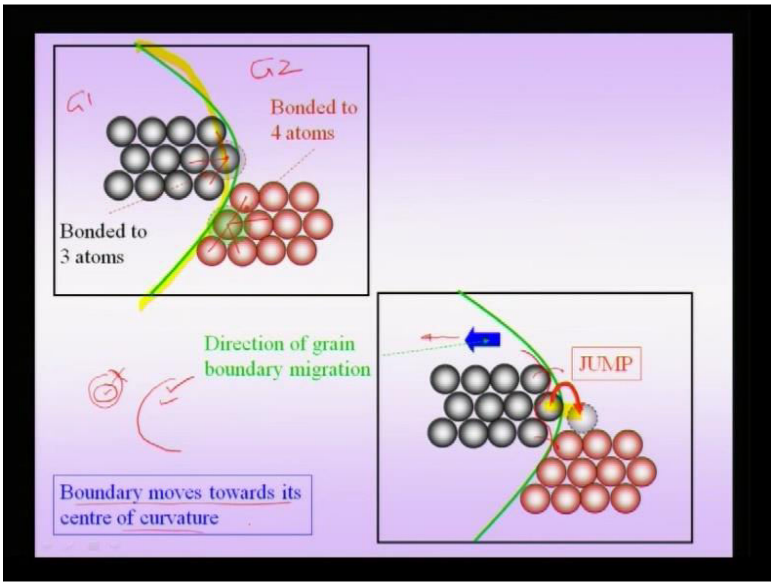

Bonded to 4 atoms

Bonded to 3 atoms

Direction of grain boundary migration

JUMP

Boundary moves towards its centre of curvature

So, for instance to take this schematic for instance there is a grain boundary here, and this grain boundary separates 2 grains which I can call grain 1 and grain 2. If you look at the because, of the curvature of this grain boundary you can note that, the atom sitting on the right hand side, right hand grain to is actually bonded to 4 atoms. On the other hand the atom sitting on the left hand side is only bounded to only 3 atoms; that means, the energy of the atom on the right hand side is lower, it has lowered it is energy more as compared to the atom on the grain 1 the grey colored atoms.

Of course, here we had note that the 2 atoms these are just been colored differently, but they are actually the same atom shown in two different grains. Then what can happen is that, suppose this atom jumps from grain 1 to grain 2 as shown schematically here, about it has to jump over a small barrier. But, this jump can take this atom from grain 1 to and then it becomes part of grain 2.

In the process it is co ordination number has increased from 3 to 4; that means, locally it is the energy of the system is going down, when the grain boundary or the atom in jump takes place. This atomism automatically means that now my boundary which was originally my grain line, has now become a new boundary has formed here, and the overall process can take place in such a way.

That the grain boundary can migrate to from right to left, crossing more and more when of course, this will happen when more and more atoms jump from the right direction to the left direction becoming part of the grain two and in the process the grain boundary sweeps from right to left. And overall this will lead to this grain on the left shrinking, and the grain on the right of course, growing.

And as you can note that suppose there are 2 grains of course, I am not showing them I am showing the very schematically here that there is a smaller grain, visa via larger grain you can note. Of course, that the larger grain has a lower a grain boundary curvature, and a smaller grain with a lower radius curvature, as an higher curvature and therefore, the such a grain would tempt to shrink, at this lower grain would tend to shrink, and the larger grain would tend to grow. And in the process, but overall number of grains would decrease.

Means the grain energy, grain boundary interfacial area per unit volume would decrease. So, we have seen that, this grain growth is not driven by only by the global criteria, but also by the local criteria, and the local criteria involves jump of atoms from which are poorly bonded, to neigh boring grains where there can be better bonded. That means, the system energy can come down, and in the process the grain boundaries tends to move such a way that these smaller grains tends to shrink and the larger grains tend to grow.

And in other words, boundary moves towards it is centre of curvature causing these what you might call, smaller grains to vanish, and larger grains is to grow. And overall number of grains hence comes down during grain growth. So, we have seen that during process like recovery, re-crystallization and grain growth, what we call we can now call them as micro structural transformation. That means, there is no change in phases, but there is an active change in the microstructure.

And we already know that microstructure can directly be associated properties, and therefore, let us now drag how the properties change when this microstructure changes.

We have noted that during recovery of course, it is the major changes to the point defect density, there is a small change of course, in terms of the dislocation density, and the rearrangement, but the major change is to be point defect density.

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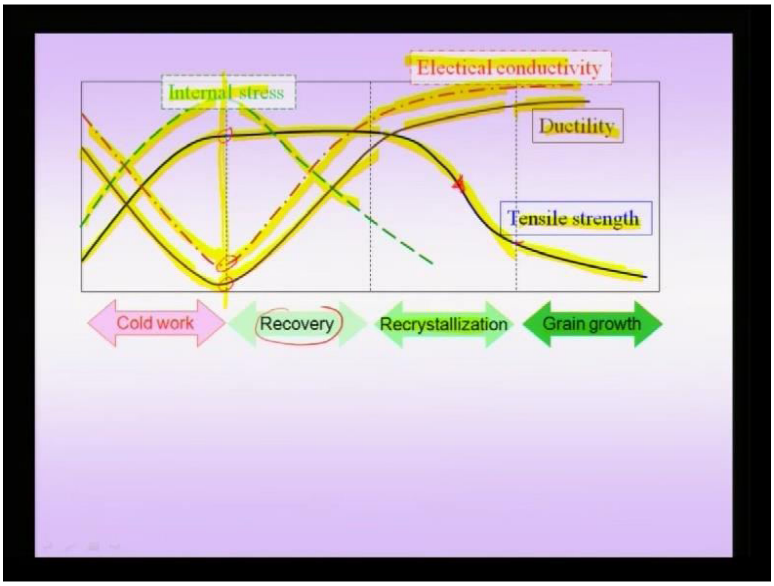

During re-crystallization we have noted, that there is a large change to the dislocation density, there are new strain free grains which may form. And; that means, that overall my entire microstructure is somehow refreshed, during grain growth these strain free grains continue to grow. That means, the overall grain size increases, and this further can lead to the change in the properties.

So, let us see how the some of these properties, and here we are talking about the properties like electrical conductivity, ductility and tensile strength. And all these of course, are a function of the internal stress, the internal stress being in the form of these dislocation density etcetera. Now, what happens during cold works, so I have this process still this line here, which I can call the cold work regime, so what happens to these three properties in the cold work regime.

You can see clearly, that the electrical conductivity which is shown in red, seriously is hampered by the increase in this point defect density. That, so what is happening during cold work of course, also because, dislocation density, so what is happening is that the electrons which were moving unintended, who had a larger mean free path. They now scattered because, of this presence of these defects which distort the lattice, and there is a decrease in electrical conductivity.

And the ductility also decreases during cold working and of course, the benefit we get is in terms of the tensile strength; that means, my strength increases, but my ductility comes down. And this is what happens during cold work and of course, because now my overall strength is coming from on a important factors being dislocation density, the internal stress also increases. So, now I have a cold work state, where my electrical conductivity is low here, my tensile strength is high, but my overall ductility is low.

That means, now if I further try to deform this material, it will not give you sufficient ductility, now if such a material is held at a temperature. So, that I just cost recovery, then what happens is that, you can see that some of the properties are severely affected like for instance now. There is serious increase in my electrical conductivity, the ductility tends to recover a little bit, my internal stress also falls on a little bit, but not totally, but my tensile strength is still not changed much because, I have an overall high amount of dislocation density.

If I further hold a material of course, at a high temperature to cost re-crystallization, during re-crystallization of course, what happens is that, my tensile strength also comes down. Since, my already I have my electrical conductivity has reached sufficiently high value, it will tend to recover a little more because, of the fact that now my dislocation density is coming down. But, it is there is no pronounced change during re-crystallization process, but the important change takes place at tensile strength which seriously falls down.

And therefore, if I cause re-crystallization of the material, my material from strong becomes week. So, I have this arrow along which it goes and therefore, now my re-crystallized material is week; that means, my tensile strength decreases of course, it does not fall down to the lowest value possible. And this actually tends to happen only during grain growth, during grain growth further there is a decrease in the tensile strength, and therefore, my material hence lose its strength.

My ductility already has come to it is original max near maximum value, you get a settle little more benefit, but not much. But, the most important or helpfully some time that even come down because, of the increase in grain size, but here we note that the important change is to be tensile strength, which continues to fall if my grain size increases, this is due to the hall petch effect. So, we see here in this slide, which I summarized now that when I try to take my cold work material with the high density.

And hold it at temperature, so that I can process technical terms being used a recovery re-crystallization and grain growth. At each one of these stages some of the properties tend to come back to its original state, so the during cold work for instance the electrical conductivity comes down, and the ductility comes down while the strength increases. And during most of the strength continues to remain, even though I have cost a recovery process.

The maximum fall in strength actually takes place during re-crystallization process, and further the strength continues to drop when I cross my grain growth. The electrical conductivity actually recovers to most of it is peek value, during the recovery itself; that means, that I do not have to wait for re-crystallization. And this is because, of the annelation of point defects mostly and therefore, my lattices less strain, and I have good amount of electrical conductivity.

So, micro structural transformations also lead to change in properties, apart from phase transformation, which we have already seen that I can cause change in properties by phase transformations. Therefore, we have noted that, if one is interested in engineering components, he has to he can control the composition, but further he can engineer the microstructure to cause changes in properties. And for engineering the microstructure he may use various thermo mechanical treatments, which may include hot working, which may include quenching, which may include quenching and tempering etcetera.

So, you can use various thermal or thermo mechanical treatments to engineer the microstructure. And the final microstructure should be such that it can serve the components well in the long term use, so this is the essential message of understanding that, that we should have a good understanding of the crystal structures. But, further we should have a good understanding of the microstructure, which comes from these crystal structure.

So, that I can understand the properties which come out of such a microstructure, so if one wants to learn material science, the four fundamental pillars of this are the physical structure, the electromagnetic structure, thermodynamics and kinetics. So, this course tends to cover one of these four fundamental pillars, which is the physical structure and therefore, we have tried to include various length scales of this problem. So, we born from point defects, to dislocations, to entire components, to understand how I can engineer my physical structure, which can therefore, give a handle on my properties.