Materials Science and Engineering
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Lecture – 30
Strengthening mechanism II

Hello friends, now we will see the next strengthening mechanism of; already we have seen about the dislocation and point defect interaction, and we looked at the solid solution is strengthening and some other issues when you have this kind of interactions. And now we will go to another strengthening mechanism and that is related to work or strain hardening, already I have told you either it can be work hardening or strain hardening both terms are equally valid.

So, we want to see that what happens when you have more number of dislocation how they interact how they kind of strengthen the material, so if you looked at a strain hardening.

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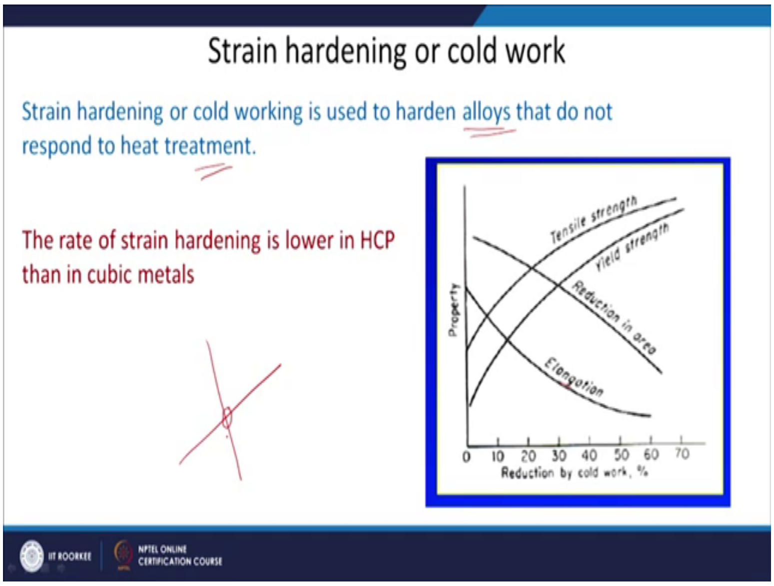

Usually it is used to harden alloys they do not respond to heat treatment ok. So, heat treatment we have already seen two types of heat treatment where we kind of had a bulk transformation for example, in steel we saw that from (Refer Time: 01:22), you can transform group coarse pearlite fine pearlite coarse bainite fine bainite or martensite,

martensite and we also discussed that martensite is very hard and have very high strength ok.

So, so you can have a hardening because of this kind of transformation, or you can have precipitation as we discussed in a aluminum copper alloy system that you can have precipitate inside the matrix and that will add into the hardening of the or this will increase the strength of the material.

Now the alloys which do not respond to this kind of a treatment for example, if you could take any aluminum alloy in which you have for example, aluminum magnesium alloy. So, magnesium is in the solution in the aluminum and it does not form precipitate inside the grain.

So, in these alloys you cannot do any hardening through heat treatment. So, in this type of alloy hardening can be only done by doing a cold working. So, cold working means basically strain hardening or you want to introduce a strain in the material, and as I told you earlier also that you dislocation can overcome the pile up by doing the climb process ok. So, if you do a another process called hot working which is done at high temperature the high temperature you will have more vacancies. So, this climbing process will be easy ok.

So, when you want to do strain hardening you have to do it at lower temperatures or room temperatures which is called cold working. At high temperature it is not going to be very effective, oh and if you see that the with reduction of cold work; that means, you introduce more cold working 10 percent, 20 percent and so on and this is the on y axis you have properties.

So, you can see as I am increasing the percentage of cold work or percentage of strain in the material I my yield strength is increasing as well as my tensile strength is increasing; however, at the cost of ductility my elongation to failure is decreasing.

Already we have discussed that the straining mechanism usually increase the strength, but at the cost of ductility or elongation to failure of course, the rate of strain hardening will be is usually lower in HCP than in cubic metals ok, you because in HCP metal you have only very few efficient slip system ok.

So, I will come to that that why you get the strain hardening, but basically strain hardening is because when you have large number of dislocation moving at different slip systems, which are not parallel to each other what happens one dislocation comes and another dislocation comes and they interact with each other ok.

So, suppose a dislocation is let it coming like this another dislocation moving from some other plane and it is cutting this and it is supposed like this. So, the interaction here of course, I am not going into details of how the interaction takes place because it will be another it can be another long discussion ok. So, there is there is something happens here when these two dislocations interact.

So, one dislocation is moving in this plane another is coming out of the plane like this for example, then there is some interaction and because of that interaction these two dislocation or anyone of this dislocation gets pinned, it will be difficult for it to deform you will need more stress to deform it ok.

So, in cubic metal because you have large number of slip system which are non-parallel to a non-parallel slip system ok, so interaction is going to be much larger in HCP we have only three very effective slip systems ok. So, the interaction is going to be smaller in them that is why you have more strain hardening in cubic metals.

So, if you look in terms of dislocation density a scientist called Taylor in 1934, he first recognized this thing that if you keep on introducing strain for example, you are doing hammering or whatever you increase the strength of the material. So, basically if you look at the strain as a function of a strain if you are plotting different stress strain curve.

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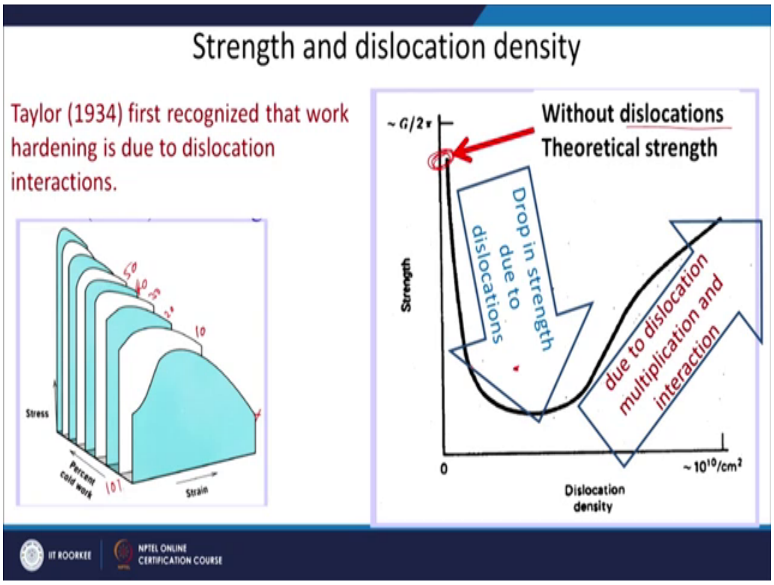

So you can see that this is the elastic part and then this is the plastic part and it must have fractured here. So, this is a stress strain curve.

Now, this stress strain curve we are plotting after giving different percentage of cold work. So, on x axis you have stress strain on y axis you have stress and then in the this, depth direction we are giving different percentage of elongations.

So, suppose I have initially I am not giving any this is as received material suppose there is no cold work then I am do doing a 10 percent cold working, 10 percent strain is introduced and 20 percent for example, this one then 30 then 40 then 50 and so on.

So, and a after each of these cold working we are doing tensile test, so what you will see. So, you will see a strains have come like this after ten percent cold working your yield stress has increased and your UTS has also increased, another 20 to 10 percent strain ok, so total 20 percent. So, yield and UTS has increased and so on ok. So, of course, and ductility is also coming down as you can see that in this case ductility is was very high and slowly the ductility is coming down, but the strength is increasing ok.

So, if you see a from theoretical point of view we discussed that if you do not have any defect or dislocation the theoretical strength will be very high ok, so, around g by 2 pi.

So, there is kind of a contradictory idea here about dislocation that we say that the there is a drop in the strength because of defect ok. So, theoretical strength should be very high, but the strength comes down or actual strength is much lower than the theoretical strength because there are defects present in the material which are dislocations.

So, there is a drop, drop in a strength due to presence of dislocations, but at the same time now we are saying that there is a increase in strength because of dislocation. So, if you have very few number of dislocation of course, there will be a drop in the strength because of presence of dislocation they are free to move, but if you stop there them from freely moving then of course, you can again increase the strength.

So, the second part is that due to dislocation multiplication and their interaction the strength is again increasing. So, sometime it becomes a little bit difficult to understand and appreciate that one at one part we are saying that dislocation brings down the strength another part we are saying that dislocation is increasing the strength.

So, basically idea is that if they are freely to move then of course, they are going to bring down the strength if we are able to provide some barrier to motion of dislocation then of course, we can increase the strength of the material ok. So, Taylors theory is that moving dislocation interact with each other and get trapped as I told you.

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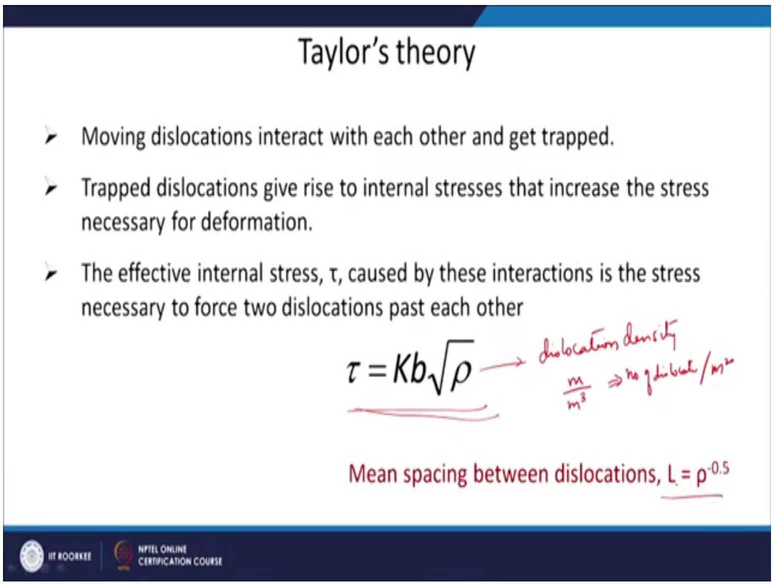

Trapped dislocation give rise to internal stresses that increase the stress necessary for deformation, the effective internal stress tau caused by these interaction is the stress necessary to force to dislocation past each other ok.

So, the stress as a function of dislocation density can be expressed like this where b is your burgers vector ok. So, it is dependent on the rho is your basically dislocation density. So, you can check our lecture on defects where we discussed about dislocation. So, it is dislocation is basically line defect. So, it is always will be measured in some length term meter ok.

So, this much meter of dislocation when we are talking about the density; that means, this much length of dislocation in this much volume of material ok. So, there is about my dislocation density. So, both the both the units are of same type.

So, I can say that these many number of dislocation per meter square. So, that is my actually density and the mean distance between the dislocation will be given by again rho to the power minus 0.5, so it will be 1 by under root rho ok.

So, when the density will be high the spacing between two dislocation will be small ok, more number of dislocation means the spacing between the dislocation will be small. So, this is; what is the relationship between the mean spacing and the density. Now when we do cold working what we do is we introduce dislocation in the material because as I had whereas, we already discussed that the deformation or plastic strain is through motion of dislocation in the material.

So, I need dislocation. So, if I give more strain in the material or I impose more strain in the material I need more dislocation ok; that means, the number of dislocation or the dislocation density will increase with the cold working with the plastic deformation.

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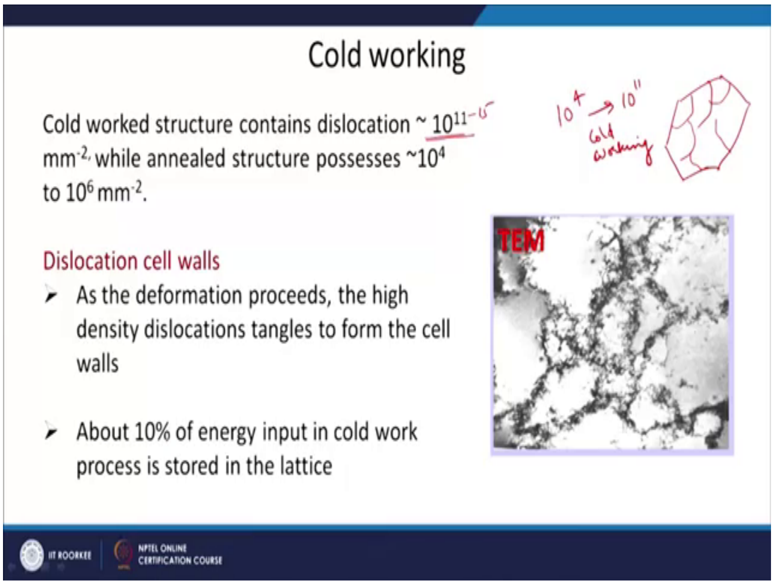

For example you can have very high dislocation density of 10 to the power to the power 11 to actually, 10 to the power 15, there can be a range of permit mm square while in annealed the structure the dislocation density is around 10 to the power 4 to 10 to the power 6, per mm square ok.

So, the dislocation density can go from for example, 10 to the power 4 to 10 to power 11 as a function of cold working; that means, dislocation generated during the deformation because for deformation I need dislocations. So, if I am having more deformation I need more dislocation.

So, there has to be some generation of dislocation during deformation and this dislocation when they interact with each other they entangle with each other and they start forming this kind of cell walls. So, this is a transmission electron micrograph at a very high magnification and you can see that these are all dislocation what you see these dark portions and it looks like a as you can see it looks like a linear curve linear some line ok.

So, the all these are entangled with each other when they interact with each other they start forming some cell wall within the grain. So, you can have a big grain, and in that you can form this kind of cell wall because of entanglement and. So, on about 10 percent of the energy input cold work process is stored in the lattice ok.

So, whatever energy we are putting through rolling process or extrusion process 10 percent of that goes into the material in the form of this dislocation. So, each dislocation has some strain energy associated with it ok. So, you can do a summation of all the dislocation to find out the total energy and that will be a approximately 10 percent of the total energy which we put in the material.

So, rests of the energy actually dissipate in different form some in form of heat and so on ok. And some gets stored in the material in form of dislocations, if you want to see the microstructure evolution as a function of a strain. So, some very precise experiments people have done this is taken from a paper in material science in engineering.

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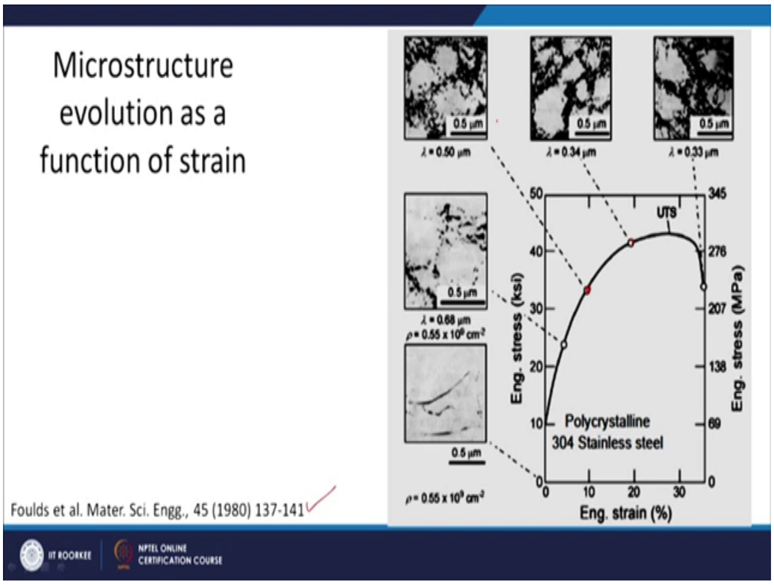

And they have taken the sample from different part of the stress strain curve. So, basically what they did, actually that deform the material and stopped the deformation at this point.

Take the sample out took the took the sample from that deform material and did the tem micrograph or take the tem micrograph then another sample deformed up to this point another sample is taken out next sample deformed to this point then sample taken out and so on. And then they saw that as a function of strain that how the dislocation density is increasing ok.

So, initially there, there is hardly any substructure or dislocation is there. So, the density is also shown here what is the density at this point then the density is increasing as a function of strain and this is how the microstructure evolved as a function of strain in the material. Now, as I told you that when you do straining I need dislocations the so there has to be some source of dislocation.

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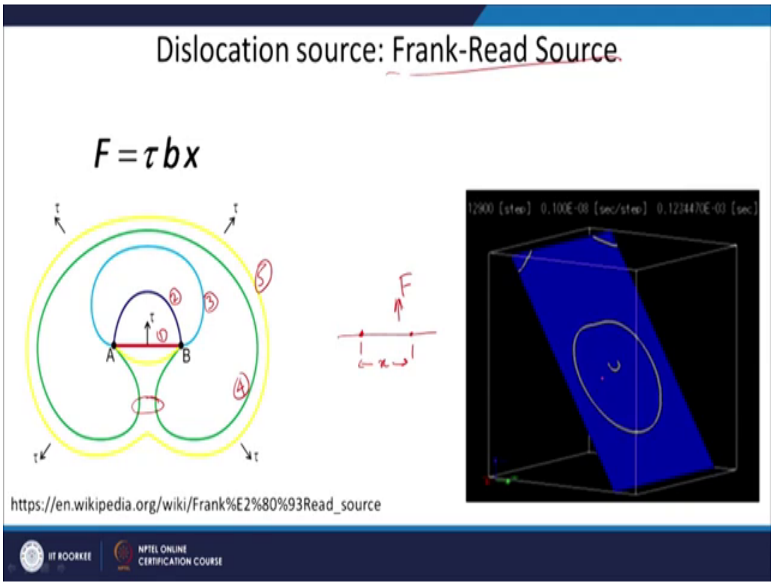

Of course, grain boundary also act as source sometime ok, but one of the most important source is called frank reed source at dislocation source of course, these are two different scientists frank and read not the same guy two people are there, who proposed the this mechanics almost simultaneously.

So, how you get this dislocation generation? So, suppose for example, this is first stage this red dislocation is a moving freely, and it got pinned by this two defect it can be anything it can be precipitate or it can be anything else. So, the main idea is that the dislocation is there it is moving, and it got pinned by these two defects here let us say these are two precipitates. So, these are two pinning agents there ok.

So, you are applying a shear stress tau here and because of that you are producing a force on the dislocation. So, the dislocation is experiencing this force f because of the shear stress tau and the x is the distance between these two pinning particles ok. So, a between a and b the distance is x.

So, of course, if x is high your force will also be higher. So, I am applying a shear stress here because of that now you can think of this as a as a bow and arrow kind of things. So, you your bow is fixed on one end and then you are stretching it.

So, when you are applying a force it will get stretched between these two pinned points. So, it will become from a straight line it will become a curved surface like this. So, this is at first stage the this dark blue color is the second stage and then it will start getting bored out like this, so this is my third stage then what will happen is to reduce the energy of the dislocation it will like try to get us spiracle or a circular geometry.

So, basically it will try to get a geometry like this, now what will happen that these two ends of the dislocation have opposite sign or opposite burger vector. So, how the one contained the upper half plane another content the lower half plane ok. So, they have a opposite sign ok, so when they come very close to each other the two dislocation attract each other and there they will annihilate each other ok.

So, what will happen is that at this local point, so this is my fourth stage basically it has annihilated each other and now you will end up with a with a dislocation loop ok. So, this is my fifth stage and again the remaining part will go here ok. So, the remaining part will remain here between the two pinned particle and you have a loop which is already generated and this dislocation loop will move and the animation is shown here that how this takes place. So, you start with this and then this is kind of joined together and you end up with a loop and then another cycle of same thing starts happening ok.

So, this is how we generate dislocation in the material, but if you do the annealing what will happen when you do annealing you take the material to higher temperature ok. So, at high temperature you will have more vacancies ok, so basically at high temperature.

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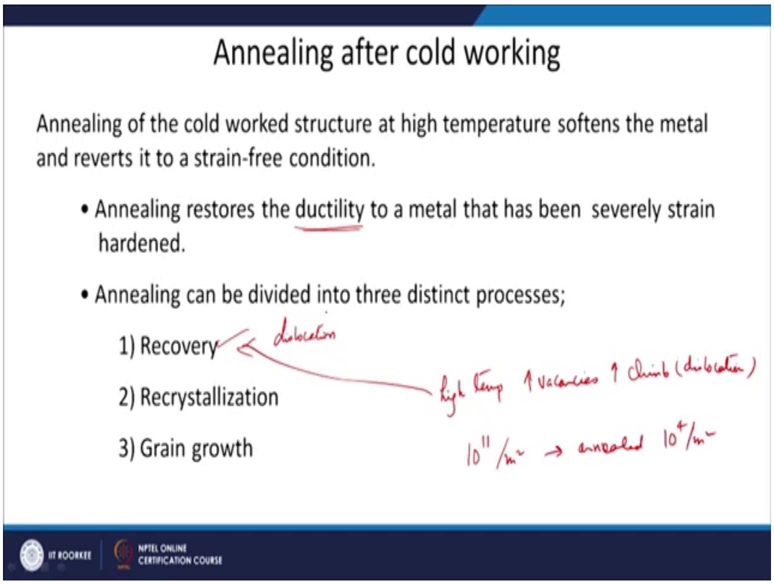

So, more vacancies equilibrium vacancy concentration will increase vacancies then you will have more climb process dislocation climb ok.

So, if you do a dislocation climbing what will happen the dislocation will disappear from the grain, because it keeps on climbing and then it will be absorbed into the grain boundary.

So, what happens when you have annealing actually the dislocation density reduces as you we, we told you that for a cold work material it can be 10 to the power 1 11 per meter square for an yield sample after annealing, it can be as low as 10 to the power 4 per meter square ok.

So, if annealing reduces the dislocation density and because of that basically the strain in the material also reduces and as I we told you that when you do any cold working or strengthening the ductility comes down a strength increases. So, if I do annealing I can restore the ductility.

So, this is a very important make mechanism in the sense that I can keep coming back to my original position ok. So, I strengthen the material if I think, now it has very low ductility I can do an annealing and restore the property. So, that is a very important thing with any material that I can always go back to my original position by doing some another kind of processes.

So, annealing can be divided into three distinct processes one is recovery which is actually related to this the climbing process. So, dislocation recovery ok, so dislocation gets recovered then another process is called recrystallization and then you have a process called grain growth. So, all these three processes are shown here.

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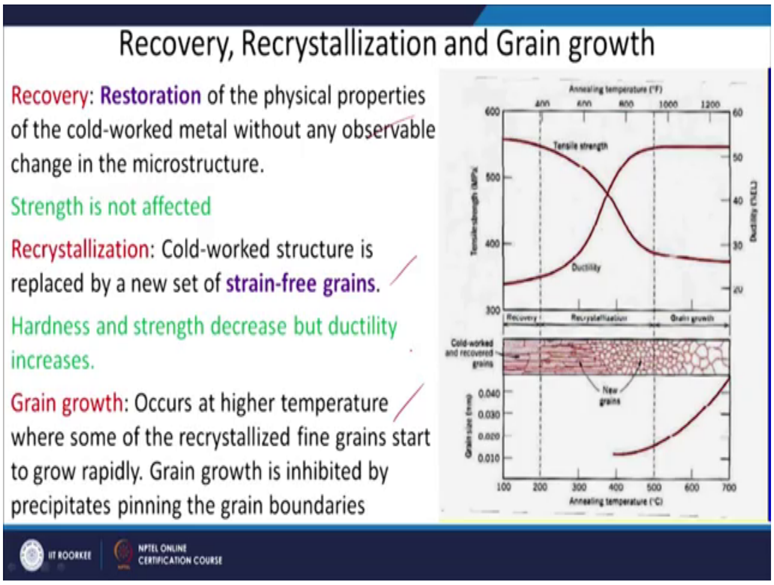

So, recovery is restoration of the physical properties of the cold work metal without any observable change in the microstructure.

So, there is no observed change in the microstructure, microstructure is will look more or more or less similar, but the there will be recovery of dislocations ok. So, you will be a you can get a restored microstructure. So, if you see in terms of a tensile strength the tensile strength will drop if you do a recovery process, but the ductility will increase ok.

So, up to this you have a recovery process. So, in the microstructure suppose it is this is the cold work or rolled microstructure elongated grains, then you will see elongated grains only because only the dislocations have recovered. So, there is there is not going to be any visible change in the microstructure.

Recrystallization basically these strained grains will get a new set of grains which are strain free ok. So, when you have very high strain energy because of the high dislocation density my material wants to go to low energy by nucleating new strain free grains and these grains will grow and consume the whole material. So, the cold work structure is replaced by a new set of strain free grains hardness strength decreases, but ductility increases.

So, in this case also the strength can decrease it depends upon the size of the grain and ductility will improve ok. So, not necessarily always that this a strength will decrease then grain growth occurs at high temperature where some of the recrystallized fine grain is start to grow rapidly grain growth is inhibited by a precipitated pinning precipitate spinning the grain boundary ok. So, if I do this fine recrystallized grain if I do further annealing at high temperature what will happen this grains will grow.

So, basically the bigger grain consume the smaller grains. So, it is like if you remember the soap bubble kind of analogy where if you have a small bubble and if you have a bigger bubble and you join them together ok.

So, the smaller bubble will shrink and the bigger bubble will grow if you remember your high school physics same thing will happens here also that smaller grains will shrink and bigger grains will grow and overall if this process is taking place then there will be overall increase in the grain size of the material.

So, after cold working this is some three very important processes which takes place in the material if you do any annealing process it can be you can do a recovery or you can do a recrystallization or you can have a grain growth process ok.

So, with that thank you, so we have covered a very important strengthening mechanism which is cold working and that you will see very often for example, if you see roadside some blacksmith is there he is hammering the material basically he is trying to increase the strength of the material by doing a hammering process. So, this is one of the very important strengthening mechanisms.

Thank you.