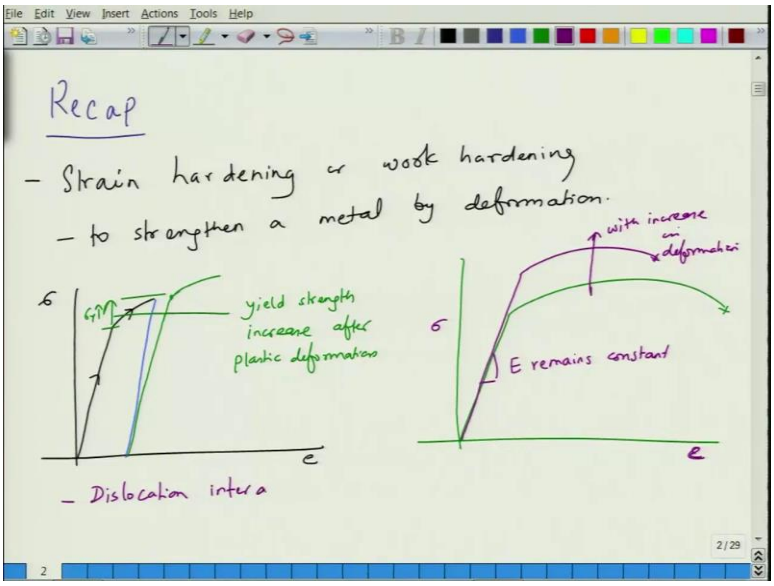
Project of Materials (Nature and Properties of Materials: III)
Professor. Ashish Garg
Department of Material Science & Engineering,
Indian Institute of Technology, Kanpur
Lecture 31
Grain Boundary Strengthening

So, welcome again to the new lecture of this Properties of Materials course and let us just briefly see what we did in the last class.

(Refer Slide Time: 00:24)



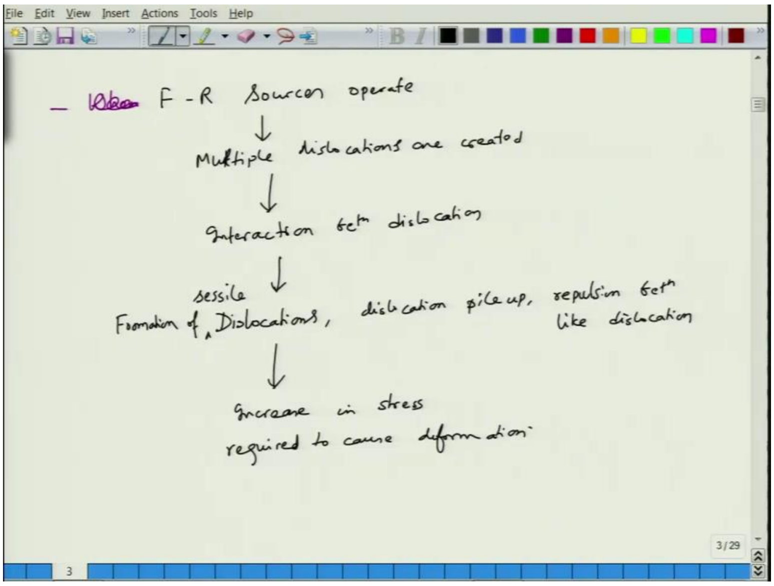
So, in the last lecture we were basically talking about strain hardening or you can say work hardening, which is a method to strengthen a metal by deformation. So, essentially when you deform a material, let us say you have a stress strain curve go through elastic region, then you go into plastic region and let us say, so if you go like this and let us say when you come back to this point you recover all elastic strain, but you still have the plastic strain and you go after this again, the second pass, the second pass will start at this point. So, your yield stress basically increases from here to here.

So, this is the sigma y increase as a function of deformation. So, yield strength increases after plastic deformation. So, the curve will now follow this behaviour. So, this would be sought of extension of the curve if you did not stop earlier. So, essentially what happens is that, when you makes the plots.

So, let us say if a material is less deformed, it might show a behaviour like this. But if we deform a lot then the material will show the behaviour like this. So, this is something, so this is with increase in deformation. So, the yield strength changes. The modulus will not change, the E remains constant because we have not made any change to the materials composition or temperature.

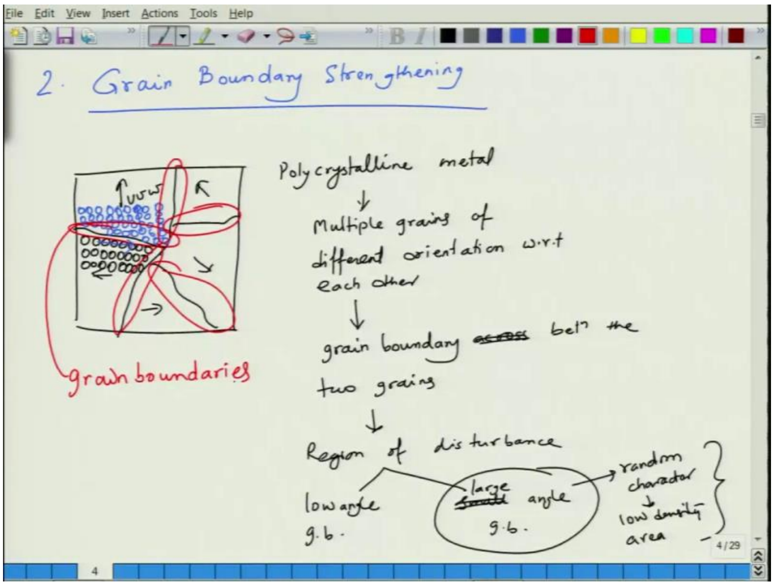
So, essentially it is the yield strength which increases. But generally, by strain hardening you make the material stronger by increasing its yield stress but you also makes the material less ductile. So, that the total strength shown by the material is also lower. So, why this happens is, this happens because of the dislocation interaction.

(Refer Slide Time: 02:43)



So, basically you lead, so when, so there are multiple things happen when you apply stress. So, Frank Read sources operate multiple dislocations are created. Now these multiples dislocations then start interacting and this can lead to things like dislocation, formation of, let us say sessile dislocations, dislocation pile up, repulsion between like dislocations extra and all of this will lead to this happens as a function of deformation and all of this leads to increase in stress required to cause deformation. So, basically this is what is called as strain hardening or work hardening. So, this is the first mechanism that have looked at.

(Refer Slide Time: 04:11)



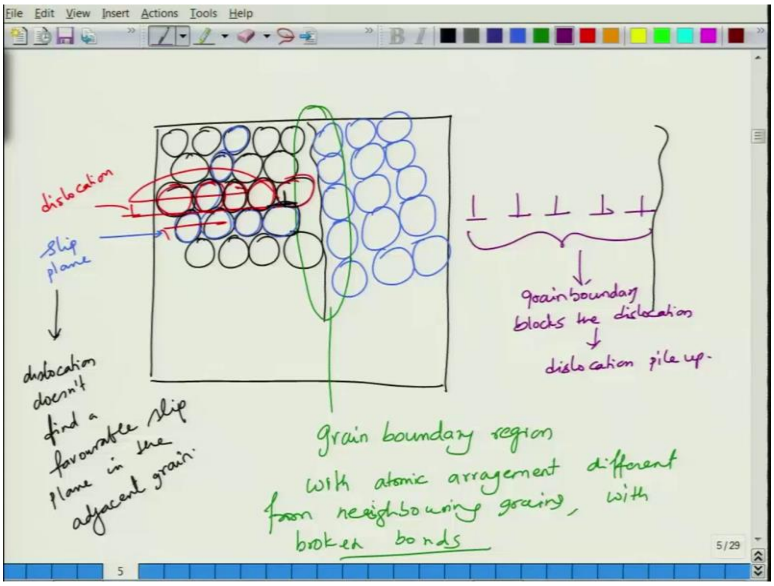
Second mechanism to strengthen the material, number 2, is Grain Boundary Strengthening. Basically, here what you do is that, you reduce the grain size. So, in a poly crystalline material you have a grain structure which is like this. So, these are, so this is a poly crystalline material metal which means it will have multiple grains of different orientations with respect to each other.

So, the phase is same but the direction u v w may change, so on and so forth. So, this is u v w direction which changes in plane, it may also change out of plane as well. So, the out of plane direction may also randomly orient as well as in plane direction may also be randomly oriented. So, this leads to basically every grain having different orientation and the boundary between these grains.

So, it is possible that atoms in this case are oriented in this direction and atoms in this grain could be, you know. So, basically the orientation here is this, orientation here is that. So, basically what we have is, grain boundary across between the two grains. So, this is a grain boundary is basically you can say a region of disturbance and you can have various kinds of grain boundary such as low angle grain boundary small angle grain boundary depending up on the angle of misorientation.

There are other definitions as well but we will just stick our self to small and low angle grain boundary. So, these grain boundary basically have, you can say in some sense especially the, low angle and large angle. Especially the large angle grain boundaries which are very common in materials. Large angle grain boundaries may have random character and it is generally a low density, low density area as compared to rest of the material. So, when you have these grain boundaries. So, these are grain boundaries. So, these are grain boundaries.

(Refer Slide Time: 07:39)



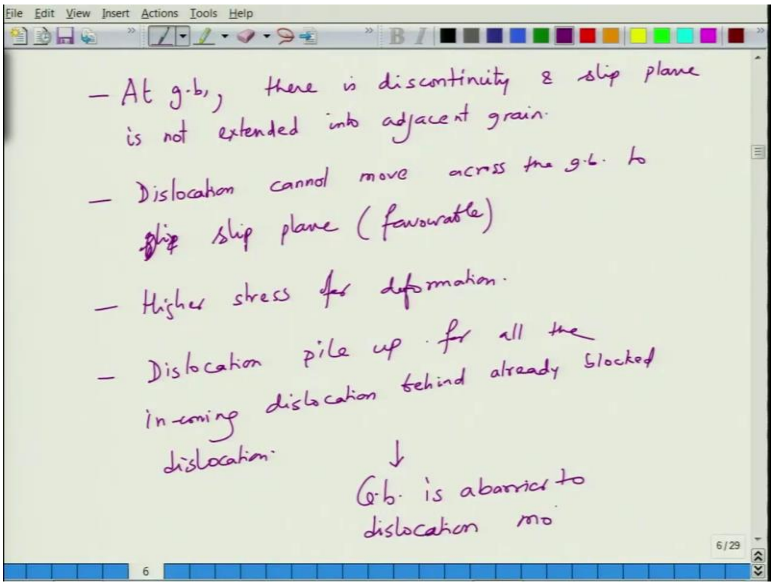
So, now if we just sort of exaggerate this. Let us say we have a crystal in which grains here are oriented in this fashion and then across this region the grains are oriented in this fashion. So, here you have the atoms like this. So, this is grain with different orientation, this is the grain with different orientation. So, this is basically the region in which the atomic correspondences is not similar in either of the grains. So, this is grain boundary region with atomic arrangement different from neighbouring grains and generally there are with broken bonds.

So, if it is a large angle boundary you will have broken bonds as well. So, basically you will have a discontinuity. So, let us say you have a slip plane somewhere here. So, let us say we have a slip plane here and this slip plane, we can assume this as a slip plane let us say, this is a slip plane let us say. So, if this is a slip plane, then let us say we have a dislocation moving. So, let us say this row of atom on top, we had extra plane of atom which is moving here on top. So, this was undergoing shear.

Now when dislocation reaches here. So, you had a dislocation somewhere on this plane which is, this is a dislocation and when this dislocation reaches here let us say, this is the new dislocation. It does not find a slip plane to move on. So, when, so dislocation does not find a favourable slip plane in the adjacent grain.

So, as a result basically, this is going to get stuck. So, if you have this as a grain boundary you will have one dislocation getting struck here and all the dislocations which are following this are going to get struck. So, this leads to, so basically you can say the grain boundary blocks the dislocation and then it causes dislocation let us say, pile up. So, this is the dislocation pile up is going to happen.

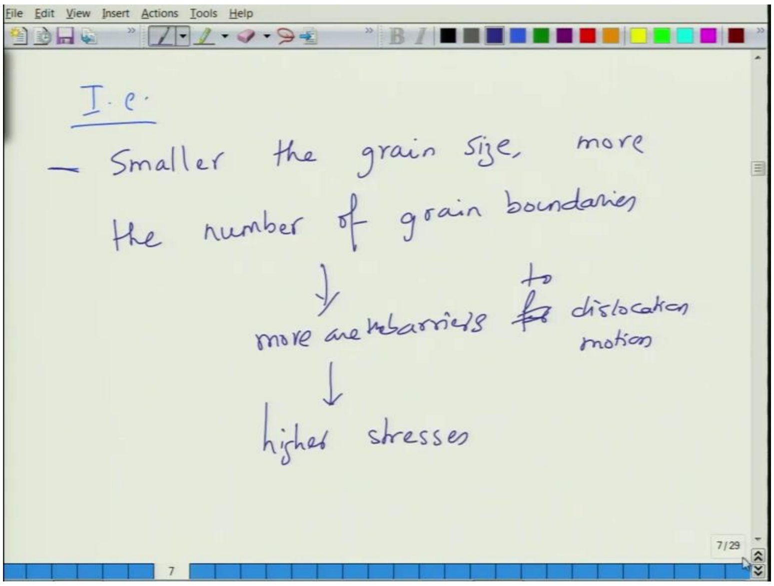
(Refer Slide Time: 11:02)



So, essentially what happens is that, at grain boundary, there is a discontinuity and slip plane is not extended into adjacent grain. So, basically dislocation cannot, cannot move across the grain boundary to slip plane which should be favourable for it to move. So, it should follow the condition of shear stress and resolved, the resolved shear strength, so and so forth.

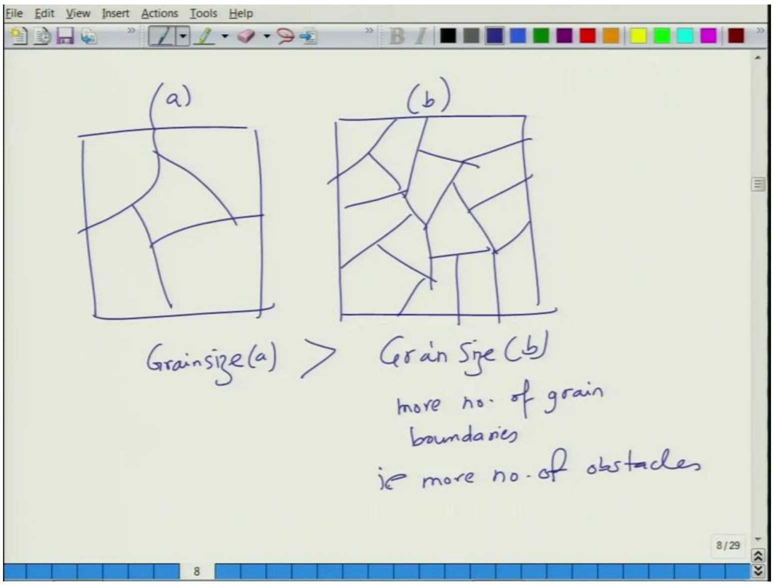
So, as a result this causes higher stress for deformation and this also leads to dislocation pile up for all the incoming dislocations behind already blocked dislocation. So, basically what it means is that grain boundary acts as a barrier for dislocation motion. So, grain boundary is a barrier to dislocation motion.

(Refer Slide Time: 12:55)



So, this suggest that if we decrease the, so what it implies is i.e, that smaller the grain size, more the number of grain boundaries and that means more are the barriers, the barriers for dislocation motion, to dislocation motion and hence higher stress.

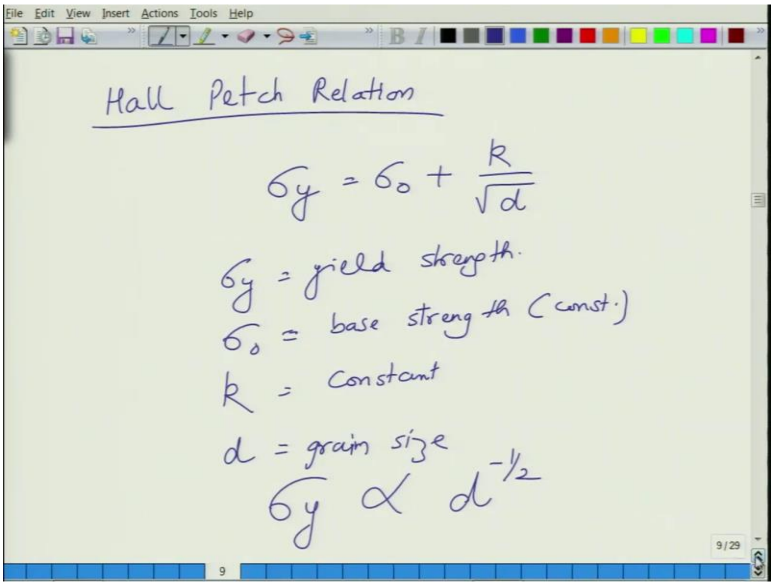
(Refer Slide Time: 13:42)



So, essentially if you conceive now two materials, one with the grain size which is like this and another with the grain size like this. So, you can see that number of grains in this, so this is, so here the grain size in let say this is a, grain size in a is larger than grain size in b. So, this is b. So, of course it has, which means it has more number of grain boundaries.

That is, more number of obstacles. So, this basically means that finer the grain size is higher the strength will be more the obstacles will be, more the dislocations will be blocked as a result higher the strengthening will be, so, this is relation.

(Refer Slide Time: 14:53)

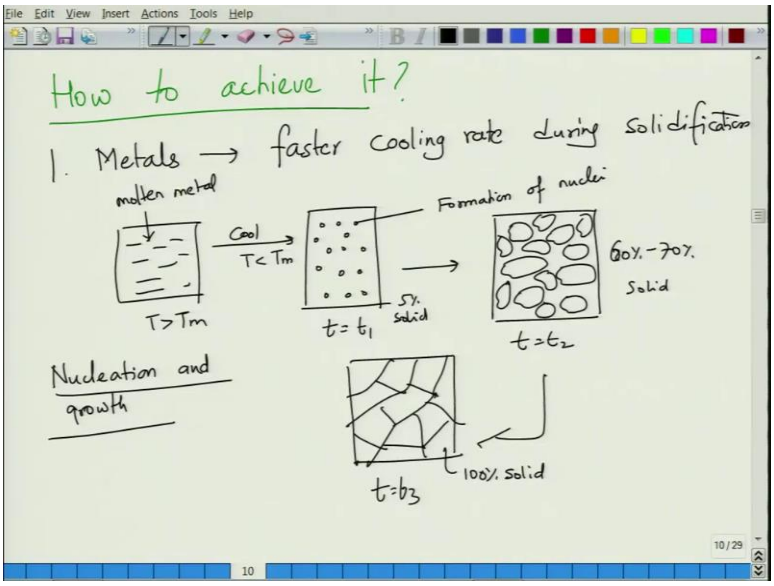


So, the relation is given by what we call as Hall Petch relation and this is that sigma y is equal to sigma naught plus k divided by square d. So where, Sigma y is the yield strength, sigma naught is essentially you can say the base strength. K will be a constant. This is also a constant and d will be the grain size.

So, you can see that sigma y is proportional to d to the power minus half. So, as you decrease the grain size, your yield strength increases. So, this is how you do strengthening by decreasing the grain size is essentially what we do is that you create more grain boundaries, those grain boundaries act as barriers to the dislocation motions.

So, you have more number of grain boundaries, more the barriers are there and more the dislocations are blocked as a result you require higher and higher stress to move a dislocation. So, this is the summary of this grain boundary strengthening.

(Refer Slide Time: 16:13)



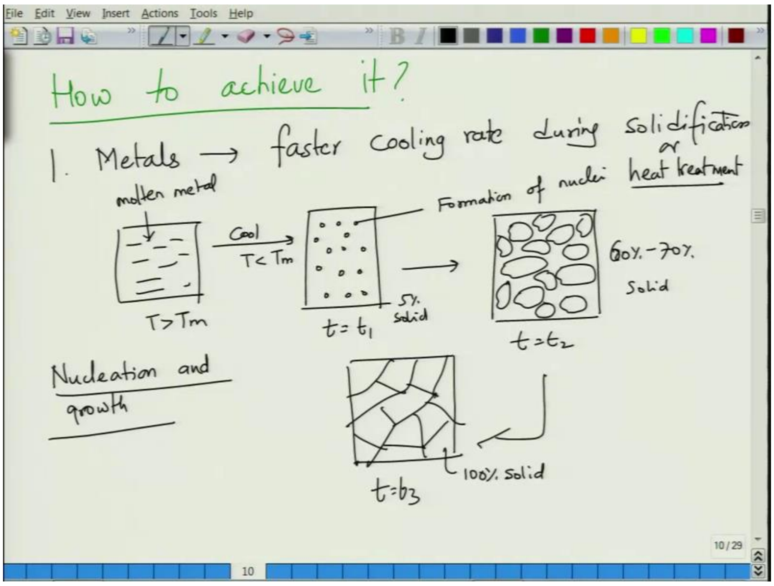
Now the question is, in reality how to achieve it? So, the question is how to achieve it? So, this can be achieved by one, in metals you can say, if you have faster cooling rate during solidification. So, when you melt a metal. So, this is the, let us say the molten metal and as you cool it.

So, this is T greater than Tm. Which is melting point, as you cool it to a temperature T less than Tm it solidifies. But solidification process requires the formation of small nucleis. So, smaller nucleis will form. So, this is formation of nuclei. So, this is let us say time t is equal to t1 and these nuclei if you wait for some time, time t is equal to 2, these nuclei would have grown little bit and at time t is equal to t3 all of these nucleis will merge into each other and they will give raise to this kind of grain structure.

So, these nucleis merge into each other. So, this is now 100 percent solid. This is let us say 5 percent solid. This is may be about 60 percent solid, 60 to 70 percent solid. So, it is a time dependant process basically solidification is a time dependent process, just like we see when we form ice from water, you do not form ice all of us sudden if we keep water at zero degree centigrade, the formation of ice takes some time and this is because of, because of phenomena that we call as Nucleation and growth.

Nucleation and growth require time and it is dependent on the cooling rate. So, the cooling rate determines, so if you if you cool it very fast, you form many nucleis. But since the temperature is low the growth does not happen very fast as a result you generally have a grain structure which is a final grain structure. But if you cool it very slow, slow cooling leads to lower nucleation rate. But higher growth rate as a result you have coarse grain size.

(Refer Slide Time: 19:15)



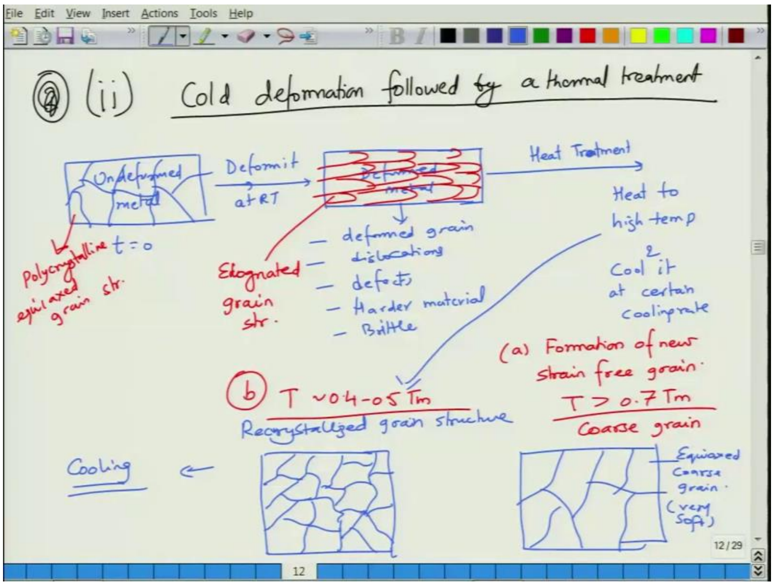
So, basically slow cooling rate will lead to lower nucleation rate and higher growth rate and this gives raise to coarse grains. So, basically d is large. Fast cooling leads to higher cooling rate and lower, higher nucleation rate and lower growth rate and this leads to smaller or finer grains.

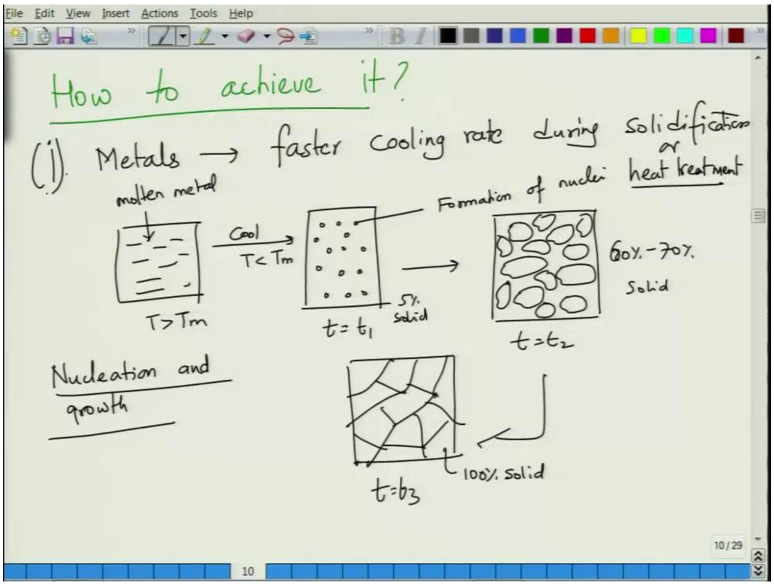
So a small d and this is generally what is done in case of copper or steel or any other engineering metal where we carry out this process. So, pure copper, if you are making then pure copper can be cooled fast or slow to give raise to higher or lower grain size. So, fast cooling will give you smaller grain size, slow cooling will give you coarse grain size.

Similarly steel, steel generally little complex with it is an alloy. So, the room temperature phase in in steels are ferrite cementite. The distribution of those frighten cementite phase is can be, distribution in the size of those phases can be controlled by controlling the cooling rate of steel from high temperature to lower temperature. Principles are the same, it is not necessarily, solidification also, it is also the basically, during solidification or you can say during heat treatment.

So, both of these give rise to basically you can say smaller grain size and this smaller grain size will, faster cooling basically achieve to, is done to achieve the smaller grain size, this is the first method of producing smaller grain size.

(Refer Slide Time: 21:32)





Second method to achieve smaller grain size is, so this is the first method. Let say and the second method will be basically cold deformation followed by thermal treatment. So, depending upon how you do it, you may achieve again some. So, basically what you do is that you have a material, let say you have a piece of material. So, at t is equal to 0, then you deform it, at let say room temperature.

So, you change its shape let us say and when you change its shape you change the basically this is the deformed crystal, deformed metal, this is undeformed metal. Deformed metal will have deformed grains dislocations and defects. So, this will be a harder, harder material, but this also becomes brittle. So, you cannot basically work around it any more, when it becomes very brittle you cannot keep deforming it and so what you need to do is that, deformed metal is then subjected to heat treatment.

Heat treatment is a process in which you heat to high temperature and then cool it at certain cooling rate. So, what happens is that you might start with the grain structure which was like this and the grain structure after deformation becomes elongated let us say. You have these elongated structure and there is lot of strain energy you have lot of dislocation them.

So, this is let say elongated grain structure with lot of dislocations and defects it is very hard and this is polycrystalline equiaxed grain structure. So, the grains are roughly of similar size they are of random orientation and they are equiaxed, randomly oriented equiaxed. So, what you do here is you heat it to high temperature, when you heat it to high temperature through the.

So, these when you heated to high temperature the first stage that happens is formation of new strain free grains and if you, if the temperature is more than 0.7 Tm, then you form coarse grains. So, this grain structure will convert to again the similar poly crystalline grain structure. So, you will have, you can say equiaxed coarse grains.

So, this will becomes softer. So, if you heat it to very high temperature you create coarse grain structure if you heat it to temperatures, around 0.4 to 0.5 Tm, then we have, what we call as recrystallized grains, recrystallized grains. So, this will makes the material very soft. But recrystallized grain will mean that you have a grain structure which is finer than this grain structure.

But again the grain size is, the grain, grains are randomly oriented. So, it is a equiaxed grain structure. So, recrystallized grain structure, this will have strength higher than the coarse grain structure and more elongation. So, these are, so and again you can again do the cooling if you cool at different rates you again modify the grain structure little bit.

But by heating the material to different temperature holding for certain time depending upon weather the temperature is more than 0.6, 0.7 Tm or between above 0.4 Tm or less than 0.4 Tm you will have different grain structures and these grain structures coarse, medium size or deformed will give rise to different strength which will be determined by basically the grain boundary strengthening.

So, in this cases, in these two cases the left one has the finer grain structure will have more strengthening as compared to the coarse grain structure. This is another way of changing the grain structure of a material and thus you can modify the strength. So, what we have done is we looked at the grain boundary strengthening in this lecture and in next lecture we will now discuss the other methods of strengthening that is solid solution of strengthening and if time permits precipitation strengthening. So, we will stop here. Thank you very much.