Principles of Physical Metallurgy

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Lecture No. #27

Metal Working: Deformation Processing

Good morning. We have seen last several classes that metals, and alloys when it solidifies, it is made up of at one or multiple phases, and we have seen that the ease segregation, and the metal. Metal is known for its ductility, but cast metals we find that it has poor relatively poor ductility, and unless it is given working or deformation processing, we do not get the optimum amount of strength and ductility.

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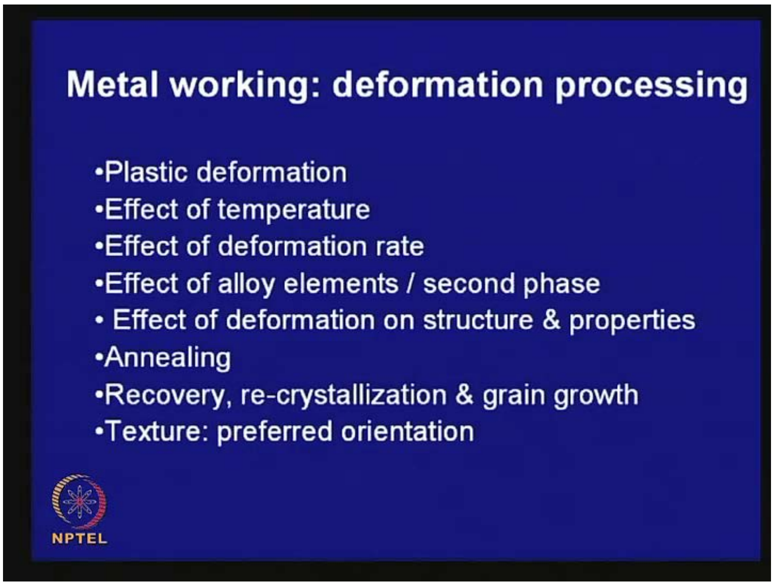

So, we will see how the metal working or the deformation processing helps to improve, not only improve the properties of material, but also it gives it the desired shape in which, it can find applications So, under this we will talk about plastic deformations, because the shaping that processing what we are trying to do, we have altered the shape of the metal from its cast form, and the main mechanism is plastic deformation. And we have seen earlier, how plastic deformation takes place in crystal. We will build up on that. We will see what is the effect of temperature on the deformation processing? What is the effect of deformation rate? We will also see that how the process of working metal working. How it is guided or depends on alloy elements or second phase that is present in the material.

We will also see effect of deformation on structure and properties. We will also see that on the certain condition by giving a heat treatment called annealing. What it is? We will know and how it helps restore the structure, which is altered during plastic deformation. We will know about different stages where that through which this alteration takes place, which are known as recovery, re-crystallization, grain growth. We will also see in certain cases how as a result of deformation texture or preferred orientation deforms or develops under certain conditions and how it can be controlled or how it can be removed to get isotropic properties.

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Now, if we look at what is plastic deformation, we apply load to a metal and under load, the material deforms. Metals are known for its ductility. It can be formed into useful shapes by such deformation processing. There are several methods of metal processing and these can be grouped in few categories depending on ways the force is applied and which are listed here like direct compression, indirect compression, tension, bending and shearing. Now, when a metal is cast, we have seen that there are lots of segregation in the material.

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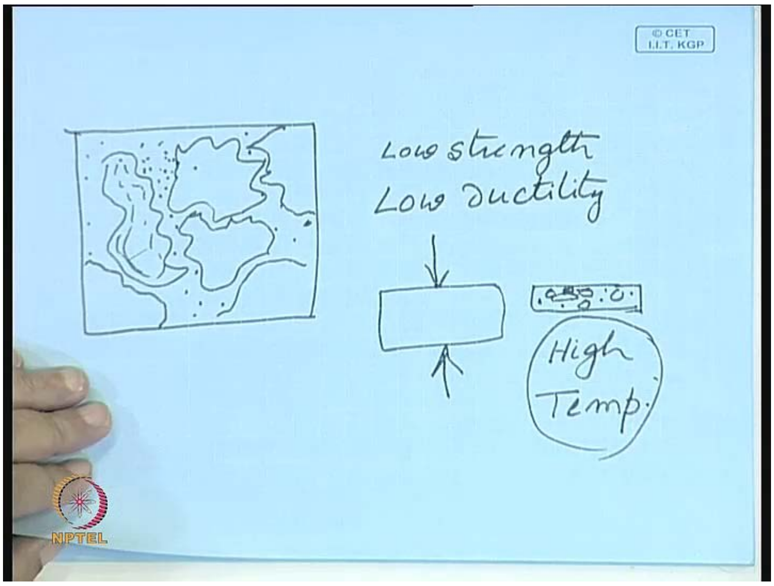

And if we recollect our earlier lecture, say in a metal; when they solidify, it forms in these dendritic structures or their there are different grains. And if you look at this structure of metal, you will find this types of dendritic grain structures and inter dendritic channels often you have precipitates. Within this also, there is a composition gradient; sometimes there may be micro pores here. So, this is the cast structure. Therefore, this has because of this type of micro structure, it has both low strength and ductility as well as it has low ductility. And best way to remove this cast structure; that is to give it subjected to compressive loading. And on the compressive loading at high temperature, it will not only allow these grains to homogenize, but also these precipitates which are there.

They are either dissolve in the matrix these grains or they break into smaller particles and then softer matrix flows around it and they sealed up; they weld up. And what you get as a result of this kind of a deformation processing? That means, you apply pressure here; the material becomes smaller. So, the grains deform also they re-crystallize and most of this primary processing is done at high temperature. And high temperature the stress as we go further, we will see at high temperature stress (( )) to deform the metal is also very low. And this helps you to get a uniform structure, which is ductile and more usable and it can also be by this processing, it can be given different types of shapes that we need.

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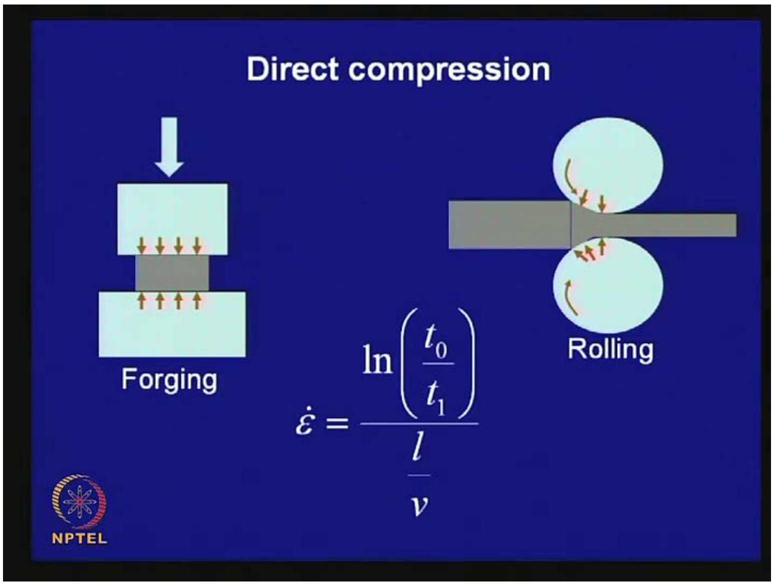

Let us look at pictorially some of these deformation processes. One is forging here you apply. So, this is an annual on which, this is the work piece the job which is kept and you apply pressure and under this pressure, the material flows and it can be normal press forging or it can be hammer forging. In that case, the material flows in this direction and the other direction perpendicular to the plane also; so, two directions.

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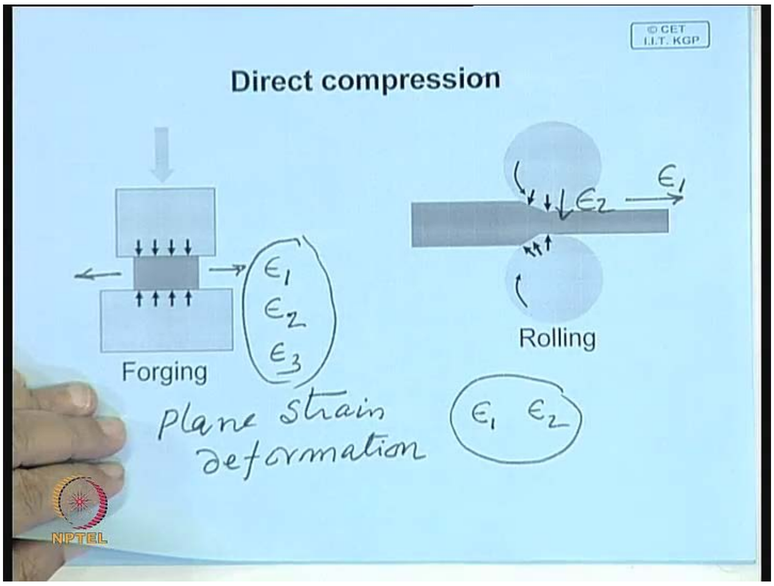

So, this is actually what we say this kind of processing is a plane strain deformation. plane strain you have deformation in two direction plane strain deformation. So, we have three principle strain axis if you have epsilon 1 and epsilon only epsilon 1 and epsilon 2. So, these are strain. One is let us say this direction is epsilon 1 and the direction perpendicular to the plane is epsilon 2. So, these two are exist. Say, one is this direction; another it elongates in this direction and another is this sorry I think you need to correct it. So, in this case say normally if it is a die, stop this. If we allow in that case ofcourse, the other side is free to move. It will be strains all three; epsilon 2, epsilon 3 all will be present.

But more common deformation processing; but if you do it in a die, you can stop the deformation in one of the direction. Then it becomes plane strain; whereas in case of a rolling, main stream is one direction is this is epsilon 1. Another is the thickness direction; this is epsilon 2. So, width direction there is not much of strain; in the direction perpendicular to the plane, there is not much of strain; So, most of the bulk of this deformation processing, which are used primarily to break down the cast microstructure. This is one of plane strain deformation and many of these plastic deformation processes are can be considered as a plane strain deformation like die forging, rolling and many other processes as well.

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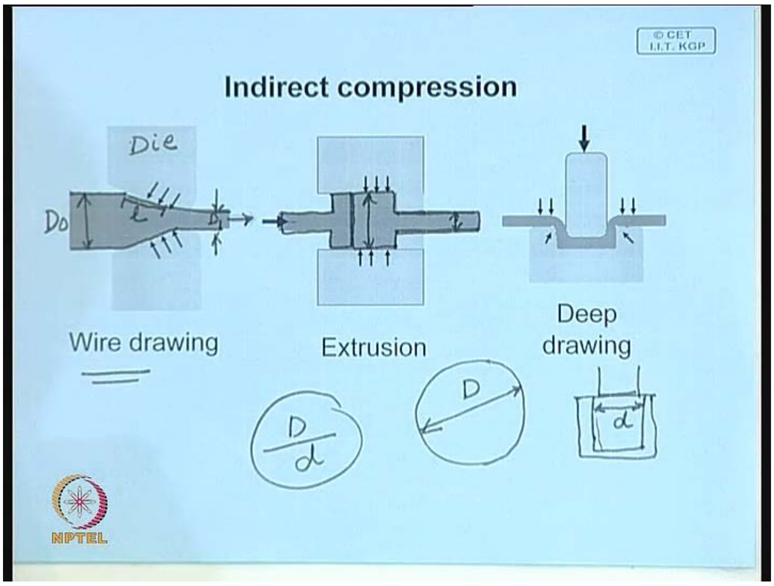

Now, here the slide it shows the case of indirect compression indirect compression. Here this is you are applying tensile load here; you are this is wire drawing. So, this is your job; this comes here and this passes through this and it is pulled through the die. This is die and this is the joule in which, you can say this is the zone or let us say length of this zone is l. This is the zone over which deformation takes place. Similarly, in case of extrusion, you are applying compression here. This is the job. Let us say, this is the job here and this part is the mandrel through which, you are pushing the job. And then there is a hole here; through this, the product comes out. So, you have a deformation here.

So, you have one dimension here and here another dimension. So, this represents say suppose this is the initial diameter; this is the final diameter. So, the ratio will give you that reduction that you are getting and in this case also, this is your initial diameter; this is the diameter after wire drawing and the ratio is the reduction percentage. You can say percentage reduction or if you go back here also (Refer Slide Time: 06:47) Now, in case of rolling also, you look at this. This is the region over which the deformation is taking place. This is the region where you have the plastic deformation taking place and after this, this is the final product and this is your initial thickness, t naught.

This is your final thickness and the true strain we know is given by ln initial thickness over the final thickness. This is the true strain; same is here also. You can say that initial thickness is sometime is t zero and final thickness is t 1. So, here also more or less you can say here this also is the region that length of the job is that over which the deformation is taking place. So, here we can say that if the rate at which the material is flowing say in this rolling end, say the rate at which this product comes out. It comes out with the velocity v. In that case, we can say that this time it takes to pass through the roll is l over v. So, therefore we can calculate strain rate and this is a quite important parameter.

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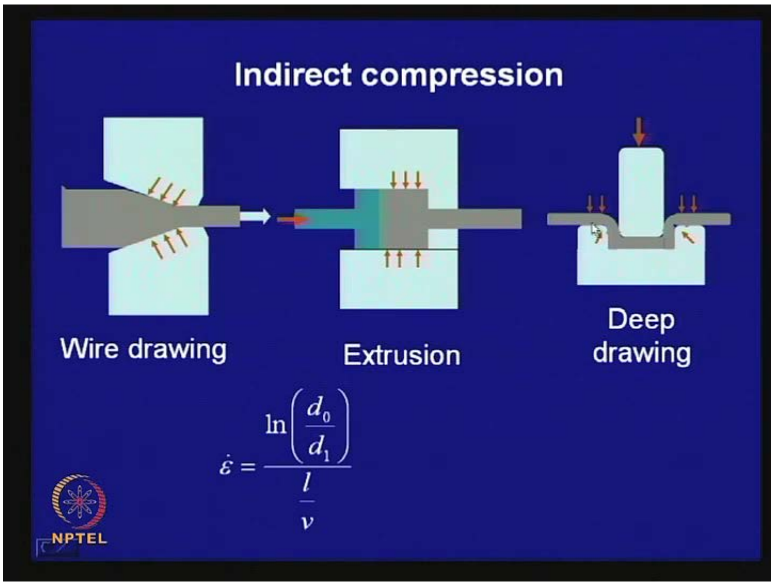

And same thing it is possible to calculate even in case of wire drawing as well as extrusion. Now, deep drawing is another method of forming and usually it is the often you will say that this is the final step of forming, where you take a thin sheet here; which is placed in a die and (Refer Slide Time: 09:35) this is the mandrel, which pushes the material in to it and here what you have? Say, suppose you have a disc, which is put in a die. So, die is a cylinder; this is the top view, which is kept in the die and which is placed over here. This is the die and the mandrel it pushes it into it and if the material is ductile enough, it will take up the shape of the die and here this drawing ratio if this is your diameter of the job and the diameter of this die is d and the drawing ratio is D over d is the drawing ratio.

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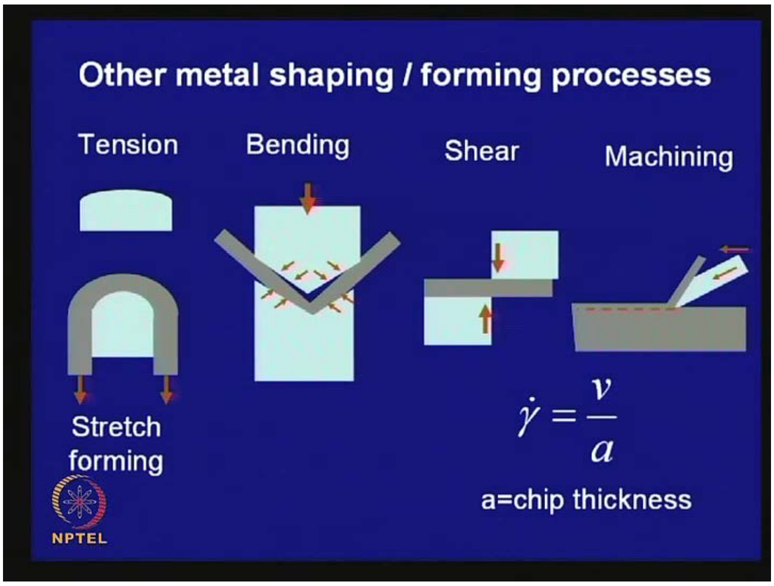

Now, similarly there are many other forms of metal shaping where in the previous one (Refer Slide Time: 13:22) this is one of indirect compression. Here you see apparently we are applying tension here; but ultimate load is compression. Here also you are applying as if; here is the compression; but here it is getting stretched. Here the strain will be one of… although you are indirectly you are giving this compression here. But it is not nature of the state of stress here will be something different. The other metal shaping forming processes which are listed here. It can be one is stretch forming; stretch forming here is the die and on the die you keep.

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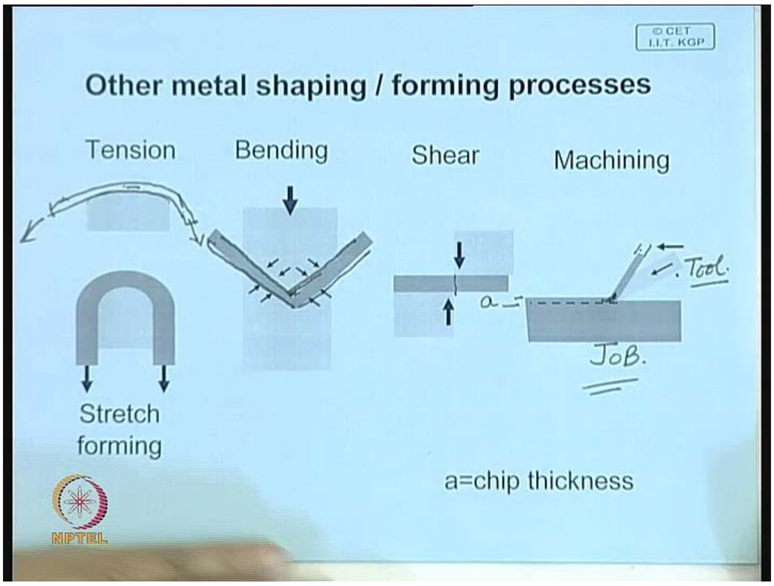

With the help of the die, you try and you put this sheet and try to stretch it; over the die, you try and stretch it. So, here the main applied force is also tension and here also it is tension. Similarly, you can bend a sheet into a particular shape. This is kind of a bending operation; this is the die; this is the punch. Now, machining and shearing, cutting here also; you know the stress of state you are applying is one of shear and it shears through this. Similarly, when you are machining, the tool you know cuts into the metal (( )) and this is the chip thickness which comes out.

And your deformation zone is something similar here which is of this order of same as this chip thickness and this is the tool here. This is the tool and this is the job. So, you can have this is one way of classifying the methods of deformation and here also (Refer Slide Time: 14:46) it is possible to calculate the strain rate for shearing process like at what rate the tool is moving or the job is moving if tool is fixed. So, if v is the velocity and then your strain rate will be this is the velocity; this is over this is length a, which is the chip thickness. This you can see that this will be there your strain rate.

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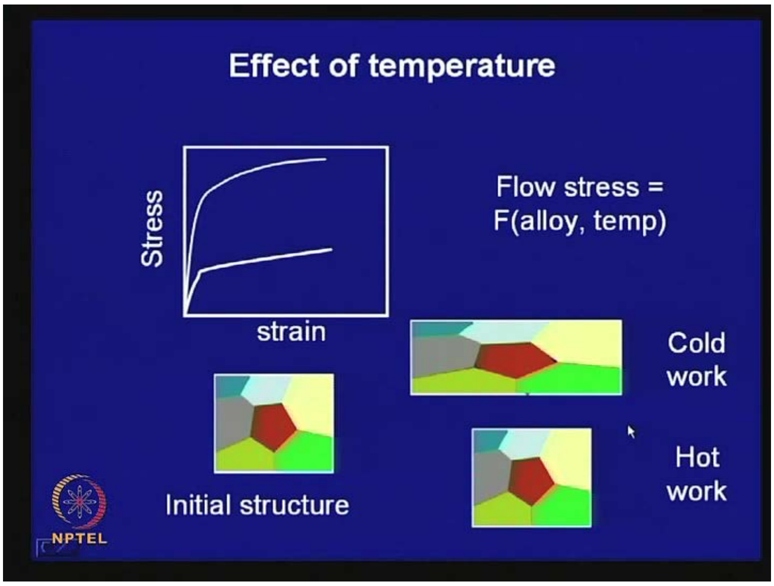

Now, let us see that why does the material differ, we have talked about it earlier in detail.

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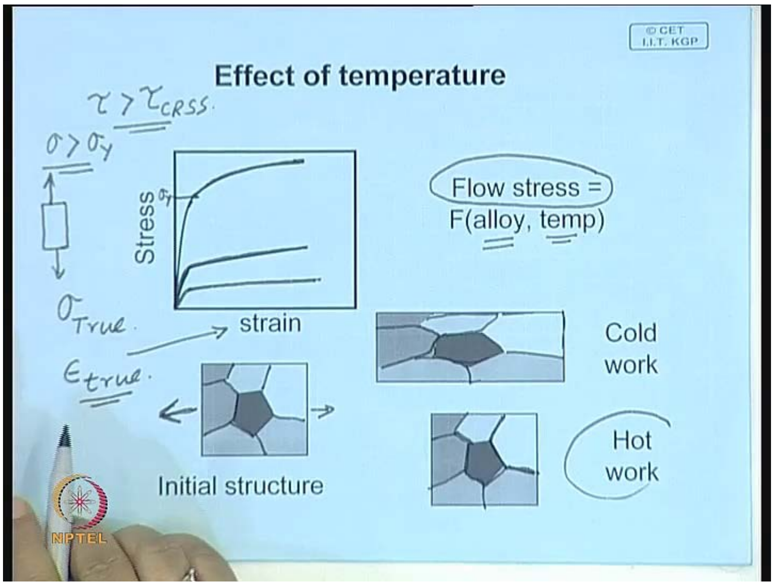

And we have seen that when you apply stress to any metal whether it is tension or compression in a metal, after the stress exceeds a critical stress called yield stress; the material deforms. In case of single crystal we have seen, the deformation takes place. When the shear stress on a particular slip plane is greater than critical resolved shear stress and typical nature of the stress versus strain plot is something like this. There will be no doubt; an elastic portion where it is linear and once this yield stress is exceeded, this is the yield stress; we say that this is the plastic region. And in case of metal working, we are more interested in this part and we often ignore this part that elastic part.

We ignore and let us see what is the effect of temperature. If you increase the temperature; in that case, you will find the plane stress goes down significantly. It is something like this. You increase it still further; you may find it goes down and usually if you do it at room temperature, you will find with deformation strength increases. But higher the temperature you go, you find the strength does not increase. So, there is little strain hardening at higher temperature. We will see why does it happen and all in subsequent part of this lecture and another important (( )) we should make here that why we talked about this kind of stress strain plot in tensile testing.

In tensile testing, we are more interested in determining yield strength and ultimate tensile strength. But when we want to work a metal, we want more information about the ductility and in that case, how much is the ductility and higher the ductility more easier it is to form. And we know that the strain here therefore will be better to define not as engineering strain. We will define strain as true strain; so far metal working, often we deal with true stress. This stress is sigma is true stress and strain is true strain. This epsilon strain is true strain and these were defined in earlier lecture. And if we look at microstructure; say suppose initially the metal has this type of microstructure, you have different grains here differently oriented grains you have differently oriented grains.

And if you deform it say suppose you are pulling it in this direction; in that case, if you are doing it at a low temperature, you may find that grains get elongated these grains get elongated. So, this is how the deformation proceeds. But when you work at a higher temperature, you will find after hot working; if you look at this structure, you may find still it has a similar type of equally (( )) grains. So, apparently hot work structure; if you look at the microstructure, you may find that before working and after working the structure may be same. I am not talking about that initial. Let us say dendritic structure here ignore the dendritic part of that structure that will get reformed in hot working.

But apparently if you take a initial that (( )) material which looks homogeneous in this type of structure; after hot working also, you will get similar type of structure. So, something happens during that deformation processing. So that, you still after working, you get a similar (( )) structure; whereas if you cold work, you will see these kinds of elongated ring and it will also depend on the temperature at which you are giving the deformation. It will also depend on the alloy, which you are working with. And in case of metal working, we do not talk about yield strength or UTS. We talk about a stress called flow stress. So, this is the stress at which material flows easily and lower the flow stress, better is it is its work ability or form ability and we will see how to find out flow stress later and this is shown over here.

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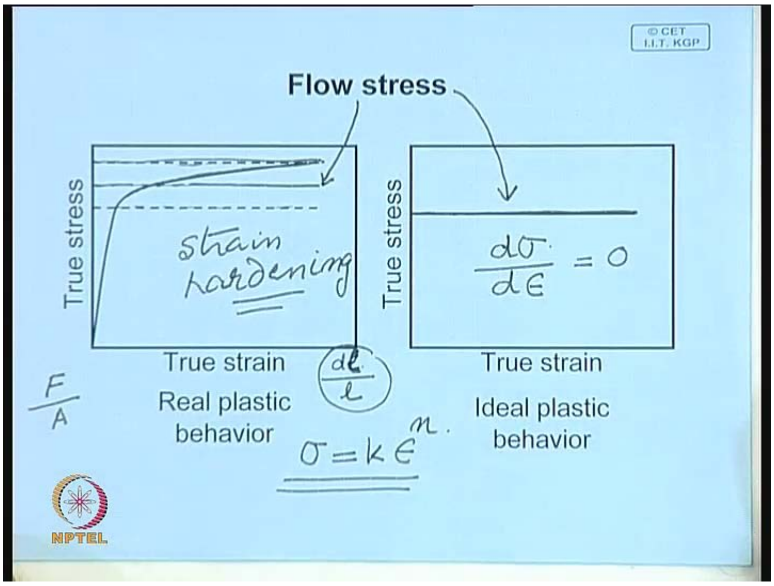

As we mentioned that in metal working, we are more interested in true stress. So, true stress means load or force per unit area. But this is not the original area; this is instantaneous area and similarly, true strain is change in length over instantaneous length. So, this is true strain and now here normal a real plastic behavior most material say at room temperature, we will show this kind of a behavior. True stress, true strain plot will be something like this. So, here this is your yield stress; this is your final stress. I mean, when it is about to rupture and then what we say at average value, this is the flow stress.

This is given by (( )). The average stress is the flow stress. Now, ideal plastic material is one which flows without (( )) easily. So, this is your flow stress. So, in this particular case, flow stress increases as the material deforms. So, this is called strain hardening. So, there is a strain hardening here. Most material you will find some amount of strain hardening. But ideal material plastic material, where strain hardening is zero; strain hardening usually represented as this. We say that this is zero and real plastic material, you will find that sigma; the flow stress follows an expression something like this and these were talked about in earlier classes.

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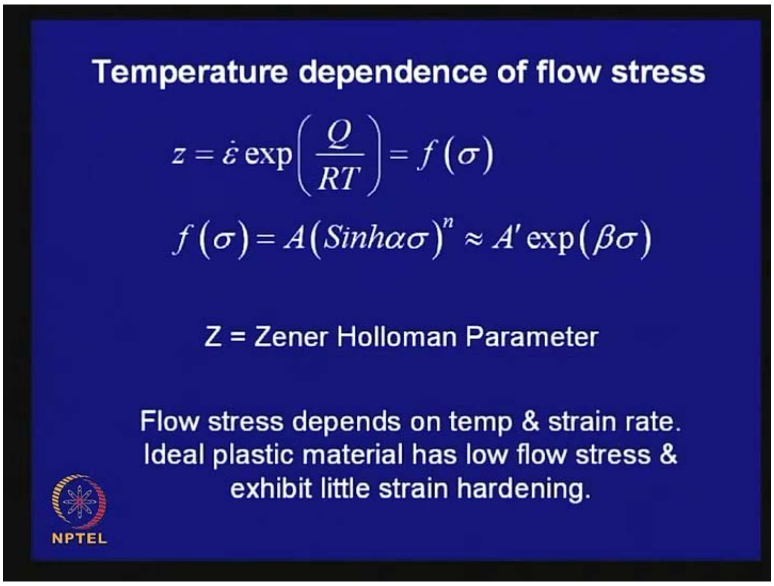

Now, let us see how does flow stress get affects by temperature. Now, this is given by this famous expression a parameter often in hot working. We introduce a parameter called Zener Holloman parameter. Now, hot working depends not only on the stress that you apply; the temperature at which you apply the stress, but also depends on the rate at which the load is applied on the strain or rate at which the material is deforming. Epsilon dot is that strain rate and in that initial few slides, we showed that expression for the strain rate for different types of metal working processes like rolling and forging. Now, this is the expression. Now, what is the nature of this function; the stress?

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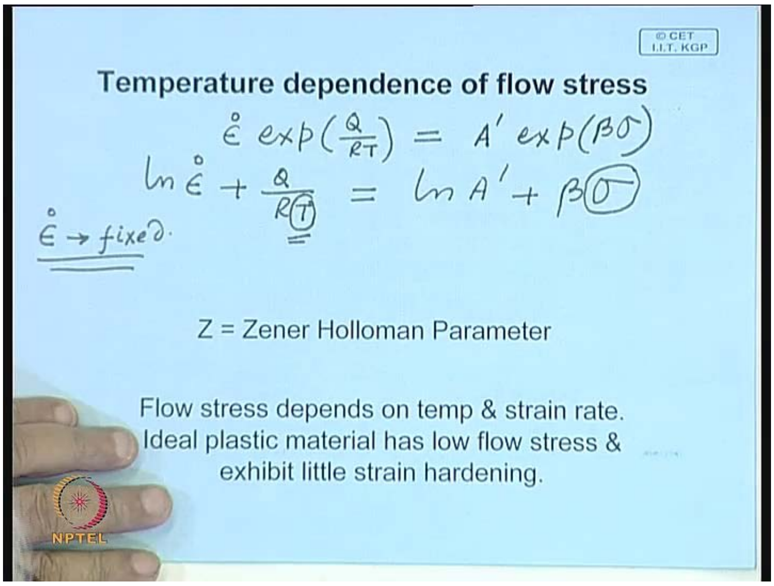

Now, usually these are derived at say if you say the Zener Holloman parameter. This is equal to the strain rate exponential Q over R T and this is equal to a function of stress and we say that we take it some function (( )) exponential beta sigma. Now, here if you easily you will be able to show that if you take log, this is equal to Q over R T equal to beta sigma. Now, if you assume that any deformation process now often the strain rate may be fixed nearly same. From process to process, material to material it may vary. But by enlarge this will be constant and if it is constant, in that case only variable is the stress is inversely proportional to temperature and therefore, here if you make a plot, what will the plot look like?

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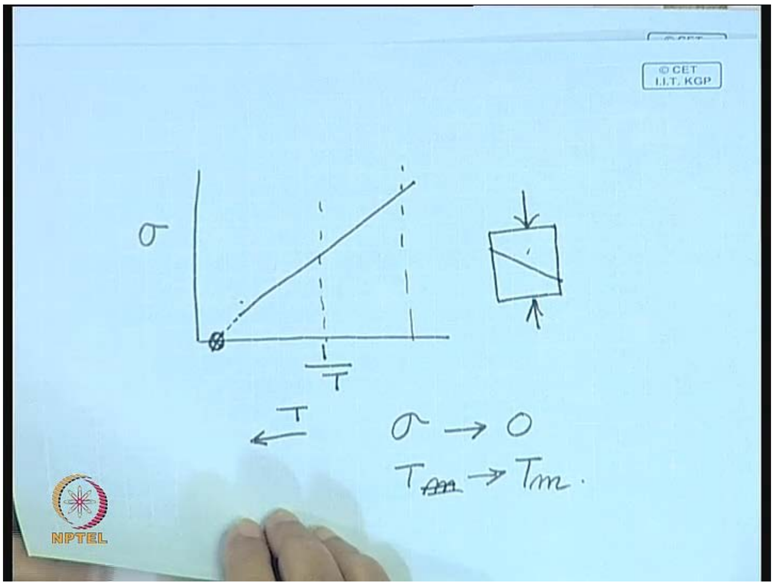

If you make a plot of sigma against 1 over temperature, so the temperature is increasing. So, that means T is increasing this directions; that means higher the temperature, lower is the strength of the material. So, it is something like this. So, at a low temperature room temperature they give strength may be somewhere here. But if you increase the temperature, it is more amenable; most material where the strength goes down, it will be easier to deform it. If you extend it, it may reach a point zero. Infact a deformation in solid takes place through shear and deformation say even if you are applying compressive stress, a deformation takes place on the plane at which… on these planes through slip.

Deformation takes place in crystal through slips and slip is a process of simple shear. And usually, the shear planes are inclined at an angle 45 degree to the direction of the principle stress. Now, metal has shear strength but liquid does not have. When it approaches melting point actually the material loses its shear strength. So, this is what if it is extent; sometime we will see that when it approaches melting point, the strength of the material approaches zero or the shear strength approaches zero, where the melting point T approaches melting point. And infact, most of the metal working temperature is decided based on the melting point of the melting range of the alloy (Refer Slide Time: 26:25) At higher temperature, therefore the material the stress is also very low and it shows very little strain hardening.

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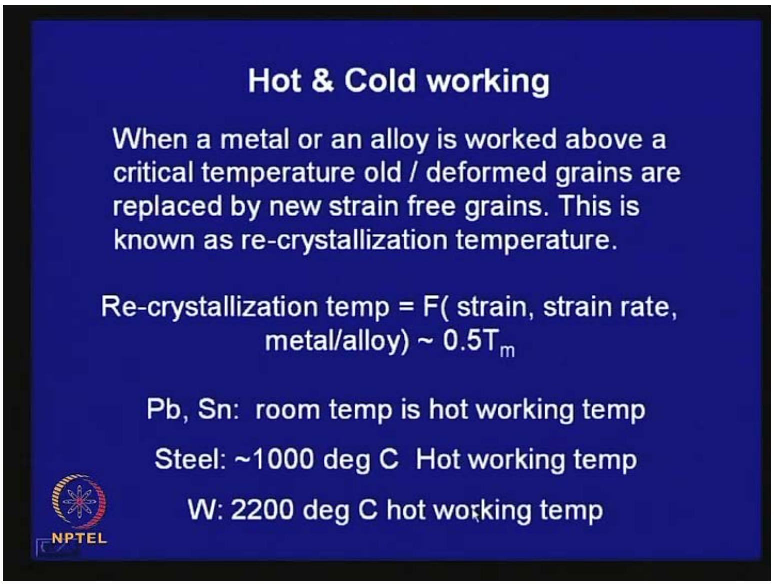

And usually, we find there is a critical temperature is a metal say room temperature, there is strain hardening. But as you increase the temperature, what happens is the deformed grains are replaced as you keep deforming.

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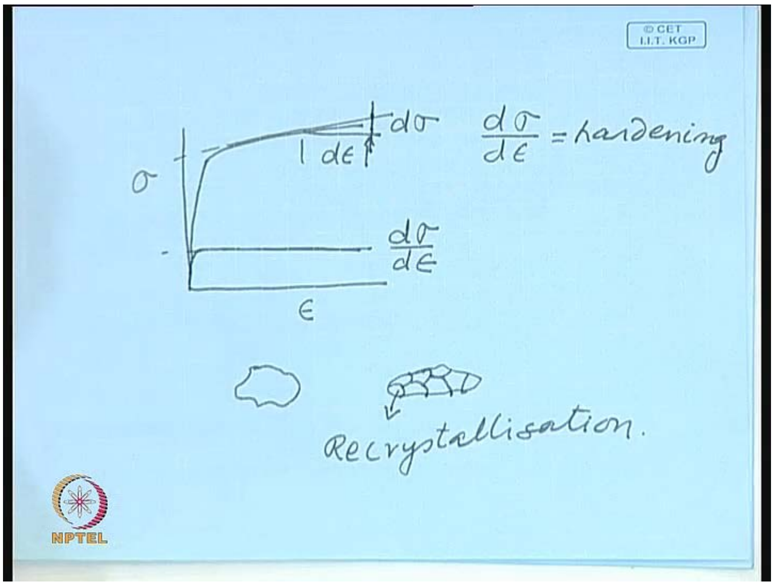

The deformation say if you are your stress strain plot say at room temperature is something like this. As you increase the temperature, here still it is there is some amount of strain hardening; the slope is this plot; the slope is this is the d sigma; this is d epsilon. The slope of this plot is strain hardening and when you go to higher temperature possibly you may look like this. So, there is hardly any hardening. So, what is happening the soft. As you deform a grain, you see it gets deformed. But at high temperature, because of the deformation fresh grains nucleate and these are replaced by new strain free grain and this process is known as re-crystallization.

This process is known as re-crystallization. (Refer Slide Time: 31:22) and this re-crystallization temperature, re-crystallization happens at a particular temperature. I mean and this temperature is a function not only of the amount of strain that you put in with this, the strain rate strain that is accumulated; also the strain rate and also depends on the metals and alloy. And infact, roughly one can say that it is half the melting point of the metal; T m is the melting point in degree absolute. So, therefore even now the melting point of lead and tin are very low; tin melts at 232 degree centigrade; lead at 327 degree centigrade.

Therefore, room temperature is quite high in case of both lead and tin. So, this is the case room temperature working for lead and tin is hot working. But room temperature working for steel is not hot working. It is cold working and steels are hot work at temperatures may be 900 or 1000 or above; whereas, for Tungsten is melting point is very high. It is above I think 3000 degree centigrade. So, here even if you work at say 2000 degree centigrade, it may be cold working. So, this is your rough hot working temperature for Tungsten; 2200 degree centigrade is the hot working temperature for Tungsten.

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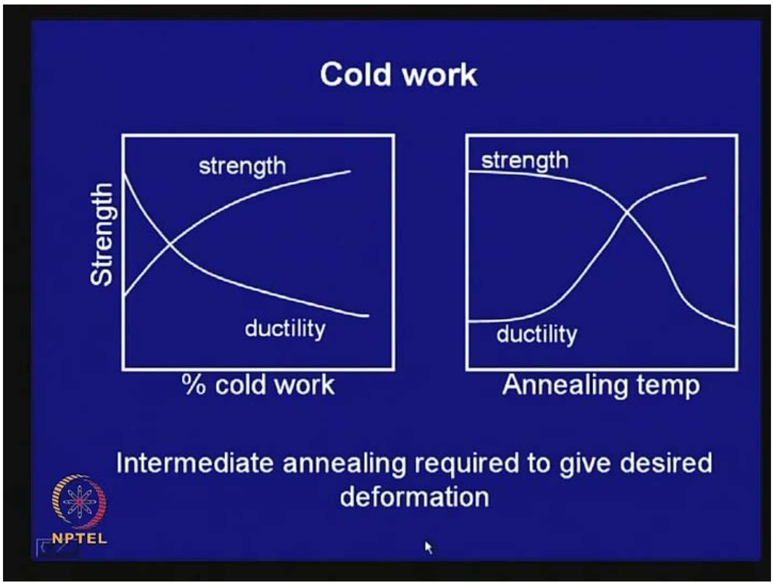

Now, what happens when you cold work a material? If you cold work; in that case, you see your strength increases. As you give more and more cold work, your strength increases; this ductility decreases with percentage of cold work. So, therefore if you have to give very large amount of deformation often it may not be possible in single stage, you may have to after giving some amount of cold work, you may have to bring down the strength; otherwise the load required to deform will be very high. And the tools, which are available with you is that you may not be able to give that amount of deformation.

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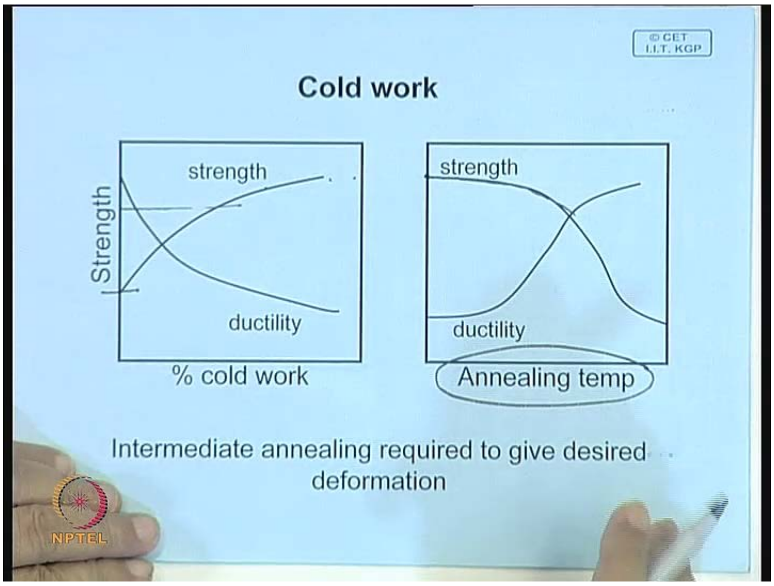

So, therefore after certain amount of cold work, say the strength comes over here imagine. Say, initially your stress required was here; here may be it has become double. So, you may think that my press is not large enough to press this much of load; we must somehow bring it strength. Then some kind of heat treatment is given to it. We will talk about it later. So, that means cold work you may have to give; you may do the first cold work at a room temperature. But intermittently, you have to give some heat treatment to bring down its strength.

So that, the desired amount of cold work; desired amount of deformation is you are able to give to get the final thickness or final dimension and this is what is done through process of annealing. And when you anneal, the strength… this is the annealing temperature. If this is the strength it has gone from after cold working; when you anneal, its strength comes down and its ductility also improves. So, annealing is the heat treatment process, which restores the microstructure or restores ductility and strength of a cold work structure and intermediate annealing is required to give desired deformation to any work piece.

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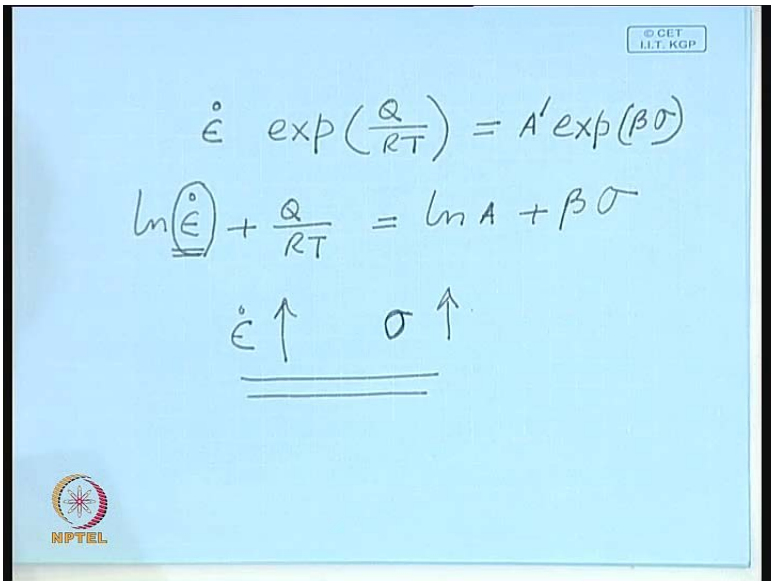

Now, let us look at what is the effect of strain rate. Now, you can easily see that if you want the strain rate, the same equation that Zener Holloman parameter. If you look at Q over R T, this is equal to let us say A exponential beta sigma and in logarithmic form, this is Q over R T. Now, so far we were looking at the process of deformation at constant strain rate. Suppose we increase the strain rate, different types of forming processes; we have different strain rate. We can also form there is a process of forming called explosive forming, where the strain rate can be several magnitude several order of magnitude higher than normal deformation process. So, it is quite important you know what is the effect of strain rate on flow stress. So, clearly it is evident from here if you increase strain rate, the flow stress increases. So, that means your processing units the press hammers or rolling mill should be able to withstand higher stress. If you are rolling at a higher speed, rolling mill should be able to withstand higher stresses and usually, some of the effect of strain rate which are listed here.

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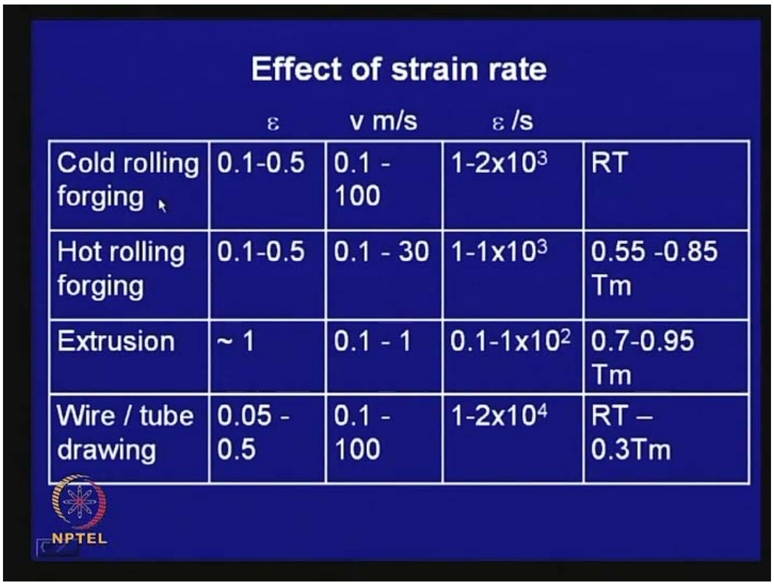

The strain rate can vary from the process of deformation; one process to another like cold rolling.

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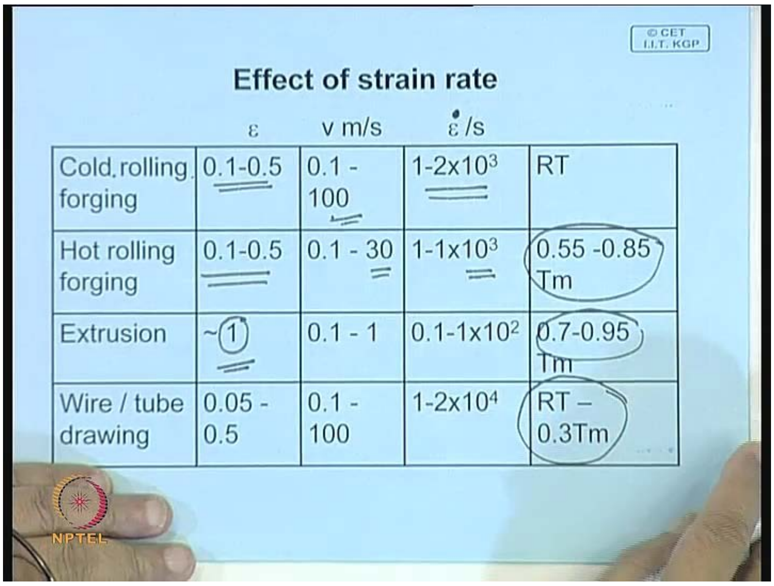

Usually, this is strain rate; this is the amount of strain that is normally given in cold forging or cold rolling and forging. So, this is around say 20-30 percent per (( )) around that kind of working is given in cold rolling. And this is the velocity at which the process takes place and the strain rate is of the order 10 to the power 3 around of the order of 10 to the power of 3 per second. Hot rolling also the strain rate may be same; but your amount of strain is also same. But it takes place at a much higher temperature. Extrusion, the total amount of strain that can be given is much higher. Velocity is not as high as in case of cold working or hot or hot forging or hot rolling. But the temperature at which extrusion is done is much higher. Now, wire cum tube drawing here this is a cold working process. Usually, wires or tubes are drawn; the tube can be drawn at a high temperature also. But wire drawing is usually a cold drawing process; it is usually done at this temperature range.

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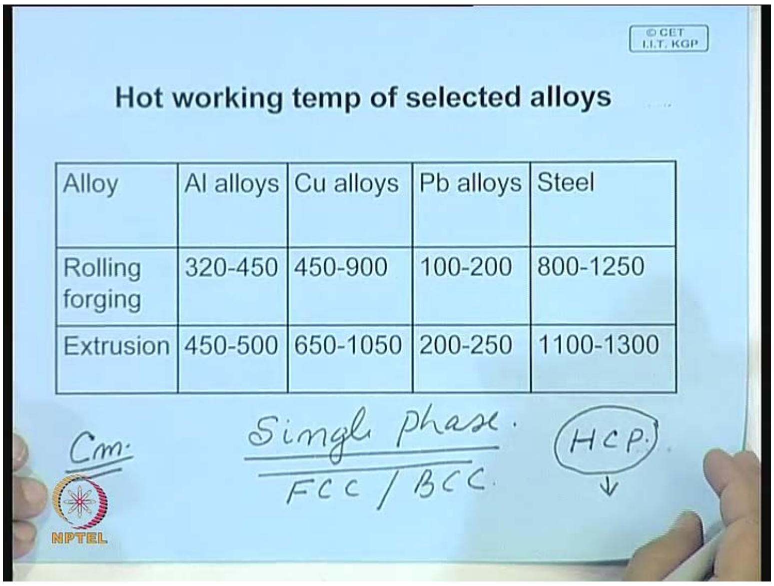

And here are some of these different alloys can have different temperature range in which working is done and which is listed here. The all scale with depending on their melting point. Lead has a low melting point. So, therefore rolling and forging hot working temperatures for several alloys are given. Another important thing which comes up during hot rolling is that material ductility often is determined by its micro structure. The materials often have a… and it is easier to give higher deformation, if the material is of single phase. Single phase material is more ductile. If the material is single phase, secondly this phase must have favorable crystal structure say like face centered cubic, BCC crystal structure. They are easy to deform.

Hexagonal close pack say ideal hexagonal close packed structure; they are difficult to deform. They do not have enough number of slip systems or enough number of mechanisms by which deformation or shear can take place in the metal. So, they are difficult to deform. Similarly, if the materials there are some material because of its crystal structure, they are inherently very hard something like even if you have carbides like cementite or some of these inter metallics. They are very hard; they are difficult to deform; they can fragment. But point is if they depends on if they are present in bulk quantity then it will be even difficult to deform. So, it depends on the microstructure is quite important to know whether the material can be given or can be processed by deformation processing.

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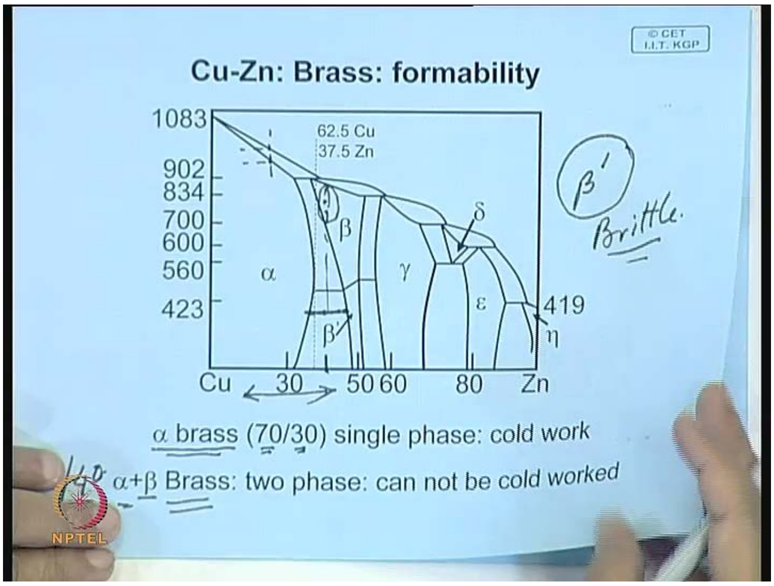

Let us look at the case of brass. Now, last class we talked about the phase diagram. This is the typical phase diagram of brass and usual commercial brasses are within these regions only. Most commercial brasses they fall within the zinc and one of the common brass, which is very popularly known as cartridge brass; that is an alpha brass. It is a single phase. It contains 70 percent copper, 30 percent zinc somewhere here. This is a single phase material. So, if only a small amount of deformation, it is to be rolled into thin sheet. They can be rolled in to very thin sheet; they can be shaped; they can be deep drawn into more complicated steps and few numbers of steps and this is primarily because of its uniform structure. Secondly, you look at the brass say cast brass this freezing range also is not very large.

So, here extent of segregation also will not be much. So, with a little hot working, you will be able to remove the segregation. And after this primary processing, the final processing can often be cold working and annealing; cold work, anneal. And the final stage if you want higher strength in a material, material can be left in cold work condition or if a material if you want to give a or you can (( )) give stress relief annealing treatment. But what happens if you have a brass somewhere here, which is 60-40 brass; 60 percent copper, 40 percent zinc. Room temperature, it is made up of alpha and beta phase. Beta is an intermediate phase. It can also have an ordered structure; beta sometimes becomes beta prime. Now, these are phases are very brittle and look at these slight change in this composition will increase.

Because this zone is not large; I mean not long. So, slight change in composition will make substantial increase in beta. So, here it will have significant amount of alpha; within alpha, you will have significant amount of beta and beta is brittle; this is brittle. So, therefore if you try to give it cold work, the beta will crack and it will the material will fail. So, this is not cannot be cold work. This is either used in cast form or if it has to be worked, it must be heated to this beta region somewhere here. So, 60-40 map to see somewhere here and the zone in which it is beta; this is limited. So, it has to be worked in this zone and higher temperature, it is a disordered structure. Secondly, the temperature is high and here its flow stress is low; it can be given deformation.

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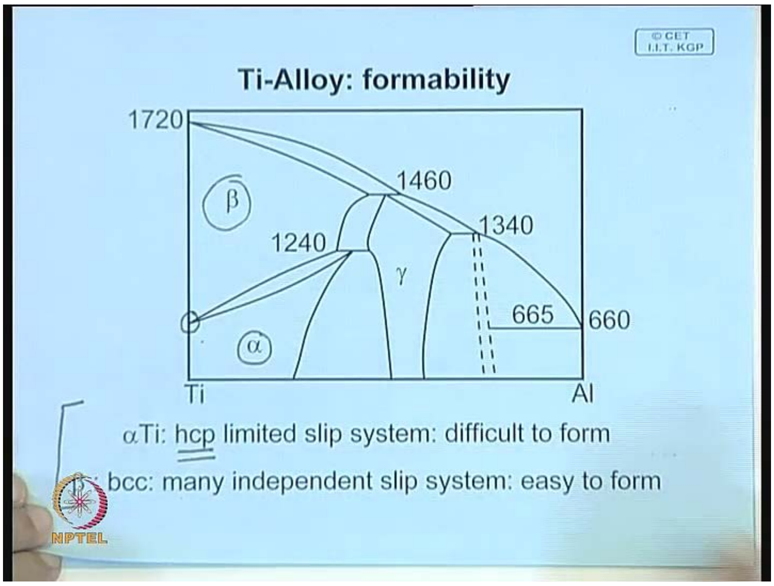

Similarly, titanium titanium the room temperature form titanium has an allotropic transformation. Room temperature, it is hexagonal and hexagonal has limited slip system; they are difficult to form. So, preferably so therefore room temperature ductility it will be difficult to… I mean because of limited ductility, limited number of available slip system, it will be difficult to give desired shape in deformation processing. So, the one we of giving large deformation is go to beta region and then deform.

And by adding alloy addition, the different there are different types of alloy additions which can be made added to this. And if we want that to protect that titanium from environment, because high temperature it will come in contact with nitrogen, oxygen and the deteriorated property of titanium. And if you do not want to work at a higher temperature, by adding alloy elements this transformation temperature can be brought down. So, this is definitely the phase diagram and alloy design can help you to design different alloy which can be which will be amenable to deformation processing at the desired temperature that you want.

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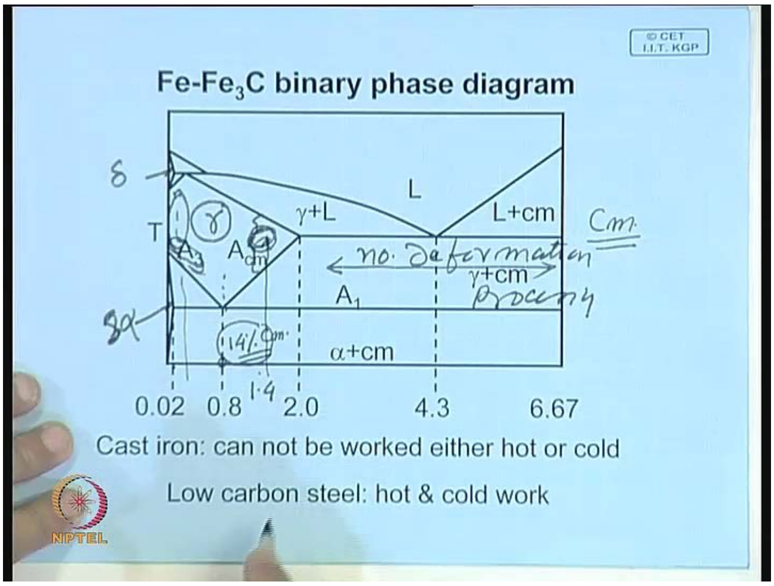

Now, let us (( )) look at the deformation behavior of iron based alloy. Now, this is the iron-carbon diagram which you are quite familiar with it. Now, here also you have allotropic transformation; the gamma this is which region you have gamma; here you have BCC iron; room temperature, you have ferrite alpha iron ferrite. Now, cementite is very hard. Now, over here up to 0.8 percent here, you have around 14 percent cementite. So, 1 is to 7 ratio. In a microstructure, this steel eutectoid steel has 14 percent cementite and as you go to this cast iron region, amount of cementite is quite high and cementite is very brittle.

So, therefore the cementite is not amenable; not only cold work is ruled out even hot working will be extremely difficult. So, therefore when you have large amount of cementite, this area they are not amenable to any deformation processing not no deformation processing. Here no deformation processing; but this area they can be given deformation processing. But when amount of cementite increases; here if you want to deform a high carbon steel, it will be better room temperature cold working will be difficult. But if you go to this region heated austenitic region, here it can also be forged.

So, tool steel high carbon steel something like 1.4 percent; tool steel if you want to give it a shape here, you may have to go to this temperature. This is your working range. But bulks of steel are very low carbon steel. They are within this region of the diagram and here the amount of cementite is very less and they can be they can be and there amenable to both cold working as well as hot working. And hot working is usually done in these regions. We will see later. It is preferred to finish hot working at the lower temperature as low a temperature as possible. So, that in the final product, you have a fine grain structure.

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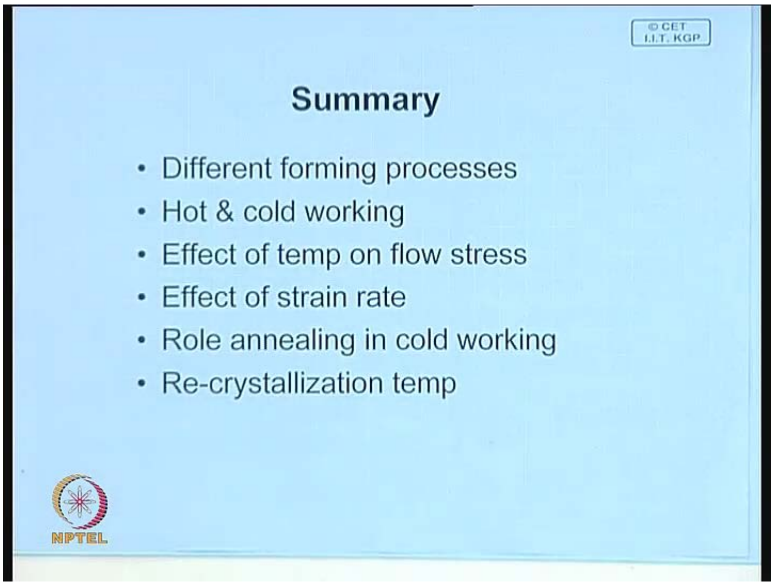

So, with this we finish today’s lecture what we talked about is deformation processing. Now, deformation processing is necessary. First is primarily it will remove cast and dendritic structure in the material. Next, we also saw how deformation processing can be given. There are several types of processes. They can be grouped. They can be classified based on the way the stress is applied and the processing also depends on the operating parameters like the temperature at which you give the deformation and the strain rate that you applied. It also depends on the type of alloy. We also looked at Holloman (( )) parameter, which helps you to determine or get an estimate of flow stress at higher temperature.

And we also looked at how why what happens when cold working is done and we have seen to give large amount of cold working, the strength increases. So, if you want to give a desired shape, but only by cold working often it is necessary to give intermediate annealing treatment. And we also talked about a temperature called re-crystallization temperature, which actually determines whether a process is hot working or cold working. If working is done above the crystallization temperature, it is hot working and if it is processing is done below the crystallization temperature, it is cold working. Thank you.