Principles of Metal Forming Technology
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Lecture – 11
Introduction to theory of plasticity and flow curve

Welcome to the lecture on introduction to theory of plasticity and flow curve. So, we had seen about the elastic theory. In the last lecture, we discussed about some of the relationships where the stress and strain is related and we got certain relationships between some constants like e g k and nu and all.

So, now, will move towards the theory of plasticity because in the case of metal forming, this theory is important you know for knowledge; because when we are going for plastic deformation, it is beyond the, you know yield limit. So, basically it is not in the elastic range. Basically we are going into the plastic range.

So, basically the deformation is to a large extent in those cases and so, there is need to know about it because and the case of elastic deformation we know that, there is there are rules like Hooke’s law. Once you know the strain, then you can predict the stress by using these Hooke’s law and others, but that rule is no longer valid, when you are going to the plastic range.

So, what how these, what are the, you know theories in plasticity; how plasticity, what is the plastic flow curve, how the material behaves when it is elongated or it is deformed. So, all that we will have some introduction about its theories.

So, coming to the, you know; first of all we will talk about the flow curve. So, if you talk about the flow curve, actually the flow is related to the plastic flow of material.

So, when we talk about the stresses, we normally talked about the stress that is engineering stress in earlier case; when we talk about the elastic reason. For once we go to the plastic reason, then the engineering stress does not have much of the significance because once the deformation starts, in that case the area is basically reducing and you will have not you cannot find the stress by dividing with the original area. So, your area is basically changing. Instantaneous area is coming into picture and in that case, you have a different type of curve that is known as the true stress, true strain curve.

So, this curve basically is known as the you know flow curve. So, flow curve basically the, it is the curve between the true stress and true strain and that is known as the in the flow curve. So, what is seen that if you draw the typical you know flow curve; if you see. You talk about the normal engineering stress and then you talk about the you know true stress and true strain.

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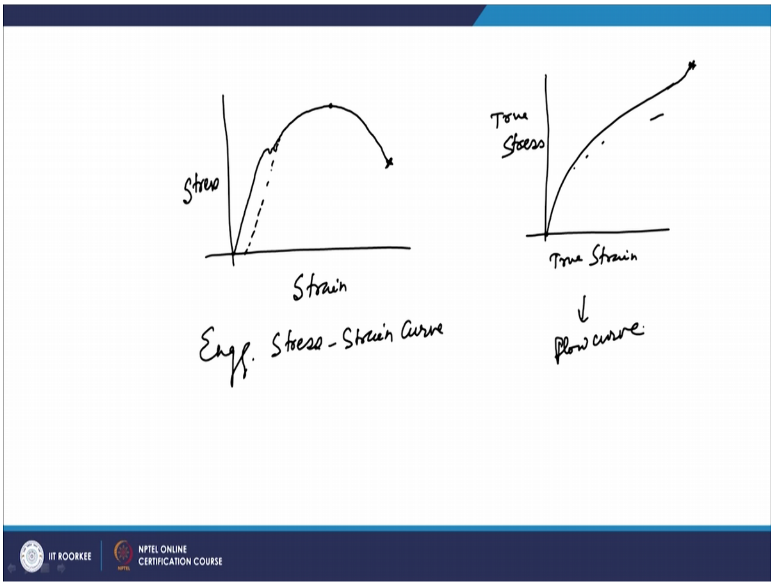

Now in the case of normal engineering stress is what happens that you have, this is the stress and this is strain. Now in this case, we assume so in that case, we assume that the area is same. So, what happens that you, the curve goes like this and then there is deep and then it comes and then it comes like this? And here is the point of facture. Now in this case, this is the point which is the maximum you know, you get the maximum point here; this is pointing related to the ultimate tensile strength of the material.

Now, in this case this is the yield point, you have certain these on up to which you have the proportionality holds good and then, this is the in this is a reason where the strain hardening is taking place. And ultimately at this point, the material will be you know after that and this is will be the fracture point after that, we in fact, the stress value is coming down. And ultimately your this because the flowed which is there load will be basically not required, load will not be more. So, basically in this case you are getting the stress as load by original area.

So, what you sees that in the case of engineering stress strain curves. So, this is your engineering stress strain curve. Now in this case, you see that this is the maximum, but after that the load is decreasing and then ultimately, this is the point of fracture. Now thing is that when we talk about the, actual stress which is calculated; what we see is that after this point, actually there will be necking.

Now the thing is that I mean there will be yielding. So, this is the point of yield and after that as we know that, since it goes into the plastic range. So, before these if you are leaving the material, you are not you are removing the loading on the material; in that case the material will come to its original position ah. So, there will not be any strain, but once you are going beyond this point. So, suppose had here, so it will come like this. So, there will be certain strain which is leftover.

So, that is basically the plastic strain, but the thing is that after this, there is this is not actually the actual stress because your, once there is a elongation in that case; as we know that once there is elongation, you have the increase in length in certain direction. Then in the other two transfer directions, you have the contraction. You have the change in the dimension depending upon the property of the material.

So, basically the cross sectional area does not remain the same. So in fact, this is not the true representation of the value of the stress which is there at a particular instant. So, what we do in that case is that you try to find this and that the stress which is based on the actual area at particular instant. And in that case, that is done by separate curve and this curve, this curve is also the stress versus strain curve, but this is true stress and true strain curve.

Now what happens in this case as you see that it will go and then it will go and somewhere it will fracture? So, this is the fracture point in this case you see that it will go up to certain points. There are stress is propositional to strain. So, with the before that range, it will be behave in the similar fashion, but after that it goes like these and then it deeps, but here is does not deep. So, basically after this reason; if you go in this reason now this reason is basically the strain hardening zone. So, here the because the material is strain harden and that is why stress value goes on increasing and ultimately it will go till the point where the fracture is initiated.

So, basically you need require the stress which is required to plastically deform the material and that stress value is known as the flow stress of the material. Now in this case this true stress true strain curve, this is basically known as the flow curve. Now this curve basically, it is giving you actually the stress which is required to cause the metal to flow plastically. So, that is why that is known as flow stress and this curve is known as the flow curve. Now what are the characteristics of this flow curve or the true stress true strain curve for a typical ductile materials.

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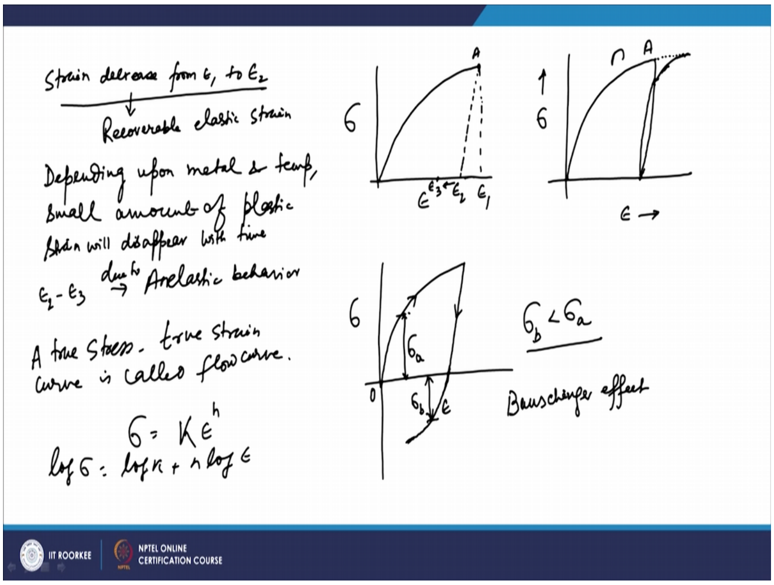

So, now let us that we have to see, how this true stress true strain curve or flow curve looks like for different type of materials. Now suppose you have a material which is ah, so we are talking about it ductile material. But you see that if you look at the typical flow stress curve. So, you so, flow stress true stress is denoted by this and this epsilon sigma and epsilon.

Now in this case, this is the typical flow stress of the curve. But the thing is that suppose we have gone up to point a up to that it is loaded. Now from here ah, when the load is released in that case the total strain, we have reached up to this point; but then once we release the load in that case immediately so you this suppose this is e epsilon 1. Now once we release that the load is released, the total strain will immediately decrease. So, it will immediately decrease from epsilon 1 and it will come to epsilon 2. So, this is upon the immediate release of the (Refer Time: 10:45).

So, you are here at this point and at this point the total strain is epsilon 1, but once you release that load immediately, the strain comes back to epsilon 1 to epsilon 2. Now this is because of the elastic nature, elastic property and you know this epsilon minus 1 ah. So, this basically will be nothing, but it will be equal to sigma by e. So, as we know that this is strain which is elastic strain this is nothing, but the stress value divided by the module of so, rigidity. And that value sigma 1 to sigma 2, this is known as the recoverable elastic strain. So, strain decrease from epsilon 1 to epsilon 2 and this is known as recoverable elastic strain because this amount of the strain is anyway recovered. So, that is why it is known as the recoverable elastic strain.

Now still the strain which is here, now that is epsilon 2 is still that is not the permanent one. So, basically what happens, the depending upon the metal and that temperature conditions; a small amount of even the plastic strain will disappear with time. So, depending upon metal and temperature, the small amount of plastic strain will also disappear with time.

So, now what happens that we saw that epsilon 1 to epsilon 2 that is your recoverable elastic strain. And then it will be you know, somewhat going towards this with time and then ultimately it may come to this point that is epsilon 3. So, this epsilon 2 minus epsilon 3; so this is basically the because of the an elastic behavior. So, this is known as an elastic behavior of, this is due to an elastic behavior.

So, normally because of the complexity, we normally assume that this is there is no such phenomena which occurred in the in this figure. Now what we see that in normally, it will be coming to epsilon 1. This is total strain that will become going to strain to epsilon 2 because of the recoverable elastic strain and then ultimately it will be coming towards epsilon 3 because of these inelastic nature.

I think is that suppose, now this we are further loading it. So, suppose you are further loading. So, you are coming back and then you so, your flow curve is like this A. So, this is your point A. Now from here, what you did is so, now it goes it; it comes down and then it further if you are further loading it, then how it will behave. So, actually when you un unloading the you know this specimen from here; so unloading will not be actually completely parallel to the elastic reason of these curve. Then now once you are unloading, so it will come to this point.

And if you are further loading it, so now, if you further load it will go like this. So, it will come to a smaller value and then if that that goes so, it will be going like this. Now what does that mean? So, this means so if you look at these curve, you have unloaded so, this is the cycle in which it has come down. So, this is your true strain and this is your true stress.

Now the thing is that when you have unloaded, then if you (Refer Time: 15:33) it, what you see that further it will be an extension to this curve only with some more plastic strain. At this point what you sees that this becomes an extension of the same curve which was coming. So, what you see that the reloading curve, it will be basically bending over and as the stress will approves the linear value have been the original value and from where it was unloaded and some additional plastic strain is experienced and after that we what we see is you see the same curve which you have got as then extension of the original you know flow curve which was seen by us.

So, what you see is that there is a hysteresis behavior in such cases, in the case of true stress to strain, when you are loading and unloading then what you see that there is a hysteresis type of loop which is formed and this is terraces behavior normally we are neglecting, in the case of these are true stress true strain analysis.

Further going to the another aspect, if you see this is this specimen is basically strained in tension. Now the thing is that if the, you are doing this. So, once you have suppose, you have deform the material beyond the yield point plastically in one direction. And then, suppose in the tension and then you are further unloading it to 0 and then further you are trying to reload in the opposite direction, then how it will behave?

So, if you look at the flow curve it goes like this. So, it will come here and you are further unloading it coming to 0. So, here you have, this is as sigma and epsilon. Now the thing is that this is suppose your yield, yield stress in tension and so, you have gone loaded in the direction and further you have reloaded when unloaded and coming to the zero stress state. And further you are loading it in the opposite direction that is in the compression.

So, if you are going in compression. So, it behaves like this. So, suppose in the compression what you see you get the, this is the yield point yield stress in the back side, in the opposite side. And what you see that normally; when you go in the opposite direction, you do load in the opposite direction. In that case, the sigma b which you get and if this is your sigma a basically in that case what you see is that sigma b will be less than sigma a.

So, basically what you see that your yield stress. Yield strength is dependent upon the nature of loading and loading path and the direction. So, this type of effect, this type of behavior is known as the Bauschinger effect. Bauschinger effect, which is there because of which the yield stress strength will vary in one particular direction, it will be lesser in one direction; it will be more in other direction.

So, this is because of the loading path direction and this is known as the Bauschinger effect and the Bauschinger effect is basically neglected again in the case of the flow curve. So, it is neglected in the theory of plasticity and what we assume that yield strength in the tension as well as in the compression yield stress value is same. So, this is known as the Bauschinger effect.

Now the value as we already knew that the you know the graph for the curve between the true stress and the true stain is known as the flow curve. So, the flow curve is it will be giving you the stress. So, the we can write that it true stress- true strain curve is called a is called flow curve.

Now flow curve, it comes from the fact that flow stress; it gives you the flow stress value that value of stress which is required for the plastic deformation of the material at a particular given value of strain so, that that can be found from this curve and it has been tried to give a mathematical correlation to this mathematical relationship to this. And most common mathematical relation which describes this flow curve or plastic behavior of the material is sigma equal to K epsilon n. So, sigma is the true stress value flow stress value.

Epsilon is the strain true strain value, K is known as the strength coefficient; K is nothing, but if you take and as basically epsilon as 1. So, sigma will be K. So, will be nothing, but it is stress at a epsilon equal to 1. So, that way you can find the value of K and n is known as the strain hardening exponent. So, you can have the, if you take the log on both the side log sigma will be log K plus n log epsilon. So, that way you can have log sigma will be log K plus n log epsilon.

So, you can get n as log sigma minus log K divided by log epsilon. So, that way you can find the you know this n. So, that is basically if you have a log curve, so it will be the slope y equal to mx plus c. So, if you take as y equal to m into x plus c. So, if you take log sigma and log epsilon log sigma as the y axis and log epsilon is the x axis. So, this n will be the slope of that linear curve that will be talking the log curve for the sigma n epsilon and it will be the strain hardening exponent. So, this way we this n value will be varying for the materials.

So, now the this flow curve will be different for different types materials and materials maybe you know ductile or brittle and the flow curve basically will be giving you the flow stress which is required for deforming the material plastically at any particular value of the strain.

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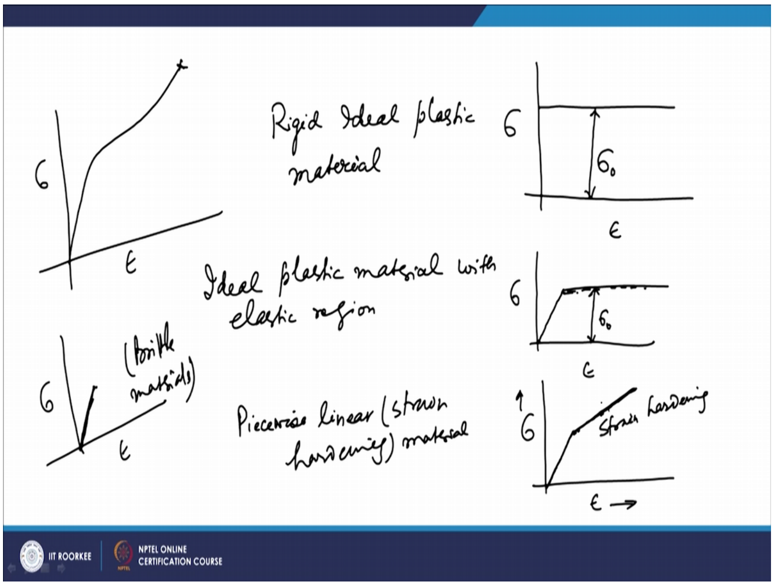

So, you can we can have the glimpse of the different types of flow curves. Suppose you are drawing the flow curve for the idealized, you know rigid ideal plastic materials. So, if you are trying to draw the rigid, I mean idealized flow curve for a rigid ideal plastic material.

Now if you look at this rigid ideal plastic material, now in this case what happens that the flow curve which is sigma n epsilon. Now it will start like this. So, you will have this as the sigma naught value. So, this is actually the rigid ideal you know plastic material.

Now in that case, you have a constant flow stress value and you will be having the deformation this way.

Now if you talk about the ideal plastic material with elastic reason. So, as we have seen that once you have the elastic reason, in that basically when you are going to deform the them so, up to certain point, your Hooke's law is valid. So, in that actually stress is linearly proportional to strain. So, if you try to draw the idealized flow curve for that, for a material which is ideal plastic material with some elastic reason. Now in this case, so in the elastic range; it will go like this and then since it is a ideal plastic material; so it will go like that. So, this will be your sigma naught.

So, this curve tells that initially when you are trying to deform it. So, it will be going in the elastic range and the elastic range basically stress will be proportional to strain. So, that way it will be going and then add the ones that yield point is reached, then is being the ideal plastic material; so with constant stress value the material will flow. So, this is the idealized flow curve for the ideal plastic material with elastic reason.

Now more importantly we required to know the, you know idealized curve for a material which is piecewise linear. So, what is there? In suppose you have a flow curve which is of these states, what we see? Now what we see? That in this case you have this is the linear one and this is basically the at this point the flow stress remains constant and the material is getting deformed at constant flow stress value. Now what happens that when you have the strain hardening material as we see in normal typical cases in the trial materials. So, what happens that in there up to the yield point where we reach? Now up to that you have so, in the elastic reason you have the you know straight you know you have a straight line with slope.

Now after that still you have you know an increasing value of a stress. So, what if you recall in earlier side, we had seen that your topical goes like this. Now this is not basically linear. So, this is a reason which is basically the reason of strain hardening. Now in this reason when basically when the plastic deformation starts, if you try to see it metallurgical after that you know you your you require larger stress to remove to move the this location. So, in that case the true stress value basically increases as the strain is increasing. So, if you look for a material with one idealized; suppose you have a piecewise linear material.

So, here you have the strain hardening zone. Now what we see is this will normally we seen encountered in typical ductile materials. In those cases you have the up to this reason, this is linear and again this is a linear, but here it is further increasing and this is the reason of strain hardening because there is straining taking place and as the plastic strain is increasing, the material gets hardened and hardened. So, hardness is going on increasing.

So, that is why this is the strain hardening zone; strain hardening is taking place during this process. So, that is when you know clear in many of the ductile materials, in most of the typically ductile materials which have which are formed. So, when you called form them, in those cases you can see that you require. So, larger stress every time you wants to called form, then you further try to call form then you required larger stress value for the same incremental strain.

So, this is because of the strain hardening effect because of this strain hardening effect, the amount of stress required for the deformation for the strain becomes larger and larger. So, this is for the typical of for typical you know materials for suppose a brittle material is there or for a ductile material is there, for ductile material; it will move like this for brittle material, it will come and then it will fracture somewhere. So, and for brittle material it will come and stop somewhere. So, for an ideally brittle material, it will come and stop here because there is no plastic deformation in the case of the brittle materials.

So, this is normally for brittle materials and for the ductile materials, it will move and go towards you know increasing and then ultimately it will fracture at some point. So, this way you have and maybe for some materials you may have some degree of you know ductility. So, in those cases it will come and then further it will move towards this side and then it will fracture.

So, with the limited ductility, it will further extend towards the strain hardening zone and then there it will basically you know fracture. In case of brittle materials, what happens that you have cracks? So, it will go up to with without much of the appreciable deformation, much of the these strain it will go and then there itself, here it will be fracturing.

So, this way the flow curve for different types of materials can be seen and can be visualized and from they are you can have this value of the so, strain hardening exponent can be found for these material.

So, as the slop will be larger and larger, it will be more you know you know and value will be more and more. So, that is how the slope will be changing for the different you know material. So, that way you can analyze the different materials stress strain true stress true strain curve that is flow curve.

Thank you very much.