Mechanics of Sheet Metal Forming

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Week- 01
Lecture- 01
Introduction to Sheet Metal Forming and Tensile Tests of Sheets

So, welcome all of you for the first chapter on mechanics of sheet metal forming course that is introduction to sheet forming process. So, in today's class we are going to see the first chapter ok and it will continue for the next class also ok. So, now this first chapter is divided into actually two parts, one is basically introduction to the sheet forming process and then we will see an important aspect of material testing that is tension test ok. So, let us go to introduction of sheet metal forming process as you all aware of the fact that metal forming operations can be divided into two categories mainly, one is bulk forming process, the other one is sheet forming process and this course is predominantly on sheet metal forming process mainly the mechanics part ok. So, when it comes to introduction ok. So, I have given three important points in the slide ok.

So, we are all aware of the fact that we have hot roll strip and cold roll strip sheets ok in the form of sheets ok. So, they are basically you know deformed, plastically deformed and certain shapes are made ok to make useful components in you know you can see automotive industries, household appliances, building items, you know aerospace structures and commonly used food and you know drink cans and variety of other known products ok. So, the sheets are actually deformed using several sheet forming process to make a particular shape, permanent shape changes allowed in that ok. Generally we want these days a strong strength to weight ratio.

So, all parts are manufactured, material selection and the process optimization everything is done keeping in mind that strength to weight ratio is going to be important ok. So, what are the common sheet forming process? Of course, you all know that bulk forming process are of different types say for example, forging, extrusion, rolling ok. So, wire drawing that we generally study in manufacturing and technology courses. Similarly, sheet forming process also can be deformed to you know several types and it also depends on what type of components you are going to make. For example, blanking and piercing ok, bending, deep drawing ok and there are other sheet forming processes ok like roll forming ok.

So, we are speaking about sheet it could be tubes also tube forming is also possible to make certain components ok. So, to start with we are going to briefly see some typical examples of that. Say for a first instance you can take blanking and piercing ok. A schematic is given here in this diagram you can see ok. So, you have a sheet here ok and the sheet is actually clamped using blank holder ok.

So, the clamp it is called the clamp ok. So, the sheet is held on one side and the other side is free to you know deform ok. So, and you have a punch or you call it as a die that is called cutting die. The cutting die is slightly different from other dies which we use in other sheet forming process. Here the main purpose of die is actually to cut the sheet ok.

As you see in this diagram so the sheet is undergoing severe plastic deformation in this region and you will see that at one particular stage fracture is going to get developed and these two regions will get separated ok. And this part will actually come down ok and it will be separated from this part of the sheet ok. So, generally this operation is done in process ok and additional blanking may be required later to remove extra material and punch holes ok that is the entire process. And if you closely look at this it is actually a complex process of plastic shearing and fracture ok. So, you need to have plastic deformation in this clearance region, this clearance is also very important in this case and this particular parameter clearance is going to be generally you know designed in such a way that appropriate cutting is actually done ok.

And you will see that this edge region, this edge region that means this region which is undergoing deformation ok will undergo localized hardening ok. So, that is very important and this shearing as such is not going to make a shape you know shaped component rather it is going to be helpful for sizing ok. So, next important one is called as bending. So, this bending is a very common process used to for making several sheet components ok. For example, you can have household utensils, washing machine parts like that the components are actually bent at certain locations and other than that several other forming process are also available to make their component ok.

So, this schematic is actually straight line bent ok. So, that means this portion was initially you know you can see horizontal in nature and we will see in the next slide ok. There are you know pressures which is used to bend it to about 90 degree you can imagine ok. So, the angle is about 90 degree here ok. So, and the bending is done in one line ok.

So, that is why it is called straight line bend ok. It is a basic plastic deformation process. So, and the plastic deformation happens here only in this bend zone you can imagine ok. This portion and this portion are not going to have any plastic deformation ok. It is unaffected region ok.

But this type of bending process will also have some problems. For instance, they will have elastic spring back which we are going to discuss elaborately you know little later part of this course. But the brief idea here is, suppose this angle is 90 degree. So, you know you can imagine that after we think that bending is over then we remove load. So, this will not be 90 degree this will be rather a different angle ok.

So, that change in dimension is because of we can say it as elastic spring back ok. So, this spring back has to be minimized. There are several methods that people follow in the subject ok. We will see how to model this elastic spring back in a very you know simplest fashion. And the main problem is if you allow spring back then assembly of these parts with respect to other parts will be a difficult task.

So, what are the different bending methods? These are some schematic I have given here A, B, C, D ok. So, you can imagine that bending is done using 4 different processes ok. The A part is going to be little folding type of thing ok. You can hold the sheet in this particular region and ok the sheet is actually clamped here and it is rotated in this direction or of course you can rotate in the opposite direction also and you can make a sheet of like this. Sheet will be bent like this ok.

So, to get a previous one this type of L shaped bending is possible ok. So, there are other ways of bending. This is another example the B part is called V-die bending ok where you have a die and there is a groove ok V groove on which you have a sheet and the punches are of same size of the you know V-die ok. And you can see that the punch is going to move down and it is going to touch the flat sheet and further you move down it will be bent like this ok. So, once you remove the punch ok it has to have that particular shape ok what do you need of a desired dimension.

For example, fully bent sheet should have this type of bent section is not it. So, that is the another bending process ok. So, roll forming as I was telling you so roll forming is another method where you can see that rolls are used these are all actually rolls and a sheet is kept in between and the roll is actually going to roll and then it is going to create this type of bending ok. So, you can have channel sections ok you know like for example, wide panels like roofing sheet or intricate channel sections can be produced using roll forming you know machines. And you can have numerous sets of rolls successfully bend the sheet ok it is just not in one section you can have different you know sets of rolls and it getting continuously bent ok to make any channel section.

This D type is called flanging and it is a relatively well known you know method like in piercing you have a cutting die instead of that you have a just a flanging tool and it is not going to cut the portion with the bend region it is just going to bend it ok. So, it is not going to really shear cut the sheet rather it is going just going to bend it and you will see that finally you are going to make a L shaped component like this ok. So, basically the flanging tool is going to move down in this way and it is going to push the sheet towards the die which is kept stationary here ok. And once you release the flanging tool we want this 90degree shape but then there will be some slight change in the angle which is what I was referring to as sheet spring back which we will discuss elaborately later on. Section bending, section bending is little complex in nature when compared to other simple process we discussed before ok and here as given in the schematic you can see it is basically channel starting from here to here and the channel is also of complex shape that you know like you can see that there is a significant height of deformation given here and there are lot of problems here because you will see that there is a bending here and there is bending here ok and the edge region is going to undergo deformation ok.

And you can also see that as referred to the schematic there is a small fracture here and there is lot of wrinkles here ok and because of that you will see that this height is going to be lesser than this particular height ok. So, the sheet is curved into more intricate shape ok it shows the schematic of the process the flange of the channel is strained and many split at the left end of the portion and legs height h will drop that is what I was telling you ok. So, you are going to be little bit careful in this type of defects ok. Wrinkling and an increase in flange height ok are possible on the right hand side ok. So, here fracture is possible here wrinkling is possible because of that your you know your height of deformation here and here are going to be slightly different.

So, one has to be careful ok when you deform this kind of intricate shapes using bending. So, there are other sheet forming you know operations like a famous one is stretching ok as the name says. So, the schematic also shows that as an example you can see this is the actual sheet the upper part ok and you can see the setup here in B part ok where the same sheet is actually clamped between the die and the blank holder. I hope you all are aware of the fact that in sheet forming you need tools for example die and blank holder and punch to deform the sheet plastically ok. So, die is kept on top and blank holder is going to clamp the sheet onto the die and you have friction between at the interfaces here on both the sides ok.

And you can imagine that in the top view it is going to be of this particular type of deformation. So, punch is going to touch the sheet first and further displacement in the punch will deform the sheet in this fashion and you can see A part is nicely going to be a section view of how the deformation is going to be ok. The punch is pushed into the sheet ok. Now, one important point here is the sheet most often it is not going to be drawn in this movement is generally restricted here because of the clamping force and your friction, interface friction. So, what happens is there is going to be significant tensile forces that are generated at the at the center forces at the center region ok.

These are the forces that cause deformation and context is between the punch and the sheet is very much lower than that of generally yield strength of the sheet that is what generally people say. So, this stretching ok we are going to discuss elaborately in further chapters can also be used as a material testing method ok. So, you can use this as a formability test ok. So, to see you know what is this particular let us say what is the height of deformation ok let us say this is height ok. So, let us say this is your for example, it is your height for example, so what is the height of deformation you can have at which you have a fracture in this location ok that can be used as a measure for sheet formability ok.

So, that can be well discussed with respect to this figure as h let us say this height of forming ok. So, more complex details going to come in future but I am just giving you an idea here and then hole extrusion is another you know sheet forming process it is also called as a hole stretching. So, the same stretching operation you can imagine that a sheet has got a hole at the center ok there is a hole at the center and there is a punch ok there are standard methods for that we are not going to discuss about that but ok the punch is going to deform the sheet but where hole is located ok. So, then you will have this kind of you know deformation ok this is the height at which to which the hole is deformed ok. So, a small hole is made ok a small hole means a hole should be diameter should be lesser than that of the punch diameter is initially bored into the sheet the punch can then be forced into the sheet to raise the lip, lip means this particular region ok lip.

So, now what will happen this whole edge will undergo a typical deformation process and the material should not fail before it reaches one particular height and especially failure will happen mainly in the edges. So, you have to be little bit careful in that. So, your hole stretching ok or extrusion of punched hole is very important to understand how hole is going to deform when you go for actual sheet forming process ok depending on this one can select the you know the material responsible for making good material which is be useful for making that kind of components. So, I have just written here that the splitting will limit the height of extrusion will be appreciated ok. So, the larger the height it will be better at the same time you should be able to make the you know the hole stretching operation ok without any problem ok that means the fracture should not happen at the edge region.

So, this stamping or draw-die forming is another method like deep drawing which you are going to see in the next slide. So, here you will see that stamping is generally a shallow deformation process it is also called as draw-die forming ok. So, draw-die forming. So, I have given you some schematic here you can see that it is a shallow drawn part ok not like your deep drawn cup it is a shallow drawn cup ok or a pan something like that you can imagine. So, the sheet is kept on the you know above the die you can see that here it is a die and there is a punch that is a punch is shown here in the b part and it is going to deform the sheet and the sheet is a clamped actually between the blank holder and the die.

So, the idea is same as punch stretching previously stated except material for a component is supplied by allowing the outer edge of flange to draw inwards while being restrained. So, that is the main difference here that is why I told you in the previous slide that you will see that this movement of sheet in the radial direction is not allowed here ok. But on other hand you will see that here it is actually allowed the material can move in this direction but of course with some restriction ok. The restriction is mainly because of holding as well as because of friction ok. So, it moves inwards and then you make a component of this particular shape.

So, what are the applications? A lot of applications you can see one is automotive body panels ok are created and there are several you know stainless steel simple pans are used for many you know applications. So, they are all made by this type of process ok. So, the tools are same ok you have punch you have a die ring or a you know you can also call it as a draw ring and then a blank holder which is used to make this particular component. So, deep drawing, deep drawing is similar to this particular process only thing is here the drawing is actually little deeper ok. So, you make larger cups ok like for example you have this you know soft drinks can those things are made by components are made by deep drawing-process.

Of course there are several stages in that predominantly it is deep drawing process and the tools are going to remain same. So, you have punch you have die you have blank holder. So, purpose of blank holder is going to is nothing but holding the sheet and that is going to lie above the die and you have a punch which is going to touch the initial sheet which is kept like this and then the punch is going to move down and the sheet is going to get deformed in this way and this movement radial movement ok inward radial movement of sheet is actually permitted ok. And you will see this particular example is for partially drawn sheet that is why you have a cup bottom, a cup wall and a flange region ok. So, this portion is called flange region of the sheet and this is cup wall of the sheet and this is your cup bottom of the sheet ok.

So, here of course when you speak about deep drawing ok so the ideal you know actual aim is basically to make a full cup like this ok there is no flange region here. So, you have to make a full cup in this. So, that means the whole flange region should be converted into a cup wall. Whole flange region should be converted into a cup wall that is the meaning here ok. So, here there are 2 or 3 important parameters other than the sheet material properties itself one is this clearance like let us call this as C, this C has to be very important ok.

If C is less then something is going to happen that we will see in next slide. If C is large then also it will lead to some other problems defects during deep drawing. So, this clearance should be appropriate that actually depends on the sheet thickness let us say thickness is t_0 initial thickness is t_0 ok and instantaneous thickness is let us say t ok. So, this clearance should actually take care of this particular thickness. Let us say for example you have 2 mm thick sheet means the clearance should be slightly larger than this 2 mm thick sheet that is the way you have to give clearance.

There are formula available for that so one can look into it. So, now other than that lubrication is important so you have a friction between the punch and the sheet ok then you have blank holder and the sheet ok and die and the sheet ok. So, interface friction is going to be important and that is why we are using lubricants. In the deep drawing chapter later on we are going to study very briefly about redrawing of sheets. Redrawing means so this deep drawing is done in several stages ok.

There are 2 varieties in that that we will see later on but redrawing is also possible. Redrawing means instead of one stage you make the component in let us say 8 different stages again and again and again the material is actually redrawn to make any component but the principle process is going to remain same. So, tube drawing is also possible like I gave an example before that sheets are raw materials here but other than that you can also have tube as a raw material and you can see that this tube ok, tube means metallic tube ok made of aluminium alloy or stainless steel like that ok. And so those tubes can be deformed on its edges or somewhere in the middle to make certain components or shapes. For example, flaring, flaring is one way of making some shape change to the material ok.

Tube sinking is possible, tube reduction is possible like what we have in water cans know at one end the diameter is actually reducing right. So, that is that can be made by your tube reduction ok. So, diameter is actually going to reduce and that can be made using this type of arrangement like you have a die and you can see that this diameter is larger when compared to this diameter ok and you will get a nice shape change given to this tube like this ok. So, this is also possible in tube drawing there are several components one can make with this tube drawing operations. Then comes a totally a new type of sheet forming process called as fluid forming or it is famously called as a hydroforming.

So, until now whatever the sheet forming process we have discussed are predominantly done by you have punch, you have a die, blank holder ok and mostly it is done through these three important tools ok. But instead of rigid tools, rigid tools means the sheet is actually deforming all other tools ok like punch, die and blank holder are actually rigid ok. They are not going to be deforming at all ok. Instead of using rigid tools what people do is they use fluid pressure ok as a deformation medium.

An example is given here ok. So, you want to make a sheet part like this. This is your sheet, the bottom part is actually sheet or part or component you can say ok and there is a die here ok. This is your die as written here and you can see that there is a pressure container it is written as pressure container which contains a fluid ok and you are going to pressurize the fluid in the way it is given ok and the fluid pressure is going to deform the sheet ok to make this particular shape ok. So, between the fluid and your sheet you can have a diaphragm. Diaphragm is given here, this particular part is actually diaphragm which is given here ok.

So, diaphragm is typically put over the sheet of material and pressurized in a container to make flat pieces ok. So, the diaphragm is actually going to, it will not allow physical contact between your fluid and the sheet ok. It is going to prevent the contact between fluid and the sheet ok. So, mainly to take care of you know the other negative effects of you know fluid onto the sheet ok.

Just to avoid that ok you have this diaphragm. At the same time the diaphragm should not disturb the plastic deformation of the sheet ok. Special presses are needed here that is the main thing. So, you cannot use a conventional pressures used for your sheet forming process you know you need a separate press for this which can take care of pressurizing the fluid, controlling it, measuring it all those things are required here. The pressures needed to keep the container close substantially stronger than those acting on the punch in a draw die because the pressure to form a sheet in sharp corners can be very high. You will also see that in the initial part of the deformation ok you will have deformation other than the corner region this die corner region and later on you will see that the pressure is required to push the sheet to take this shape.

So, this corner filling is going to be very very important so in that case you need to have significant pressure acting on it. So, here this example is mainly for sheets right. Similarly, tube hydroforming is also possible ok. Tube hydroforming is also possible. So, we will see one chapter at the end of the course predominantly on tube hydroforming and why it is important for us ok.

So, complicated tubular forts for plump fittings and bicycle frame brackets are heavily depend on fluid forming ok. So, you can make this kind of plumbing fittings ok and bicycle frames ok. So, they are made by this kind of tube hydroforming process which is generally made by you know like two different process. Say for example, you make one tube you make another tube and then you go for welding at the wherever you want to assemble ok. So, the main advantage here is you avoid post forming process like welding ok.

So, that is one important advantage of fluid forming or hydroforming it could be sheet hydroforming or tube hydroforming. Ok, so just to complete this particular small chapter coining and ironing, coining and ironing ok. So, of course coining as you see in the schematic ok there is a sheet and there is a coining tool which has got slight impression over here and that impression will be put onto the sheet in this region ok. So, it is basically like some sort of shallow plastic deformation that can happen but that is going to be very very intricate ok because the sheet as we speak what we speak is of the order of let us say 1 to 2 mm ok or maybe 2.5 mm and you have to give some shape on the in the thickness direction.

So, you have to be you know that shape is going to be little intricate and you know finer dimensions have to be captured ok. So, that is one important thing when you speak about coining. So, during coining I will come to ironing after this ok. So, during coining the sheet material is heavily compressed in the through thickness direction to get the desired shape.

Through thickness direction means let us say this is your t thickness. So, in this direction you are actually deformation is given but within the sheet thickness that is why you know intricate shapes are made using this kind of coining. So, now ironing is also another important one process in which through thickness compression is actually going to happen like this. And this is what I was telling you before in deep drawing that suppose you keep clearance ok this clearance let us say you can see this clearance in deep drawing this clearance we were speaking about right this clearance let us say is smaller than the sheet thickness. Just for example I am saying sheet thickness is let us say 2 mm t_0 is let us say 2 mm and the clearance is let us say just 1.9 and 1.8 mm. So, what will happen? This ironing will happen ok ironing will happen you can see that actually this is your sheet and this is the cup that is formed ok with the same punch and you have ironing die and you will see that here the sheet the cup is going to take this clearance ok this clearance this particular clearance dimension it is going to pick up ok. So, you will see that the thickness is actually getting reduced while a cup comes out. So, it is just not making of cup with a particular thickness rather it is going to be specifically designed tool such that you want a particular thickness in the cup wall ok. So, you want particular thickness in the cup wall then you should go for ironing operation and you should also note that the thickness here ok and thickness here and thickness here ok they are not one and the same ok. So, I will say that an ironing die that is pushed through a cylindrical cup is slightly smaller than the punch plus the thickness of the metal this is what I was telling you ok the wall thickness can be decreased by more than half in one pass when numerous dies are used ok.

So, the wall thickness the cup wall thickness have to be want specific cup wall thickness then one can go for ironing operation ok and that can be done mainly by controlling the clearance controlling the clearance between the clearance which is nothing but the gap between your die inner and the punch outer ok. So, we will briefly see some details about ironing later in the deep drawing chapter ok. So, with this I am I will stop my first introduction to sheet forming operations ok which is nothing but a chapter 1 you can say ok and we will immediately move on to chapter 2.

So, in chapter 1 just to summarize what did we see is basically some basic sheet forming operations you know right from let us say your stretching, deep drawing, then you have stamping ok then you have simple bending ok and different bending operations available ok and shearing or blanking where you want to cut the sheet and then finally we have seen some specialized process like tube drawing, hydro forming ok ironing operations like that. So, I think we appreciate the fact that all this forming process involve plastic deformation ok permanent shape change is given to this raw materials which are in the form of sheets ok.

So, now let us go to the second chapter that is nothing but material properties specifically we are going to discuss about a tension test here ok and when we speak about a tension test I hope all of we are all aware of the fact that there are other material testing methods also ok. Say for example you have compression test they are meant for different situations ok of course you have tension test you have studied this in you know material science you know book or maybe material manufacturing technology ok then you have hardness then you have fatigue testing ok then you have creep ok. So, there are several you know other testing methods available ok but with respect to sheets if you see if you want to model sheet forming processes ok then you need to know how to calculate basic mechanical properties which are generally done by tension test and this tension test just to give you very brief significance this tension test are not only used to evaluate the basic mechanical properties of sheets it also used to select which sheet material is suitable for what type of applications ok. Say for example in houses we have stainless steel wash basins ok so stainless steel you know like why we one need to choose stainless steel for that application is a question ok. Then it basically connects us to several important requirements one of that is properties ok.

So, it is a significantly drawn pan is not it so the height of drawing is significant right so you need such type of material so how do you calculate how do you evaluate how do you measure that is by doing tensile test and get its properties. So, the properties have to cross certain requirements to make that particular component ok. So, tension test used for that purpose ok. So, selection of material for one particular application is very very important for us. So, when we speak about sheet metal forming and tension test first of all we need to define there is something called as formability ok.

This formability is a term which is defined you know along with ductility. So, if you know ductility what is ductility then we can define formability also. So, before deforming the workpiece to a certain desired shape choosing work-piece material is very critical this is what I was telling you which is the first point. Strength, density, stiffness, corrosion resistance are some of the attributes that are most crucial when choosing a sheet metal for a workpiece correct. So, what is the strength? How strong it is? Ok. So, what type of density you have? What density you have? How stiff is a material? Whether corrosion resistance is significant or not that depends on the applications going to have ok or some of the attributes or quality that we look into it ok.

So, now in this context if you want to define formability we define it like this. A typical definition of formability is this. The ability of a sheet metal workpiece to withstand plastic deformation without being damaged is referred to as formability ok. So, ability of sheet material to withstand plastic deformation that we already know because we want to give permanent shape change so naturally plastic deformation is mandatory without being damaged. Without being damaged means it should not have any instability that is getting developed during the course of deformation. So, what is instability? We will see it in a separate chapter but otherwise you can take it as here as damaged means let us say fracture ok.

The material should not fracture at all ok that is the main requirement here we have ok. So, wherever you know the material fractures then we say that its useful formability is over and any shape change that is given to the material you know before that is going to be helpful for us beyond that you cannot give useful shape change to the material that is the meaning ok. So, that is why you know I was telling you deep drawing that the height of cup that is formed is going to be very very important ok and until you make that component it should not fail anywhere in that cup ok. So, formability this is the ductility also means in a way it has got the same meaning ok. Its ability of a sheet material undergo useful plastic deformation ok without being damaged or without being fractured that is referred to as formability ok.

And in this context you know the meaning of elastic and plastic deformation so we will not discuss much on elastic deformation. I think you might have studied this in solid mechanics. Elastic deformation is generally small ok. So, whenever you do you know tension test first of all it has to cross elastic deformation then you enter into the plasticity part ok.

This elastic deformation generally small and sometimes can be neglected ok. But at some certain situations like spring back which you will see here which is nothing but something called as elastic recovery ok wherever spring back occurs the elastic shape changes the final component shape and its compatible with other incompatible with other mating parts ok. So, it is going to disturb two things one shape change and is also going to disturb its compatibility with the other mating parts. At that type of situations the elastic deformation should not be neglected. Otherwise whenever you go for large plastic deformation elastic deformation is generally you know it can be neglected if it does not have any other problem like this when you go for modeling. So, now shape change in sheets permanent shape change in sheets is accompanied by plastic deformation ok that is you are going to give permanent shape change to the material ok.

We have already seen some examples ok a cup formed or a shallow drawn cup that is formed by stamping or a simple bending ok all involve permanent shape change. So, now when it comes to tension test ok which is what the main aim in this particular chapter ok how is it generally done ok. So, when we speak about the tension test here ok or tensile test we are speaking in terms of sheet in terms of sheet ok. So, of course the concepts are same for rods also but sheet is a raw material here so we are looking for sheet here.

So, how does the sample look like it is like this. So, I have given you a schematic here so you can see that the sample has got two important regions one is a shoulder region other one is the deforming region here ok. A shoulder region actually goes into the clamp so this part actually goes into the clamp and this part also goes into the UTM clamp of the UTM ok and then it is actually held rigidly such that there is no slipping between the clamp and the surfaces ok. So, generally what you do is you hold it on one side and you give displacement on the other side ok. So, displacement will come in the X axis ok and depending on the material it will take a particular load to reach that particular displacement or deformation that is actually called as P ok. So, this sample has got other important features so one after another I have written it here but this tension test is one of the most common and simple mechanical test to understand the deformation behavior of sheet material.

This I already introduced to you and this figure is a tensile test piece and when we speak about this kind of dimensions one has to refer some standards ok. For example, ASTM standards E8M-22 could be one reference there are other references also standard references you can follow ok. That means what? That means this shouldered you know length and this radius and this distance and this l_0 ok all are fixed ok. It is established over several years and one has to follow that.

And thickness will change depending on what material you want to test. Let us keep it as a $t_0$ok. And you will see that the initial width of the deforming region is let us say $w_0$ok. This l_0 is a reference length that we are picking up it is generally called as a gauge length ok. It is called as gauge length and another dimension you have that is t_0 here that is the initial thickness ok. So, this is a characteristic of a variety of standard test pieces that have parallel reduced section for at least 4 times that of width w_0 that there are standards meant for that ok.

So, now what do you do? So, your $w_0$is known to you because you are going to cut this. So, l_0 is known to you, you are going to take this reference and t_0 depends on the material thickness and you hold it on one side and pull it on the other side and you calculate load and that is given by the machine itself ok. And the load on the specimen at any instant that is P is measured by load cell in the testing machine. So, UTM has got load cell that is going to give you load at each and every displacement ok. And the displacement is generally referred with respect to l_0 which is nothing but gauge length ok.

The gauge length is like for example 50 mm for you take it. So, 50 mm will become let us say 51, 52 ok it will reach up to let us say 60, 70 or 80 depending on what material you are going to deform ok. Large material is good from ductility point of view means you can extend it to a larger dimension, larger lengths. And that change in length is generally monitored by extensometer which is separate device which is used to clamp it at the gauge region ok. You have to clamp it ok and you have to measure the displacement ok. So, the extensometer monitors a gauge length l_0 in the middle of the specimen and at any instant the gauge length l and the extension is given by $\Delta l = l - l_0$.

So, this Δl is called as the extension ok, Δl is given by $l - l_0$. l is a new dimension and $l_0$is the initial gauge length let us say 50. So, 51 minus 50, 52 minus 50, 53 minus 50 will give you Δl. So, this P and Δl ok these two are very important fellows to calculate a load displacement graph which is the raw data that the machine can give ok. So, then my next slide will show you, you know the details about load extension diagram which I have given it here ok. So, you whenever you do tensile test of a typical metallic material ok then you will get a load and extension like this ok.

So, load in Y axis generally you can imagine that unit is in kilo Newton and extension is in that is Δl which is in mm, extension is in mm, load is in kilo Newton you can imagine ok. And you all know that load generally increases ok and it crosses let us say yield strength ok that we will discuss now. So, let us say now it is P_y, P_y is a yield load ok. So, and after that you are going to enter into plastic deformation this region you can call it as plastically deforming region or plasticity region and it reaches P_{max} that is maximum load. And you will see that after P_{max} the material is going to deform with reduction in load and it is going to come here this way and you will have a fracture here ok.

It is fully fractured, the sample will become two different you know regions like that ok.

So, you will see that generally fracture generally fracture happens somewhere in the middle it is expected that fracture happens in the gauge region ok. So, now this particular figure I already introduced which is load versus extension diagram and here there are some important points as I told you P_y is called the initial yielding load at which tensile strip starts to plastically deform ok. P_y is actually a transit region you can imagine ok. So, P_y is a transit region after that it is expected to deform in a plastic manner ok that means a permanent shape change ok. So, just after the yield starts ok just after the yield starts the material undergo strain hardening that means when you cross P_y ok when you cross P_y you will see that the material undergoes strain hardening in this region ok strain hardening ok.

The consequence of strain hardening is nothing but load will keep on increasing with extension the material becomes harder and harder when you extend when you deform the material right because of strain hardening ok. And you will see that the strain hardening occurs when tensile try to resist the deformation under loading condition ok due to strain hardening a phenomenon that most metals avoid display the strength or hardness of metal increases with plastic deformation. So, why strength increases during plastic deformation is the mainly because of strain hardening of course there is one can understand the mechanism more from material science point of view but for this particular course this this would be more than sufficient ok. So, the strength in the load increases with displacement in the plastically deforming region is mainly because of strain hardening. So, once you cross the strain hardening portion you will reach a maximum load called P_{max} ok $P_{max}$is the maximum load and after that something is going to happen or once P_{max} is reached something is going to happen ok.

So, what is that during strain hardening the load increases to P_{max} which is a maximum load attained during the tensile test fine. So, beyond this point strip deformation stops being uniform. So, P_{max} is a reference for uniform deformation P_{max} is a you know reference for uniform deformation. So, any shape change that you are going to give you should be able to give when it before it reaches that particular point ok and whenever P_{max} is reached it is a hint for you that there is some sort of instability like for example diffuse necking that is already started in the material if it has got one ok. A diffused neck appears in the decreased portion and a non-uniform extension keeps occurring inside the neck until strip collapses.

So, what does that mean? So, that means when P_{max} is reached ok you may have necking in the material ok. So, diffuse necking means what? So, this is a gauge region and the gauge region will have some sort of necking like this ok over a large region ok over a larger gauge length you can imagine this is the gauge length let us say ok you can imagine that this kind of neck will be formed. Neck means the dimension is going to be area of corrosion is going to be less here as compared to the other regions as compared to that indicates that the materials ductility is almost over so we have to be careful ok. So, after that what is going to happen? You are not going to stop it you are going to pull the material apart then what will happen the diffuse necking for example will be localized in a very small region ok and then that the both the materials will actually split. So, you will have two different regions like this, you will have two different regions like this. This is your gauge length let us say this is your gauge length initial gauge length what you are referred in the previous graph is this now ok so is this now.

So, that is the whole process and you call this as a fracture here. So, P_y indicates a transit between elastic to plastic deformation then P_{max} you have to be careful one moment you reach that it indicates that some instability like necking is started and then further deformation will happen but a reduction of load because there is not much area to support that you know load bearing ability of the material ok. So, then what happens is the load will decrease with further displacement ok. So, the load increase here is because of strain hardening and this load decrease is mainly because the deformation is localized in the form of necking. So, now this load displacement graph or it is called as load extension graph is just one stage that the material is that the machine is going to give you ok. So, you will see that this load displacement graph may not be sufficient for further analysis for us so we introduce something called as engineering stress strain curve ok.

Engineering stress strain curve is obtained from load extension curve by simply dividing the load by initial cross section area. This load divided by initial cross section area will give you engineering stress you will see that formula later ok. So, although this had the advantage of providing a curve independent of the test piece initial size correct. So, now same material different dimensions are there ok. So, you can have a common engineering stress strain curve just by normalizing it with respect to or dividing it with respect to initial you know area of cross section ok.

So, that is the advantage it has got though this is the case we are saying that it is still not true material property curve ok. So, the true material property curve will come in the next stage ok. So, now what is the actual definition of engineering stress? These are all standard definition that probably you might have studied I will just summarize it here ok. Engineering stress sometimes is called as S sometimes called as $\sigma_{eng.}$ it is a $\frac{P}{A_0}$ where P is a load that you got in Y axis and A_0 is the initial cross section area and like engineering stress you also have engineering strain which is nothing but in X axis ok it is called as small e or sometimes called as $e_{eng.}$ it is $\frac{\Delta l}{l_0}$. What is Δl ? Δl is nothing but the formula which you have used before is not it Δl is nothing but this fellow ok $l - l_0$ ok $l - l_0$ is your Δl ok that Δl by initial gauge length divided by 50 into 100 will give you that in percentage.

That means what 51 minus 50 divided by 50, 52 minus 50 divided by 50 like that you can calculate it and you will get engineering strain in percentage you can keep it in as it is also ok where Δl is a change in length and l_0 is a original gauge length ok. So, now here one thing is very important that what gauge length you are going to pick up that is why we are saying that your gauge length l_0 is a reference length to calculate any strain ok. Any strain if you want to calculate this reference length what length you are going to pick up is very very important for us ok. And yield load we have seen so from yield load you can get initial yield stress ok it is called as σ_{f0} or it is called as σ_{ys} also and nothing but $\frac{P_y}{A_0}$ where P_y is a load at yielding and A_0 is the initial cross section area. So, if P_y is known in the previous diagram you have seen P_y is known divided by A_0 ok as it is will give you your σ_y or σ_{f0} ok.

So, now by using this formula and by using engineering strain formula you can get engineering stress versus engineering strain graph in this way and you will note that this particular point is nothing but your material yield strength ok and this is your UTS ok and this is your same fraction ok. So, how do you get UTS or σ_{uts} it is nothing but $\frac{P_{max}}{A_0}$ will give you. Like $\frac{P_y}{A_0}$ here $\frac{P_{max}}{A_0}$ ok. And there are two important properties other than this that is measured here with that is nothing but uniform elongation and total elongation ok. This total elongation is nothing but up to fracture whatever elongation does got up to fracture which is given actually in the previous graph itself I have noted down here it is nothing but

$$E_{Total} = \frac{l_{max} - l_0}{l_0} \times 100\%$$

.

What is l_{max}? l_{max} is the gauge length once it is fully fractured say for example 75 ok $\frac{75-50}{50}$ ok. So, that is going to give you your E_{Total} and for E_u ok it is the same formula only thing is you need to know what is the extension at which this E_u has to be referred to. So, for that you need to know what is uts and the corresponding your you know the length of the sample ok. So, that length ok minus l_0 divided by l_0 that will give you E_u. So, uniform elongation is the elongation at maximum load ok or what you can do is like since you are already converted everything to engineering strain already you are converted so the corresponding strain is nothing but E_u that is what is written here ok. So, from here to here what you call is nothing but E_u but up to fracture full fracture if you refer that is called E_{Total} that is nothing but total elongation and this is nothing but uniform elongation.

So, for most of the material this is important E_{Total} minus E_u this distance ok E_{Total} minus E_u that is nothing but this value this is going to be very very crucial ok. So, now some other known properties you can get for instance you can get yield strength ok that we already indicated σ_y as yield strength but σ_y is generally not obtained by this formula because here P_y is also not known to us ok. Practically σ_y is evaluated by a method called as a proof stress evaluation ok but before that you know how to get Young's modulus of the material so it is nothing but your yield strength divided by E_u the slope of elastic part of the curve is nothing but elastic modulus also called as Young's modulus so you know how to calculate it ok. And in some materials what happens is the transition from elastic to plastic deformation is going to be unclear ok. So, there will be a smooth transition there will be a smooth transition from elastic to plastic so in that type of materials you have to be careful and for calculating the yield strength and for that we are going to use this particular method.

So, what we do here is you zoom in to the initial part of the deformation initial part of the curve engineering strain curve which is what is given here ok. You will see that in the engineering strain X axis you pick up 0.2% strain assuming that engineering strain is given in percentage ok you pick up a 0.2% strain and then you draw a line parallel to the elastic part ok.

So, wherever it is going to hit the curve the corresponding one you can call it as a σ_y ok. So, in this kind of instances where the transition is going to be smooth you can use proof stress this is the stress required to create a specific tiny plastic strain typically 0.2% or roughly twice that of elastic strain at yield ok this elastic strain at yield know elastic strain at yield know. So, maybe twice than that of that that is what is referred but otherwise generally standard says that 0.2% strain you pick up and then you go and hit it in the stress strain curve the corresponding one is nothing but yield strength. As shown in the figure proof stress is calculated by drawing a line parallel to elastic loading line offset by specified amount this much amount you are doing ok.

So, this is nothing but your yield stress evaluation ok. So, now given a low displacement graph we can get engineering strain graph and we can get yield strength from there UTS from there uniform elongation total elongation all those things can be evaluated ok and of course, Young’s modulus can also be evaluated which is nothing but the slope of the elastic part of the deformation.

So, now we are going to convert this engineering strain graph into two stress strain curve ok and this two stress strain curve is predominantly used for any engineering analysis ok. So, one issue with the engineering strain curve is it is based on initial dimensions of the test piece right. So, now if you want to really get the real real picture of the deformation then one has to have some curve which is depending on the instantaneous dimensions ok which is nothing but your two stress strain data or two stress strain curve ok. Since metals and alloys can deform plastically without significantly changing their volume the two stress can be calculated from the load extension diagram using the raising portion of the curve that is nothing but your plastic deforming region between the first yielding and the maximum load ok.

So, what we do is we will define two stress and two strain and that can be obtained from the low displacement graph or the engineering stress strain graph ok and mainly in the plastically deforming region ok. Say this part ok you pick up this part of the region ok and you can get a true stress strain curve which is what is shown in this diagram ok. You can see that your Y axis is true stress unit is same mega Pascal ok. So, two strain you can keep it in percentage also and you will see that the graph starts here and it keeps on increasing ok. So, you will see that there is always an increasing trend ok that is the main difference between elastic your engineering strain graph and two stress strain graph ok and this part is your σ_{f0}which is nothing but yield strength and this is nothing but uniform elongation we have drawn up to that only ok.

Of course two stress data can be obtained beyond that also ok but this is this curve is drawn only up to your uniform elongation that is up to UTS. So, yield strength to your UTS part you are converting into true stress strain data ok. So, now what we are going to do is we are going to define what is true stress that is nothing but sigma. So, engineering stress we referred as *S*, engineering strain is referred as I think *e* ok and here true stress we are actually referring it as σ .

So, σ is nothing but $\frac{P}{A}$. So, A_0 is the initial area of cross section but A is nothing but instantaneous cross sectional area or area of cross section ok. So, P is actually given by the load displacement graph ok but how do you get A because A is going to be changing with deformation. So, for that what you are going to do is you are going to pick up this particular important you know equation volume of the gauge region is considered constant in plastic deformation ok. So, we know that it is $A_0 l_0 = Al$.

So, $A_0 l_0$ will give you initial picture of the sample or initial size and Al is going to be instantaneous one ok. So, A_0 is known to you ok l_0 is 50 mm ok A_0 is known to you A_0 is nothing but let us say area of cross section is nothing but your, you know width into thickness. So, width of the sample is known to you w_0 which is known to you and thickness is known let us say 1 mm ok. So, we can get initial volume and *A* is the one which you are going to evaluate and *l* is nothing but your instantaneous length which is also known to you ok which is also known to you ok because you are the one who is going to deform let us say 50 mm gauge length will become 51, 52, 53 so you know the length. So, from this A can be obtained and I am going to substitute here so A is nothing but $\frac{A_0 l_0}{l}$ which I will keep it here which is nothing but $\frac{P}{A_0} \times \frac{l}{l_0}$, $\frac{A_0 l_0}{l}$ so *l* goes to numerator so $\frac{Pl}{A_0 l_0}$ is going to be your σ. So, I can get true stress now because P is known A_0 is known l_0 is known l can be calculated at every each and every level of deformation so I will get it.

So, now when it comes to true strain it is generally represented as ε generally represented as ε. So, ε is nothing but $\int d\varepsilon$ you can say for small deformation $d\varepsilon$ can be written as $\frac{dl}{l}$ ok so if you integrate it from l_0 to l ok where l_0 is your initial gauge length or reference length and *l* is the length of the you know instantaneous length of the gauge length ok or the final length at which fracture happens whichever is reference for you wherever you want to calculate you can calculate it. So, it will give you $\frac{\ln l}{l_0}$ where *l* is your instantaneous length gauge length and l_0 is your initial gauge length ok. So, this is also known to you because *l* is known to you here itself so the same *l* will come and l_0 is let us say 50 mm ok. So, now you have σ and ε so you have load then you have Δl curve ok from there onwards you can directly get σ versus ε ok that is one way the other is another way also *Pl* say you can get *S, e* ok that means engineering stress engineering strain from there also you can $\sigma\varepsilon$ which is what is given here. So, you need to relate engineering stress and true stress engineering strain and true strain which is what is given in this particular discussion.

So, we know the $\sigma = \frac{P}{A}$, which is nothing but $\frac{P}{A_0} \times \frac{A_0}{A}$, I am keeping so A_0 , A_0 will be cancelled $\frac{P}{A}$ will remain so it is correct. So, what is $\frac{P}{A_0}$ nothing but my engineering stress yes. $\frac{A_0}{A}$, $\frac{A_0}{A}$ would be equal to $\frac{l}{l_0}$ I am keeping so $\frac{l}{l_0}$ will remain same fine. So, now engineering strain I will come back to this formula so engineering strain is nothing but $\frac{l-l_0}{l_0}$ that also we have seen already $\frac{\Delta l}{l_0}$ we said this is nothing but $\frac{\Delta l}{l_0}$ no, $\frac{\Delta l}{l_0}$ we said so nothing but $\frac{l-l_0}{l_0}$ which is nothing but $\frac{l}{l_0} - 1$. So, $\frac{l}{l_0}$ is nothing but $\frac{l}{l_0}$ is nothing but $1 + e$.

So, I am going to put $1 + e$ here and I will get $\sigma = S(1 + e)$. So, here you will see that if I do not want to evaluate σ vs ε graph directly from load displacement graph then I can use this route also. So, first you calculate engineering stress and engineering strain the usual procedure described before and using this formula $\sigma = S(1 + e)$ I can get σ .

Similarly, what I can get is ε also. So, ε is nothing but $\frac{l}{l_0}$. So, $\frac{l}{l_0}$ is nothing but $1 + e$. So, $\varepsilon = ln(1 + e)$. So, this will give me my σ vs ε graph which looks like the one I have written before. This is nothing but σ you can say nothing but ε it will look like this. But one has to be very very careful in using these equations because we do not know how accurately you are going to measure once the necking starts after $P_{\max}$ or after UTS you have to be careful in evaluating the dimensions because necking is going to happen one may not measure the dimensions accurately.

So, you have to use this equations this calculations suitably. So, but this is an important thing. So, here I will again tell the nomenclature here σ is nothing but true stress, S is nothing but engineering stress, e is nothing but your engineering strain, ε is true strain, e is engineering strain. So, we are going to use this σ , S, e and ε , σ , ε, S, e in this fashion only. So now, then comes how do you relate a stress and strain. So, in the elastic part of deformation we know a Hooke's law $\sigma = E\varepsilon$ which is going to be useful permanently to describe the stress strain relationship where E is nothing but your Young's modulus through which you calculate Young's modulus before.

But beyond that this equation has to be modified and there are several equations of that type we will see little later on what is it. One important is basically power law this is an important equation $\sigma = K\varepsilon^n$ this is like a power law $y = ax^b$ type. So, where σ is nothing but your true stress again ε is going to be true strain we have to be careful in this again I am saying σ means true stress ε means here true strain only. So, now this K, n, n actually is going to vary depending on the material. So different material may have different load displacement graph and hence different stress strain graph.

So, unless otherwise you do something to the material it is not going to change. So, stress strain graph is going to be a material property you do something to the material then it will change otherwise no it is not going to change. So, which means that this K and n are nothing but material property of this particular available in this equation. And this one way to evaluate this basically to take logarithm on both sides and you will get $ln\, \sigma = ln\, K + n\, ln\, \varepsilon$. So, and this you can easily understand is of the form $y = mx + c$, where c is this fellow and your m is nothing but your n.

So, and this K and n has got a specific name and we are going to use this predominantly this particular equation predominantly throughout the course. So, one should remember this where n is called as strain hardening index sometimes called as strain hardening exponent and K is called as strength coefficient K is called as strength coefficient. And again sigma is in true stress epsilon is true strain. So, K is strength coefficient n is strain hardening index or strain hardening exponent you can say. So, how to get this now so now you are converted into a straight line plot where this is your y and this fellow is your x. So, I am going to draw X versus Y where Y is your log σ and log ε you can take and you pick up the stress strain data only in the plastic deforming zone that is between yield strength and UTS and you convert all that σ ε into logarithmic plot like this and you will see that generally you get a straight line fit like this but not all materials will slope will show one straight line but generally most of the materials show this one straight line like this and slope of this curve is given by n.

If you take slope of this then it will become n. So, you will get one particular value here okay and the intercept of that will give you k and the intercept of that will give you *K* okay. So, in this way one can get *K* and *n* okay. So, what you do is basically you convert a power law into a straight line fit and slope of that curve will be given by *n* okay or in other words slope of that curve gives *n* okay which is nothing but the strain hardening exponent and the intercept in a way will give you *K* and here I have clearly written that it is only in the plastically deforming zone okay. So, this way one can get *K* and *n* and you will see that once you have a stress strain behavior okay true stress strain behavior done. So, you have load displacement graph from that you have *S* versus *e* engineering stress strain graph from there you get σ versus ε , true stress strain graph.

And true and stress and true strain are related by this particular simple power law $\sigma = K\varepsilon^n$ which actually describes the strain hardening part of the curve okay. This power law is nothing but the one which describes the strain hardening part of the curve okay and this you are converting into this particular plot okay and you are going to get *K* and *n* in this fashion which I told okay. So, now the accuracy of calculating *K* and *n* depends on how good the fit between the σ versus ε graph that you get from this equation and the original true stress strain curve okay. So, let us say you have true stress strain data that you obtain from experiments in this route okay in this route you got it okay.

Now what you have done is nothing but you are fitting the true stress strain graph into this equation okay. Let us say for example you are calculating this equation as let us say $\sigma = 200\varepsilon^{0.25}$ okay. We will see several such equations in the problems okay you will get some flavor okay $\sigma = 200\varepsilon^{0.25}$ where epsilon is going to be changing accordingly σ is going to change okay. So, if you have accurately calculated this 200 and 0.25 or *K* and *n* then your true stress strain data from the experiment and this equation is going to match. So, it is all about fitting the stress strain data that you get from experiments using this type of equation okay. So, now you will see that from a tensile test you are going to calculate this type of you know evaluate this type of equations but actually tensile test you will see that the material is going to fail at one particular strain. But in actual sheet forming operations may undergo large deformation where strains can be much larger than the strain that you see in tensile test okay.

So, in that region of deformation okay where you do not have data what you can do is you can use this equation extrapolate okay. You can extrapolate this equation and you can use it and relate sigma versus epsilon okay and relate sigma and epsilon beyond tensile test also okay. Otherwise you do not know how to extend it beyond your true stress strain data that you get from experiments. If you want to extrapolate it, you need some form of equation right and this fit equation will give you that okay predominantly in the extrapolated region okay. So, now this completes the tensile test part you know how to get you know different properties you know *K* and *n* everything you know how to get it okay.

We will work out some problems things will be clear. So, other than that there is one more important property of the material called as anisotropy okay. So, this anisotropy you will see that is a very important property predominantly for sheet materials okay. So, isotropic materials have identical qualities evaluated in all directions okay. Suppose you take a sheet okay you take a sheet okay and you know that the sheets are actually rolled sheets right. So, it undergoes a prior deformation when it comes to actual applications because of this rolling okay the properties can change with respect to rolling directions and that is quantified by you know something we define as anisotropy of the material okay. Anisotropy of the material means okay the properties okay will differ when tested in specific directions such as let us say rolling direction transverse to that and at $45°$ direction to rolling direction okay.

This deviation is generally referred to as planar anisotropy. So, we are going to define it with a simple formula in the next slide which will make us to understand it very easily okay. So, when you go to industrial sheets level which are actually rolled sheets then quantifying this anisotropy is going to be very, very important which are nothing but you take a tensile test sample and do tensile test like the way we described in rolling direction along the rolling direction or transverse to the rolling direction $45°$ to the rolling direction their properties are going to be different okay. So, now there is one more point the average of the properties in the plane of the sheet and those in the through thickness direction may also differ from one another that means on the plane suppose this has got a sheet okay the sheet plane okay and in the through thickness direction okay what are the properties in the through thickness direction they are also not going to be same they differ okay. So, now how to quantify this anisotropy in sheets okay and then we define something called as a plastic strain ratio called as R okay which is typically used to represent condition of anisotropy in materials whose characteristics vary with the direction. So, here we are specifically speaking about rolling direction okay let us say this is your rolling direction we are calling it as RD perpendicular to that is TD okay and in the through thickness direction is in this way okay and $45°$ direction means in the plane itself this is 45.

One can go for other discretization also 0, 30, 60, 90 that way also one can go. The simplest way to divide that is 0, 45 and TD or 90° okay. So, how do you define this R? It is generally referred as capital R or sometimes referred as small r also. So, R is defined as or plastic strain ratio is defined as the ratio of width strain to thickness strain okay. R is nothing but $\frac{\varepsilon_w}{\varepsilon_t}$ as we said in the previous slide epsilon means true strain so which means its width strain that is true quantity divided by thickness strain okay. So, to further to calculate this is true strain so is nothing but $ln\frac{w}{w_0}$ where *w* is instantaneous width and the thickness instantaneous thickness $ln\frac{t}{t_0}$ okay which is nothing but $ln\frac{w}{w_0}$ and $\frac{t}{t_0}$ can be written as $\frac{w_0 l_0}{wl}$ okay. So, we are saying that $w_0 l_0 t_0$ would be equal to wlt. So, you need a $\frac{t}{t_0}$ right so $\frac{t}{t_0}$ will give you t would be wl and here you have $w_0 l_0$ okay. So, of course if you do not want this requirement you can still stay with this stage of equation. So, true width strain divided by true thickness strain it means suppose if these two strains are equal when you go for deformation suppose you take a strip of sheet and then you deform it okay you will see that these two strains are equal that means *R* is equal to 1. What does that mean? That means in width direction and thickness direction you have almost same strain which means the material is supposed to be isotropic in nature.

Any deviation from this *R* not equal to 1 will tell that material is anisotropic, material is anisotropic in nature. So, *R* can be less than 1 or greater than 1 depending on the material okay. So, now how do you calculate this *R*? There are standard procedures for this I have described it here okay. So, of course ASTM standard this number is also provided here for the sample. So, what we do is a very simple test like tensile test only.

So, here what you do is you take a rectangular sample a typical dimension you can say this is 175 mm this is total length this is 28.58 mm. So, you can refer to this ASTM standard and at the geometric center of the sample you will put this indents this is 20 mm and this is a 20 mm indents you put okay. And then what do you do? It is the same UTM on which you do tensile test you hold it on one side and you pull it on the other side give some displacement you have to stop the test. So, when is it? In the tensile test actually you stopped it until fracture it has to fully fracture but here you stop it at 15% strain okay 15% of this 20 mm 15 % of this 20 mm. So, what do you do here is *R* value measurement are taken at strain equal to 15 % okay. So, what do you do? You can calculate 15 % of 20 mm okay and add it to 20 mm okay this 20 mm length because length is a measure which you can control okay. Let us say for example that has become let us say 23 mm or 24 mm like that okay. So, then what do you do? You stop the test at that particular instant. So, you know the new length right you know the new width right length will increase width has to decrease and accordingly thickness will also reduce in this particular location. So, with a change in this length with change in width and change in thickness you can calculate all the three strains is not it you can get ε_l you can get ε_w and you can get ε_t and what is the formula for *R*? *R* is given by true width strain divided by true thickness strain.

So, you need only this strain and this strain which you can get it by measuring it. With the microscope you can measure the new width that will give you ε_w with micrometer okay or a screw gauge sharpened screw gauge pointer screw gauge you can get the thickness at maybe 5 different locations and you can get new thickness taken average that will give you ε_t okay. So, from this you can get R value okay. So, then you will feel that okay R is let us say 1.3 material is anisotropic or is let us say 0.85 material is anisotropic in nature okay. So, now this R value can be calculated in 0° rolling direction we call it as R_0 along 90° rolling direction that is R_{90} and along 45° rolling direction that is R_{45} okay. So, in that way it can vary with several such angles are there is not it. So, one has to have some averaged quantity which is actually given by $\bar{R}$ okay. So, this $\bar{R}$ is nothing but average plastic strain ratio it is also representing something called as normal plastic anisotropy ratio which is generally given by $\frac{R_0+2R_{45}+R_{90}}{4}$. So, you calculate R_0 you have to test it separate true width strain divided by true thickness strain you do separate test again in this direction so you will get 2 different thing in 45° direction again you get ε_w , ε_t .

So, now you have 3 values right substitute in this formula you will get $\bar{R}$ okay. So, one has to be little bit careful when you divide this equally. So, it is not mandatory that you have to divide it only at 45° intervals you can also divide in other intervals also let us say 0 then you have 30 okay then you have you know 60 then you have 90 okay. So, otherwise you can have 0, 15, 30, 45 okay then other angles up to 90 you can calculate. So, accordingly you have to change the formula, formula is not going to remain same one has to be careful okay. And in the plane of the sheet how R value is changing that can be referred with respect to planar anisotropy okay which is given by ΔR, ΔR is nothing but $\frac{R_0+R_{90}}{2} - R_{45}$ otherwise you can also write $\frac{R_0+R_{90}-2R_{45}}{2}$ okay where R_0, R_{45}, R_{90} are plastic strain division, rolling, diagonal and transverse directions okay.

This ΔR can be positive or negative in nature this is an average value so generally it is an average quantity of R_0, R_{45}, R_{90}. Again one has to be very, very careful in using this formula for different sets of rolling directions which I have referred here this is valid only for 0, 45, 90° rolling direction okay so one has to look into it. So now given a sheet you can get R value and then you can get R bar and then you can get ΔR okay. So what is the use of this $\bar{R}$, ΔR all those things we will see in the next lecture.

And just to summarize what we have seen today I introduce a sheet forming process okay so variety of sheet forming process we have briefly discussed some of them you will see elaborately in the next future classes okay. And after that predominantly we discussed about a tension test okay which is very mandatory for any characterizing any sheets and that is also used to model the you know sheet deformation okay.

So we started with how to get low displacement graph in UTM and then converting that to engineering stress strain graph and then to true stress strain graph. So true stress strain graph we said σ, ε graph is the main you know data that we need so how to fit the true stress strain data in the form of an equation let us say power law $\sigma = K\varepsilon^n$ where n is the strain hardening exponent and K is the strength coefficient. If a fit is accurate then experimental data and the data from the equation is going to be agreeing well okay. Then I discussed with you briefly about anisotropy how to calculate the sheet anisotropy which is generally created by rolling operation okay. Then you refer something called as R_0, R_{45}, R_{90} with respect to rolling direction where R_0 is along the rolling direction and then we defined a parameter called plastic strain ratio or a property plastic strain ratio which is defined as true width strain divided by true thickness strain and how to calculate R for material is also described with simple testing procedure which is shown in this figure okay.

So from there onwards we introduce something called $\bar{R}$ which is like an average quantity and then ΔR which is going to tell you how different is R value in the plane okay. So $R_0 + R_{90} - 2R_{45}$ so you take an average of R_0, R_{90} and you compare that with R_{45} how different they are that will be given by ΔR that is called planar anisotropy of the sheets okay. So with this we will stop and then we will see in the next class. Thank you.