Mechanics of Sheet Metal Forming

Prof. R Ganesh Narayanan
Department of Mechanical Engineering
Indian Institute of Technology, Guwahati

Week- 05
Lecture- 11
Formability testing of sheet metals

Ok. So, let us continue our discussion in this module 5. So, today we are going to discuss about Formability Testing of Sheet Materials ok. So, in the previous section we introduced the concept of forming limit curve and what happens during necking process specifically in the you know the biaxial stretching region that is in the first quadrant is what we have seen. And we will introduce that again and then we will go ahead and see what are the different formability tests available to estimate the formability or forming limit or deep drawability or stretchability of sheet materials. So, in this module we are going to see only formability testing of sheet metals.

So, let us introduce this forming limit curve again. So, what is this forming limit curve? This forming limit curve is nothing, but the curve which indicates onset of local necking in both the regions that is in the first quadrant and then the second quadrant and it is nothing, but the locus of limit strains. We introduced $\varepsilon_1^*, \varepsilon_2^*$ in the previous section and if we get this data for different values of α or β right from let us say on the left hand side extreme to the right extreme if we get. So, negative minus strain to positive minus strain if we get ok.

So, then if we connect all of them that is nothing, but your forming limit curve that is what we have seen. So, this star whatever I mentioned here or forming limit strains. So, we said that it is a material property. So, unless otherwise you change something in the material it is not going to change it will remain same. And we have also seen that it is useful for various reasons one is you need to get the failure diagnosis of the sheet grades quality of sheet if you estimate it then it will be useful ok.

So, you want to select a particular material sheet material for a component then this will be useful you want to decide the process conditions like lubrication or lubricants forming temperature strain rate whether it is sufficient to form the component then this forming limit curve can be used. So, before we understand the different methods of formability evaluation you know procedures ok. So, because we introduced a forming limit curve let us discuss one or two important methods through which we can evaluate a forming limit curve ok. So, let us discuss that then we will go ahead in discussing about other formability tests. So, that is why I given a topic today is FLC evaluation forming limit curve evaluation and other formability tests.

So, forming limit curve or formability I think we understand the meaning of that it is nothing, but the ability of the sheet material to get converted into a particular shape without any instability without any necking in that without fracture that is the meaning and forming limit curve can be used to evaluate that. So, one important method procedure or test to evaluate forming limit curve of any sheet material is called hemispherical dome test it is all it can also be called as limiting dome height test. So, hemispherical dome test as the name suggest you are going to have a punch ok which is of hemispherical in shape ok. And so, naturally there are tools available for that ok. So, you can install the tools and then you can deform the sheet with the help of you know punch setup and then you keep deforming the material the sheet as per the procedure that we are going to describe until necking occurs or fractures whatever is possible for us to stop we will do that ok.

So, then it is called as a limiting dome height test. So, you are going to get a dome shape and that will be limited because of formability of the material. So, you call that as limiting dome height test ok. So, in short it is called as a LDH test. So, it is an evaluation procedure or test for metal sheet deformation capability using an experimental setup having a hemispherical punch deforming a sheet with circumferential clamping force sufficient to prevent it from sliding or pulled into the die cavity.

So, we will see that so, in this test procedure the procedure is actually very simple ok it is not that very complex. So, you keep the sheet you hold the sheet ok you the blank holder ok. So, you keep the sheet on the die you use a blank holder and hold it and then punch will come separately and push the sheet inside the die cavity until necking happens or fracture happens. And then you take the sheet out and you measure the ε_1 and ε_2 near neck region that becomes one point in this particular curve ok that becomes a one point in this particular curve. So, like this you change a strain path by one particular way you change a strain path β s predefined strain paths predefined β s ok.

That is why we say β you can imagine why it is predefined because it is α_0 and β_0 we said is not it. So, during the course of deformation during the necking it can change, but it is a predefined the strain path ok you get a limit strains in other β s. So, by the changing the strain path. So, procedure is very simple ok and in a in one sentence you can tell the entire procedure in this way ok. So, one important issue here is the sheet generally should not slide inside ok.

So, sheet has to actually stretch below the punch that is the main thing here that is why you mentioned that with the circumferential clamping force or blank holding force you can say sufficient to prevent the sheet from sliding or pulled into the die cavity. It should not draw in it should not be pulled in. So, it has to be clamped tightly like that ok. So, this is nothing, but a procedure for constructing forming limit curve of a metallic sheet by using hemispherical deforming punch ok. And generally this test is available for all sheets which has got this particular thickness of the order of this 0.5 to 3 mm thickness ok. So, before we do that there are some important definitions I thought it will be useful for us one is a forming limit curve we call it as FLC. It is a curve showing the strain levels beyond which localized necking or localized through thickness thinning. Through thickness thinning is nothing, but necking through thickness thinning means ε_3 ok. Whatever we discussed until now it is nothing, but ε_3 is very important it should not go beyond a particular limit.

So, otherwise necking will happen it is also called as necking and subsequent fracture occur doing the forming of a metallic sheet ok. So, it will show the strain levels. So, this forming limit curve can be showed in this way ok. The same figure which I have shown before, but I just shown in a different way. So, you can see that you can have different β s 1 2 3 4 5 6 7 I just indicated different stars to get the limit strains and you can see that these all are deformed and different strain parts.

Let us say it is going to be linear let us assume that way and then all the strain values below this curve are actually safe and once you reach this curve you are actually in the in the onset of necking and above that definitely sheet is going to fail. So, that is the meaning this is called the forming limit curve. So, the next important definition is called as a forming limit diagram it is called as forming FLD in short ok. It is a graph in which experimentally measured major strain ok and minus strain combinations are plotted to develop FLC. So, basically $\varepsilon_1^*, \varepsilon_2^*$ we call it as limit strains is not it.

So, you want to get that practically experimentally then there are certain procedures ok while doing that you have to calculate some strains ok. So, it is a graph in which experimentally measured major strain minus strain are plotted in one graph and there is a procedure to develop forming limit curve. So, that entire diagram is called as forming limit diagram ok. For example, I have shown forming limit diagram here and forming limit curve here both are similar meaning only thing is like this forming limit diagram will include some strain values ok which will be separated by this forming limit curve in this fashion. You can see that these are all these orange ones circle ones this of this diamond shape ok both are shown here the orange ones are actually safe strains and this red ones diamond ones are basically failed strains that is why I said fail and safe ok.

And you can see that this curve is actually separating these two data points these two sets of data points ok. So, probably these data points are obtained from one strain path, this is from another strain path and this is from plane strain path, this is from another strain path, this set will be from $\beta = 1$. So, you are going to deform the sheet and you are going to get both safe strains and failed strains and plot all in one ok to get a curve which is going to separate these two. So, if you plot all the strain values inside this diagram along with forming limit curve then you call this as forming limit diagram. So, that is the main difference here.

So, forming limit diagram is nothing, but forming limit curve plus strain values used to separate these two ok. So, strain values used to construct forming limit curve. So, then there are three important modes of deformation we have already seen five different modes, but biaxial stretching we know that what do you mean by biaxial stretching? It is a mode of deformation in which positive strains both are positive ε_1 and ε_2 both the principal strains are positive are observed in both in plane directions at a given location or a grid location ok. So, biaxial stretching means ε_1 and ε_2 would be both positive. Say for example, ε_1 and ε_2 both will be positive means all this this this this red or it could be yellow one all are be on this side of the diagram or nothing, but your biaxial stretching one case is balanced biaxial stretching where ε_1 and ε_2 are same.

So, which will give you $\frac{\varepsilon_2}{\varepsilon_1} = \beta = 1$ which will be probably an extreme case here ok. So, deep drawing mode of deformation also we have seen ok is a mode of deformation in which strains on the test specimen surface are positive in direction 1 that is ε_1 is positive it is always going to be positive only that is why you have only one Y axis ε_1 is positive, but ε_2 can be negative ok. ε_2 can be negative ok and the negative in 90 degree direction that means, along direction 2 which is ε_2. So, ε_2 is actually going to be negative in this case. So, that this is a drawing strain path is going to be on the second quadrant.

Plane strain mode of deformation is also we have we know already ok it is a mode of deformation or forming that maintains near 0 minus strain or 0 minus strain. So, $\varepsilon_2 = 0$ suppose $\varepsilon_2 = 0$ means this point this entire Y axis. So, you have any limit strain in Y axis say for example, this point or this red point or this orange points they are actually closer to plane strain ok. So, in this case you will see that there is a positive major strain and it is going to be 0 minus strain ok it is going to be 0 minus strain. So, minus strain is positive in this side minus strain is 0 on this side minus strain is negative in this side by axis searching plane strain deep drawing mode of deformation.

So, when we speak about forming limit curve there is one important level in forming limit curve one important data in the forming limit curve ok that generally we take it as a reference that is called FLD_0. So, FLD_0 is nothing, but this particular point ok is a location on forming limit curve or this particular star the star we say here in plane strain that is nothing, but your FLD_0 ok that is nothing, but your FLD_0. So, you can call this as I will write this as FLD_0 like this it is a location on the forming limit curve that has got the lowest major strain or the limit strain in plane strain mode or the limit strain plane strain mode is this part. When you go along Y axis you are going along plane strain mode of deformation and you will see that what are limit strain you have that you can call it as FLD_0 and that is actually a conservative window for forming sheets. So, when you deform a material along plane strain mode of deformation along this you will reach the forming limit curve at the earliest as compared to any other strain path any other β .

So, you are deforming along a conservative window to reach the limit strains little early as compared to the other two extreme you know strain paths ok. So, these all are actually drawn schematically schematically here. So, you see that this is the initial circle grid you know pattern we have in the sheet let us say there are several such circles you can put. The circles could be of let us say as small as 2.5 mm sometimes for easy measurement you can have 10 mm also, but the smaller the circle we can get accurate strain values at different locations in a sheet ok.

So, we can imagine that there is a particular l_0 and w_0 of course, you can say d_0 also we have already seen this d_0 ok. So, I am just mentioning it as l_0 and w_0 and you will see that in drawing type of deformation. So, it is going to be the circle is going to become an ellipse circle is going to become an ellipse with w width and length is going to increase to this red color one. The red color ones are actually deformed circles the black ones are the original circle undeformed ones ok. So, deep drawing you will see that it is going inside.

So, if you calculate along let us say this is two direction and this is one direction if you calculate strain along two direction. So, naturally it will come somewhere here. So, in plane strain mode of deformation you will see that. So, this dimension is almost same.

So, when you calculate ε_2 here. So, since a diameter is you know w_0 is going to be same as that of w. So, your strain will be 0, but you will have some strain in the one direction. So, that will be somewhere here let us say and biaxial stretching you know that you know circle become a larger circle and from this w from this l you can get strains l_0 and w_0 is known. So, you can get strains and you will see that you are going to have some data in the positive side ok. So, FLC, FLD, biaxial, deep drawing mode of the plane strain and FLD_0 these are all certain terms that is generally used with respect to forming limit curve.

So, now let us go to one simple test procedure this test procedure is actually meant for hemispherical dome test or limit dome high test you can say and this is schematic is one standard you know dimensions. So, one can fabricate in a lab and you can use it to get the forming limit curve or formability of the sheet. So, if you closely look at it the tools are conventional in nature. So, for example, you have a punch which has got a hemispherical bottom ok and you have the radius of about 50.8 mm ok and you will see that this hatched one is actually a sheet which is partially deformed partially stretched you can say and you will see that to start with the sheet is actually going to be flat and it is a flat sheet like this.

It is a flat sheet like this and punch will be touching the sheet in this fashion to start with and you are displacing the punch in this direction displacement is provided to punch in this direction. So, and the sheet is actually stretched and you will see that to avoid the radial movement of your sheet the sheet is actually locked here by something called as lock bead or draw bead ok. And this is actually called the hold down ring or you can also say blank holder and there is a die ok all are circular in nature ok. So, it is a cylindrical punch ok this blank holder is nothing, but a ring ok with a hole at the center. Similarly die is also it has got a hole at the center of course, here it is shown very sharp, but actually there is a corner die corner ok and your blank holder has also has got a typical corner radius like this.

And you will see that the gap between the die inner walls is about 105.7 mm and you can see the lock bead is spaced at about 132.6 mm now it is a circular one. So, which means that the sheet is actually clamped circumferentially that is why it is written the circumferential clamping force is applied using draw bead as well as some blank holding force ok. This draw bead if you use it will avoid the radial movement of the sheet and hence you know the sheet is going to stretch below the punch ok.

So, I have also given here this is a LDH test setup showing tools sheet and important dimensions ok. So, the point here is there are some machines already available ok or you can install this machine in your UTM ok or you can use a double action hydraulic press where this type of tools can be installed ok. So, if there are some already available machines means the machines are meant only for this kind of experiments double action hydraulic press means you know it is a general purpose double action hydraulic press. So, one action is to hold the sheet using blank holder and then a punch will come separately that is a second action ok and then the sheet will be deformed or sometimes what we do is if I make this setup and the clamping is actually done mechanically using fastener ok using fasteners you can mechanically clamp the sheet and this punch is actually held in the UTM and like any other test you know your you know the movement of punch is actually controlled by hydraulic means and it will come and deform the sheet. Only thing is in mechanical clamping you have to make sure that the sheet is actually not drying ok.

So, I have also shown said that the contact surfaces of the raw undeformed sheet and punch are actually lubricated ok. The sheet is securely clamped in the flange region using a lock bead or a draw bead here located in the die blank holder arrangement in the die blank holder arrangement for hemispherical punch and hydraulic press bulge test. Hydraulic bulge test what is it we will see separately ok, but for hemispherical punch test and or limit dome height test this is what you do. So, now what we are going to do is we are going to stretch the central area of the sheet that means, the sheet below the punch ok is performed without interrupting the test you should not stop the test you continue the test ok and you are going to do that until necking occurs or fracture occurs.

It all depends on how do you identify that ok. A series of test samples with grid patterns is prepared with different widths, but with constant length suitable for clamping. So, now in order to get the forming limit curve ok you need to deform the this particular sheet at different strain paths or β values right that is done in this test just by changing the sheet width. I will show you that just by changing the sheet width ok keeping the length constant ok and you use the setup to form the sheet until fracture until necking and you measure the strain grids in the near the neck region ok you will get the forming limit curve. So, basically a series of you know strips of one particular material with different widths, but a constant length will be deformed using the setup to get the forming limit curve ok. So, that is why you know in this diagram if you see ok I mentioned 1 2 3 4 5 6 7 so which means that you can use 7 different widths ok you can also use any in between widths also if you want to get accurate forming limit curve in between some widths also you can one can get forming limit curve ok one can get the mid strains, but let us say about the 7 different widths can be changed to get the forming limit strains in that particular strain path keeping the length constant, but length of the sheets would be such that you will be able to clamp it properly here ok you should be able to clamp it.

So, that is why length is remaining constant width can change ok. So, if you see this from the top view if you see this from the top view whatever I mentioned will look like this whatever I mentioned will look like this ok this is just a schematic I mentioned ok there are 2 things here one is this light blue which is nothing, but your sheet I have written sheet here this is also a sheet this is also a sheet this red the circular one is actually a punch the same punch ok this same punch which you see from the top view you see from the top view the punch will look like the red color circle let us say and the sheet are sheets are of this particular length which are actually same length you can see ok all the 3 sheets are of same length, but width is changing you can see this w is changed this w is changed as compared to this ok the width is different in all the 3 cases I just shown 3 cases as an example. So, if you see from the top view how does it look like is in one case ok if you want to get limit strain in the negative minus strain region that is in the second quadrant to start with that is in the second quadrant suppose in this quadrant ok if you want limit strain. So, what you need to do is you need to have a sheet of width slightly smaller than the punch diameter ok. So, negative minus strain obtained from narrow strip test specimens with respect to punch ok.

On the other hand if you want to get positive you know minus strain then this would be suitable that means, your limit strains will be somewhere here in this portion if you want that ok. So, then you use this type of sheet, the sheet is actually pretty large as compared to the punch dimension, but if you want plane strain you pick up an in between width which is say for example, width is almost same as that of your punch diameter ok or maybe slightly lesser than this slightly lesser than the punch, but larger than this or slightly larger than the punch, but lesser than this sheet that is also available ok. So, if you deform that sheet up to fracture then you will get limit strains in the 0 minus strain that is plane strain type of deformation ok. So, in between these two you may have some width let us say two different widths you assume in between these two you assume two different widths. So, naturally if you deform it up to fracture you will get limit strains in this many number of strain paths 1, 2, 3, 4, 5, 6, 7 different strain paths you can get ok.

And since you are seeing the top view of that just for a feel you will see that the draw bead is actually clamped the draw bead is used to clamp the sheet somewhere here you can imagine draw bead is used to clamp the sheet somewhere here ok. The sheet is actually this is this one. So, naturally this will be draw bead will be clamped fully like this the top view will be more clear here. So, draw bead is a circular ring know. So, you will be till sheet will be clamped fully in this blue region ok.

Now punch will deform it and only this part of the sheet is going to deform ok, this part of the sheet will not be allowed to draw in same as that of here this read will not go inside this will be arrested ok. So, that is the whole idea of this particular test. So, now what we do the punch displacement is stopped when a localized necking when a localized necking is visible ok, the localized necking is visible maybe you can put a camera you know below the sheet and you can find out where necking is going to happen. If it is a new team then you can easily visualize it if it is a other press hydraulic press industry type press then one can put a camera and find out. Sometimes what we do is like you can also get load displacement graph during this testing ok, like a tensile test know here also you can get load displacement graph and you can see that there will be some failure ok.

So, probably close to that you have to be very careful that necking might have happened just before that you should have stopped the test around by that time ok. So, if the test is not stopped as soon as test specimen ok. So, if the test is not stopped it can be test it can be stopped when fracture happens that is also possible ok. So, generally if the sheet preparation is good ok, if the sheet the sample preparation is good without any burr or other defects it will not spread across the nose of the punch ok. Instead when the punch is displayed beyond the sheet forming limit neck or fracture occurs in a ring encircling the round cap of the formed region.

So, what is the point here is like if the sheet preparation is good then it will not fail in the unwanted region like in tensile test you want fracture to happen necking to happen the gauge region. Similarly here also you want fracture to happen somewhere in the deforming region here or here or here ok in the sheet in the sheet or here ok in the sheet. If the sheet preparation is good then this problem will be sorted out. If it is bad then it can fail in the gripping region also somewhere in this edge region it can fail especially this is a problem in plane strain mode of deformation.

So, you can fail somewhere in the edge region ok. So, one has to be little bit careful in that. So, there are some important points with respect to lubrication. So, you will see that lubrication improves sliding of sheet over the punch surface and causes material fracture closer to the nose of the punch. Nose of the punch means what we are saying is you may when you do experiments you will find out that generally if you go for dry lubrication generally your fracture is going to happen away from the center ok. It may happen somewhere here or maybe here ok maybe here or here ok.

But if you are having lubricants or good lubricants is done generally it moves closer to the no punch nose ok. So, fracture will happen somewhere here. So, we are saying that lubrication provides sliding of sheet over the punch surface and causes material fracture closer to the punch nose ok. It is, but one thing we have to be very clear that it is important to note that this does not change the forming limit. Generally it is understood that if you put lubricant or you do not put lubricant you deform the sheet in dry condition forming limit will not change.

Your forming limit curve is not going to change. This forming limit curve which we mentioned just before ok this forming limit curve is not going to change ok when you use lubricant or you do the test without lubricant that is why we call it as a material. But what it does is it does not change the forming limit as the minor strain ε_2 adjust to the increased major strain. If you put lubricant the strain value can change, but accordingly ε_2 will get adjusted for whatever the value of ε_1 you have which also means that it indicates change in strain path or strain ratio β are not forming limit strains actually $\varepsilon_1^*, \varepsilon_2^*$ that will not change. Rather what will happen is will change the route of getting into the forming limit curve ok. So it also means that if you put lubricant ok, so if you do not put lubricant probably you will reach the forming limit curve somewhere here ok.

If you put lubricant it will reach the forming limit curve in some other location may be somewhere here may be somewhere here. But the forming limit curve will remain same forming limit curve will remain same, so instead of reaching a forming limit curve here it will reach a forming limit curve here, but forming limit curve will remain same only thing is there will be slight change in the limit strain values. So that is why it is said that these two strains will get adjusted as a minor strain ε to adjust to the increased major strain, but it will reach the same forming limit curve of that particular material. So now so what did you do? So now the step is basically we have done our test up to this particular point the punch displacement is stopped when the localized necking is actually witnessed if when it is visible.

Now you have stopped it ok. So now you have to measure strain and then you have developed forming limit curve this is very very important because your strain measurement has to be accurate so that your forming limit curve is also going to be accurate. If there is approximation in strain evaluation then there will be problem in the forming limit curve that is why we said that in a sheet it is better to have circles of the order of let us say 2.5 mm diameter or 2 mm diameter rather than 10 mm diameter ok. So because 10 mm diameter itself covers a large region ok 2.5 mm 2 mm would be good so that you can measure strains at a localized locations.

Anyway so now you have to measure ε_1 and ε_2 right ε_1 and ε_2 of the individual deformed grids on the sheet surface are measured near the neck of all the test specimens for the series and it is recorded. So we said that this many number of sheets know so 1 2 3 4 5 6 7 right. So these many widths are deformed to get one forming limit curve for one material is not it. So we have to measure ε_1 and ε_2 near the neck in all this 7 different strain parts. So how do you calculate it you know that $\varepsilon_1 = ln\frac{l}{l_0}$ is not it.

So $ln\frac{l}{l_0}$ is with respect to this ok $ln\frac{l}{l_0}$ will give you ε_1 and $\varepsilon_2 = ln\frac{w}{w_0}$. We have already done lot of problems in this we know how to calculate it ok. So one can also look into this ASTM standards ok. This ASTM standard is that the standard test method for determining forming limit curves you can look into it there is lot of details available in that. So now when you are measuring this you know limit strains you can use a microscope with suitable magnification ok.

So and only thing is like now this is a curve bent this is a bent sheet is not it. So you will see that the sheet is actually bent ok. The deformation is actually out of plane this type of test is a deformation is called as out of plane type of deformation and suppose you want to measure a grid here on the surface. So what you need to do is you have to you focus your microscope perpendicular to this you have to see like this ok. You have to orient your sheet in that fashion to get the actual dimension rather than the projected ones ok.

So you have to use appropriate magnification so that you can see that a neck this strains properly and you know there are lot of facilities now you can take you can take photo of a few grids around the neck region and you can process it later also ok. And it is also said from the ASTM standard the ε_1 and ε_2 shall be accurate to about 2.5 % strain. Now you have to convert you know to put into 100 200 if you put into 100 it will be in % ok.

So we have to have an accuracy of plus or minus 2.5 % strain ok that is what is mentioned in the ASTM standards ok. And now when you are measuring this you know strain data points you have to actually categorize that into three different data points ok. One is the safe, safe one means no necking it is safe it is little away from the neck region it is little away from the neck region and marginal localized necking this is what actually we want marginal ones. Marginal one means localized necking very close to the neck which you are going to measure and then fracture region.

Fracture region means these are regions which beyond your localized necking ok. These three strains have to be separated out clearly this one and this one are very important actually because we have to stop the test we have to measure forming limit strains when it is necking ok. So what you do is so you have to measure this ε_1 and ε_2 in all that seven different widths for example and you have to categorize that into probably these two important categories safe and marginal. So as I showed you before in this particular data point you can say that these red data points are failed and this orange data points I said these are safe right. So you can say that this instead of failed you can say that these are all localized strains ok marginal ones ok very close to the very close to the forming limit curve very close to the forming limit curve but it is marginal just locally necked whereas orange ones are fully safe it will away from the neck region both the strains have to be measured in all the strain paths and all such data suppose seven different you know β s you have that means seven different widths you have ok. Suppose each in each strain path each width you are measuring let us say ten different data points ok the ten different data points ok ten different data points has got $5 + 5$ let us say 5 in safe and 5 in let us say this localized neck local neck ok ten different data.

So this $5 + 5 = 10$, $10 \times 7 = 70$ data points have to be plotted in one graph clearly distinguish between different strain paths and this 5 and this 5 this has to be separately shown ok. Specifically the safe and local neck data points $5 + 5$ in each strain path have to be separately shown maybe the way I have shown could be one example. So one is in a red color other one is an orange color something like that ok. And then what you do is all the data points are coded in FLC as safe and marginal and you have to draw forming limit curve ok you know physically you have to draw a forming limit curve FLC is drawn by drawing a curve you have to draw a curve on the FLD ok you have you have plotted all the strain values now in the FLD based on the following points.

How do you do draw a smooth curve above the largest safe ε_1 strains ok. So with respect to this diagram if you see the largest ε_1 strain or these are the values let us say 1 2 3 4 5 6 7 8 9 10 11 these are the largest in ε_1 strains ok you have to draw a curve just above that you have to draw just above that draw a smooth curve above the largest safe ε_1 strains along with associated ε_2 strain. So you have to draw a curve like that such that all this largest safe strains are below the curve ok. It may so happen that some safe no localized necking strain points are intermixed with marginal ok intermixed with the marginal localized necking points if that is the case draw FLC below this marginal points ok. Draw FLC below this suppose there could be a small that is small localized you know small band ok where this marginal ones that means your necked ones and safe ones can be intermixed ok. They combinedly they are plotted together they are nearby in this diagram forming limit diagram then at the time also you have to be careful that ok then you should draw FLC below the marginal points that means none of the marginal points should come below the forming limit curve ok.

Otherwise what you need to do is in that particular strain paths you do more test more trials to get more data so that you can get an accurate distinguish accurate you know better separation between the failed ones and the marginal ones. So that is the way you have to draw forming limit curve finally you will see that you will get this particular type of diagram this is called a forming limit diagram. These many issues are there when you draw forming limit curve of a material. So, some important information about your test specimens and grid pattern. So, what we can do is the longer dimension in the strain paths could be along the rolling direction of the sheet that one can maintain ok.

And in the LDS test whichever we have discussed right now the test specimen shall be sufficiently long to have secure clamping by blank holder and die without excessive pulling that I have already explained you. So, several sets of test specimens are required to obtain sufficient repeatable accurate data or limit strains. So, one set of seven sheets may not be sufficient you may have to use the second set or third set also and then you may get 70×3 almost about 210 data points ok out of that half of that would be safe half of that would be localized next strains ok. This much data if you get you will get a nice continuous accurate it should be repeatable forming limit curve ok. So, a typical sheet size is given here for example, if you use a punch of 100 mm diameter we have used 50 mm 50.8 mm I said is not it 50.8 is not it yeah. So, if you use a punch of 100 mm diameter ok I have shown this is a radius 50.8 mm radius. So, if you use 100 mm diameter we will have a sheet widths ranging from ranging from 12 mm to 200 mm that means, the negative minus strain will have 12 mm width and positive minus strain will be about 200 mm in width at the increments of 25 mm you can say. So, that many number of widths you can use. So, you have to cut the sheet before test you have to cut the sheet by shearing machine without any burr ok edge effect is going to be important otherwise it may fail in the gripping region itself you have to be little bit careful and any unsafe handling is also prevented if you use a proper shearing machine and you may have to polish it at the edge before deforming it.

So, edge preparation is actually very very crucial here and the grid patterns ok. So, let us say this is your sheet this is your sheet ok. So, this is the best one generally we people use this circle grids ok the circle grids could be connected to each other next to next I just drawn with some gap, but otherwise this can be little bit touching each other like this you have to put several grids on the sheet surface 200 mm width and 200 mm length ok. You can imagine a square sheet of 200 mm width and 200 mm length right in that you may have to put this all circle grids very close to each other you can imagine this is about 2.5 mm diameter circle grid you can imagine.

So, many circles will come I just show on a schematic here. So, you can also people use dot pattern instead of circle you can print dots sometimes squares are also used connected square sometimes a combination can be used. So, a square and a circle combination also people use it, but this is predominantly used and easy to measure also. So, when you deform a square it becomes some distorted you know dimensions is not it. So, whereas, the advantage of using a square circle grids is basically it is going to become either circle or an ellipse. So, it is easy to measure strains, but these are all different grids available one can look into ASTM standards for more details.

This is another you know dimension just I gave you that instead of rectangular samples and square samples sometimes people use this type of samples also the edges are curved in nature. This is also LDH sample only, but sheet samples with a curved edge instead of straight edge this also used sometimes you can see that this is 20 mm width the negative major strain and probably you are a 60 or 80 would have would give you plane strain type of deformation 40 and 60 are in between 120 would give biaxial stretching and 220 would be your balanced biaxial stretching. You can imagine your 100 mm diameter punch superimposed above this the top view how does it look like ok. So, and the some of the deformed sheets are shown here photographs is only just for your information and you can see that there is a small neck here you can see and you have to measure strain closer to the neck to get the forming limit strain ok.

So, anyway let us go ahead you know to the other you know formability tests in general ok. This formability test in general ok or classified into two types one is intrinsic test other one is simulative test. So, intrinsic test ok there are some categories here we will discuss one after another uniaxial tensile test we know that plane strain tensile test, Marciniak stretching sheet torsion tests are available hydraulic bulge test I was introducing that before, Miyauchi shear test, hardness tests are also there ok. This intrinsic test actually assess the fundamental features of materials that are relevant to their formability ok. So, the type of test itself will tell you what is it actually ok. These are these are the tests which will give you mostly your you know type of like a stress strain behavior your forming limit like that which are actually material property type.

Simulative test in simulations a material is subjected to deformation that closely approaches distortion that would occur during any certain forming procedure. Say for example, you have bending, stretching, drawing, stretch drawing these are all some tests which are of simulative nature. So, you want to simulate this type of actual deformation at lab scale. So, how do you do that test? So, bending is a separate test, stretching separate one deep drawing or cup drawing separate one you want to combine stretching and drawing as stretch dot test another one buckling tests are available we will see some example these are all other tests available. So, we will see one by one intrinsic test the first one is you know you know that very well we already discussed this uniaxial tension test.

So, we also discussed that you can follow ASTM E8 standard. So, gauge length is generally 50.8 mm generally 50 mm we say gauge length and 12.5 mm wide or 12 mm wide you can say 12.5 mm 12.7 mm you can say. So, this is a standard dimension ok. So, gauge length is should be known to us and width also should be known to us and then what do you do? You give displacement on one direction ok this initial thickness we all studied this and then the ultimate aim of this tensile test is to test it until the material fails fully and then the machine is going to give you low displacement graph ok. So, so for that you are going to use a load cell and extensometer strain gauge extensometer. So, from the low displacement graph you can get engineering sustained graph we say SE ok. And from SE you can get a true stress strain graph using standard procedure that we already know ok. And from this we know how to calculate all the properties ok I just summarized here ok what all the properties you can get.

So, sample preparation as we discussed before though sample preparation is very very important here also ok. The sharp corner should be avoided you can see that ok this type of radius have to be maintained and sheared edge should not have any burr it should be smooth otherwise that will act as a notch and maybe it can fail here itself instead of having failure here. So, it can fail here actually we want failure here ok which is unwanted this should be avoided. So, you have to prepare sample properly for that edge preparation is very much required ok. And you also know that the specimen alignment should be good in the machine
.

So, the centerline of the grips you have to be careful ok. And load is measured using load cell and may have to use extensometer for some time to get the strains in the gauge region. And sometimes we may need to measure you know thickness and width of the sample for you know some details say for example, you want to get R value strain plastic strain ratio let us say capital $R = \frac{\varepsilon_w}{\varepsilon_t}$ right. So, in that case your width strain have to be measured and thickness strain have to be measured accordingly you may have to test the sample. So, gauge region is the only main region that 50.8 mm 50 mm we say gauge region is the main region which will undergo a predominant plastic deformation. And after some time you will see that the other region even may not deform also generally rate of testing is maintained at the cross at speed of 1 mm per minute. You can convert this into this is v, this is v, $v = 1mm/min$ you can say ok. And you have a gauge length ok or we can say $\frac{v}{l}$ we say maybe 50 mm right. So, you can get strain rate from this yesterday we discussed now it is nothing, but $\frac{v}{l}$. So, you can get a strain rate per second from this you can convert this otherwise I have mentioned the cross head speed this of the order $1mm/min$ ok.

So, these are the properties you can get Young's modulus you know how to get it it is a slope of the elastic part. So, you have to be careful in measuring the load and displacement or strain in the elastic portion because it is going to be very small in a tensile full tensile test. Yield strength we know how to get we use proof stress procedure already explained it tensile strength there is nothing, but the highest stress in the engineering stress strain curve. Uniform elongation is nothing, but your maybe engineering strain at the maximum stress you can convert that into true strain also right. Total elongation is a point the elongation at fracture.

So, you can also convert this into ε_t true strain values after getting e_T. n value you know how to get it, it is basically in the strain hardening region you convert that σ, ε into $ln\ \sigma, ln\ \varepsilon$ plot the slope is going to give you n. So, $n = \frac{dln\ \sigma}{dln\ \varepsilon}$. So, from that you can get the strain hardening expansion these all are known to us and in one way this tensile test is also going to tell you about formability of the sheet. So, that is why ε_u and ε_t are going to be important $\varepsilon_t - \varepsilon_u = n$ which is actually connected to n value is also important for us is not it these all are related to a simple you know test used to evaluate formability of any material. Plastic strain ratio you know how to get it plastic strain ratio is nothing, but how is the definition definition as I just said $R = \frac{\varepsilon_w}{\varepsilon_t}$ for this a separate test is there this is one of the you know test procedure which I have given here ok.

This is ASTM E 517 standard you can refer to this is a simple test again. So, you have a rectangular sheet of let us say length length is 175 mm you can see ok and you have this width total width C as about you know 28.58 mm it is both are given and thickness whatever thickness you have small t whatever thickness you have in the material you have to take it. And what you do is you put 4 indents here 1 2 3 4 indents spacing up with respect to W and G. So, W is nothing, but 20 mm and G is also about 20 mm. So, this is 20 mm this is 20 mm you have to put this indents and then what you do is you deform the sheet up to let us say 20 percent of this length of this G, 20% of this G ok 20% of the G which means G will become about let us say 25 mm 20 mm would become about 25 mm.

So, your G is known let us say G_0 is the new one ok for G_0 you will have W_0. So, W would become W_0. So, T would become T your T would become ok I will say G_i, W_i, T_i instantaneous. So, $ln\frac{G_i}{G}$, $ln\frac{W_i}{W}$, $ln\frac{T_i}{T}$ will give you 3 different strains and you can use this ratio to get R value of the particular material.

So, small t you can use. So, but one thing which you need to know about is the standard dimensions. So, your C is 28.58 and this is 175 in between you have to put a gauge width and length as a 20 mm and 20 mm ok. You can see the accuracy levels also given here. So, this is the way you can get plastic strain ratio which is also in a way related to your formability of sheet. Strain rate sensitivity index. So, this is also known to us we have also discussed this briefly in the previous section only we discussed how m affects the necking behavior and we have related it also.

And then m can be calculated using this particular equation $m = \frac{ln(\sigma_1/\sigma_2)}{ln(\dot{\varepsilon}_1/\dot{\varepsilon}_2)}$ and there are 2 different tests that people do either they use duplicate test or change in rate methods change in changing rate methods. Duplicate test is basically you do tensile test at 2 different strain rates $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ and use this equation to get m. Otherwise what you can do is you can do changing rate method in one test itself you can change the you know strain rate. For example, you keep on testing it it is deformed out to $\dot{\varepsilon}_1$ then suddenly go to $\dot{\varepsilon}_2$ deform it come back to $\dot{\varepsilon}_1$ go to $\dot{\varepsilon}_2$ ok.

This $\Delta\sigma$ is the rise in σ because you are changing the strain rate from $\dot{\varepsilon}_1$ to $\dot{\varepsilon}_1$ ok. And according to this formula you can get m value and we also just $\varepsilon_t - \varepsilon_u$ to m value is not it ok. So, now this uniaxial tensile test whatever we have seen ok though it is good, but it is going to give you negative minus strain or width strain ok. It is going to give you negative minus strain or width strain that means, if you put a circle grid on the just on the geometric center of the sample ok you will see that your length is anyway going to increase and width is going to be negative. So, it is going to give you negative minus strain ok.

But this test is not going to offer any insight during plane strain actually what happens where the minus strain is 0. So, you want a test sample ok which can deform which can be done in a UTM only, but at the same time you need to have a plane strain mode of deformation not uniaxial then this type of sample dimensions can be used. So, this sample is little complex as compared to uniaxial you can see it is a pretty broad wide sample you can see this A ok is of the order of 254 mm this B this center you can say gauge width maybe B as 165 mm and this C as about 38 mm and this radius is about 41.5 mm ok. Increasing the width of the sample increasing the width of the sample and decreasing the gauge length changes the strain state to plane strain ok. So, this dimension sheet can be fabricated maybe using your wire EDM or any other method and this region can be held in the machine ok and you can pull it by giving some displacement ok.

You will see that naturally this is a weaker portion your B region is a weaker portion and it is going to fail there and one can put lot of circles on the sheet surface ok. So, you can get you know failed strains by measuring ε_1 and ε_2 wherever making is going to happen. One can also get low displacement graph for this particular test that is one way the other way is sometimes what people do is they constrain the width they constrain width by putting some bead ok. So, they constrain the width by putting some bead in the width direction so that ok only the center region is going to deform that is in plane strain that will be in plane strain that is also people use which I have not shown here. The width constrain method involves employing a rectangular sample with circular notches leading to a center gauge region ok that is narrowed in width the gauge section is secured between two sets of opposing parallel knife edges.

Knife edges means something which is actually restricting the movement of material in that direction ok like a bead ok like a draw bead ok they are called as stingers which are aligned parallel to a sample axis and you deform it the other portion center portion may undergo plane strain mode of deformation, but this is simple to use this particular one. This is called plane strain tension testing. So, the main difference between the previous one and this one is in this case you can maintain $\beta = 0$ in the previous case β would be something relevant to uniaxial tensile test which you already discussed several times. So, if you get a forming limit strain from this it will reach your forming limit curve let us say ε_1 and ε_2 in this data point. Suppose this is your forming limit curve if you use this particular test it will grow across along this line and it will reach a forming limit curve here rather uniaxial will be on this side the axial will be on this side.

So, biaxial tensile stretch testing this is another you know testing procedure ok this is also called as you know Marciniak biaxial stretching and hydraulic bulges there are two different types of tests ok and these tests are important because your limit dome height test or hemispherical punch test which we said these actually the limit strains are dependent on the friction interface friction because your punch and sheet are in contact ok where fracture is going to happen. So, there could be chance that your friction interface friction may affect it ok. So, to avoid it you are going to use two important methods one is Marciniak biaxial stretching test other one is hydraulic bulge test. So, your Marciniak biaxial stretching is explained here with the schematic there are some intricate details here if you see. So, this is your punch ok this is your punch the punch is actually cylindrical in nature, but if you see at the at its end there is a small upward indent ok.

Actually it is it should be flat like this your punch has to be flat like this instead of that basically there is a small indent like this there is a small indent like this ok there is a small indent like this you can see this region I am saying small indent here. So, which means that the punch is not going to touch the sheet in the center location ok. So, otherwise what you have here is you have a blank holder which is going to hold the sheet and you have a die on which your sheet is kept. Now there is one more point here other than sheet ok your this part actually this part is actually sheet ok. Below sheet that means, between the sheet and the punch ok there is a another sheet with a hole here there is another sheet with a hole at the center you can see ok.

This is called a spacer sometimes it is called as washer also it is called as washer ok. So, this spacer or washer is kept between this particular punch and the actual sheet for which you have to get the forming limit ok. And this spacer has got a hole at the center and the spacer generally is same material as that of your actual sheet ok. So, the lot of details I have given here ok. So, now what do you do that basically the punch touches the sheet the initial contact portion and then you push punch down. So, punch is actually displaced ok and it will deform the sheet in this fashion and the main issue here is you will see that we expect fracture to happen in this location of the sheet.

Here only you want fracture to happen on the sheet and if fracture happens here of course, you have to put circle grids on the sheet surface to get the forming limit strains like we defined before ok. And if you see fracture here and if you measure forming limit strain you will see that this particular zone where fracture happens does not have any contact with punch at the same time it does not bend also. The same time it does not bend because this is in one plane you can see that your sheet is actually deformed below the hole in one plane. Suppose this is your hole this is your hole your sheet is actually going to fail in this region ok yes sheet is going to fail in this region only ok.

So, this region is actually has got no contact because there is a hole here and the punch is actually not contacting in this region at all. So, which means that there is no interface friction at the same time the fracture happens in the flat location which is not bending ok. So, that is the main advantage of this Marcinak biaxial stretch test, but the problem here is your hole preparation has to be properly done edge preparation of this hole has to be properly done and the size of the hole is also very important ok. And your hole should not crack before the sheet fails ok.

So, there are certain important things that you have to do. So, you have to do lot of test to evaluate this particular forming limit. So, otherwise what you do is in this test also I will show you in the next module some dimensions of the sheet that we use for this particular test you will see that there also you have several series of test that you have to do for getting forming limit curve of one particular sheet. Next one is hydraulic bulge test. Hydraulic bulge test is again like you know you use hydraulic fluid ok to pressurize the sheet like this and then it will deform in the fashion of like a dome ok. So, now, here there is no contact between the punch and the sheet because punch does not exist at all.

So, whatever forming limit strains you are going to have from this is going to be independent of a friction. The sheet metal is clamped by die rings die rings means nothing, but a blank holder with a draw bead and the hydraulic pressure is applied from one side to deform the sample into a dome shape into a dome shape. So, to prevent slippage at the end of the sample lock bead is used ok. So, you can use lock bead. So, at a different stages you can evaluate its curvature you know extension at any location you want and a fluid pressure because you are the one we are going to control it. And this type of simple relationship we already know from solid mechanics point of view in this case radial stress $\sigma_r = \frac{pR}{2t}$ where p is a hydraulic pressure you have and R is a radius of curvature and t is the you know sheet thickness ok one can relate like this.

And the thing is like this particular test can also be used along with uniaxial tensile test to characterize the stress strain behavior. You can also get stress strain behavior let us say for example, this particular location ok. This particular the nose of the dome or the topmost portion in the dome this particular location you want the stress strain behavior you can get it and you can plot a graph like what you say here like uniaxial tensile test graph you can draw ok. So that you can get the you can characterize the materials behavior in biaxial mode of deformation ok. So, here actually you know you have to clamp the sheet fully. So, which means that you may have to use only the rightmost you know dimension of the sheet that is you are the one which gives you $\beta = 1$ balanced biaxial stretching which means that you can get a sustained behavior when $\beta = 1$ that type of situation you can get ok.

Like plane strain mode of deformation we can get $\beta = 0$ that sustained behavior similarly in this type of test you can get $\beta = 1$ type of deformation you can it can prevail in the sheet deformation somewhere in this uppermost portion and when it deforms and when fails you can get stress strain graph also and of course, you can also get forming limit strains whenever it next. So, this can be used to characterize the biaxial deformation mode of the sheet ok. So, these are two test in parallel with limit dome height test you can use, but independent of friction. Now, this shear testing is another method ok I have just given you the schematic here this is also little complex in doing the test ok.

Here what you do is so there is a this is a sheet actually of 50 mm dimension. So, square sheet you can say ok and you can say that there is an outer clamped zone red color one and there is a inner clamped zone green color one ok. So, this particular test is actually called as a Marcinak in plane sheet torsion test in plane means on the plane of the sheet ok sheet torsion test something that is that means, there is some sort of rotary motion is given to the sheet and you are going to evaluate that you know the plane or shear deformation ok that is going on in the sheet that is what you are going to evaluate. So, how are we going to do that you see that a square sample measuring 50 mm on each side is effectively positioned on into three distinct zones and internally clamped circular zone and intermediate ring shaped zone free to deform that means, between this red and the green this is free to deform that is a shear zone and externally clamped outside ring shaped zone ok. That means, you are these two zones ok green yellow and red as yellow region is the one which is going to undergo is free to undergo some deformation.

The inner zone undergoes rotation with its plane in relationship to the outer zone ok induced shear deformation in the intermediate zone. So, the inner zone is actually rotated ok somehow you have to hold it and rotate it with respect to the outer zone which means that the transit zone that is your shear zone will have ok you know shear deformation in it. The sample is deformed until fracture occurs and the angular rotations are two specific radii within the intermediate zone are gauged using the calibrated drums and move in tandem with the sheet. So, you have to basically measure the rotation and you can get the angular strain or shear strain you can say and you can see that the shear stress τ can be related to shear strain by some material constants C and hardening power n , $\sigma = K\varepsilon^n$. Similarly, here also you can $\tau = C\gamma^n$ you can say ok.

This is one test there is another test called as Miyauchi shear test which is little easy for us to do ok. So, this is in plane type this is also in plane, but this can be done in a UTM like this ok. So, initial sample dimensions are given you can see ok. So, the sheet metals undergo planar shear deformation through a modified tension technique ok. What do you do here? You have rectangular samples with flat surface ok or employed with the ends divided into three equal sections by slits.

So, three equal sections means 1, 2, 3 these three sections are there at the edge ok closer to the edge and two slits actually separate this. So, what do you do here is you actually pull the outside two sections with respect to the inner section like this. These two sections are pulled in this way this section is pulled in this fashion by using an UTM ok in opposite directions you can do. So, this particular action generates shear stress within the region situation between the inner and outer section somewhere here it is going to provide some sort of shear deformation ok. And you know one can get some characteristics shear characteristics in plane shear characteristics of that particular sheet material using this test ok.

So, this is another test that people use for shear testing. There are several other methods also, but these are a little bit more complex these are little easy to understand. Hardness test is another you know important test. Hardness test means a conventional hardness test only that we generally use for any material any testing. So, for sheets also you can use so but the thing is like how do you connect it to formability that correlation is actually little one has to little bit cautious ok. The measure of formability has often been assessed through hardness which quantifies the resistance to indentation caused by a concentrated load applied by suitable indenter we know that.

Hardness is nothing but resistance to indentation and you know the procedure Brinnel hardness, Vickers hardness. So, there are a few more hardness tests also. So, but how do you correlate with formability we say the decreasing formability with increasing hardness ok. Increasing hardness also means that the material strength would be increasing. So, which will be connected to formability with the decreasing formability. However, this particular correlation generally people say it is unreliable ok.

But the test is useful to ensure the material grade has got required strength for a particular component making that much one can understand from this ok. Like your yield strength and UTS is also important for you to guess ok whether the material is suitable for a particular application this hardness is also important to check whether the material has got a particular strength level to make a particular component. Otherwise it is a correlation the formability is little we have to be little bit careful. Let us go to simulative test there are some 4-5 test in this category also which are simple to implement in lab scale ok. So, first one is basically bending test ok first one is basically bending test there are two categories in this one is a simple bending test other one is stretch bending test ok.

So, stretch bending test is also simple only, but you need some tools for that ok whereas, the simple bending is as a name suggest it is simple bending ok. So, what do you do in simple bending? So, you can simply do it in your workshop. So, you have bench wise in that you have to keep a bending die like this let us say this fellow is a bending die and you have to hold your original sample here sheet sample and then what do you do you have to apply some displacement in this direction ok and the sheet is bent the sheet is bent like this. So, this is your original sample and the new sample is bent like this new sample would be like this. So, it is bent ok.

So, either you can do this manually or you can also clamp this in a UTM ok and then you can apply displacement to it ok to bend it both are possible ok. So, basically the idea here is whether you can bend the sheet to 180° without fracture or crack on the tensile side ok. So, here the material should not in this location the material should not fracture or neck when you deform it to 90° like this ok. This is one stage this is another stage. So, and then you can further deform it to 180°. So, 180° means something like hemming operation you can say something like a hemming operation you can say that type of deformation you can see to check whether the material is actually going to fail here in this region or not ok.

So, if it is done then one can you know repeat the experiment for smaller radius in the die. So, this radius now this region could be further it could be little bit more you know smaller radius ok very sharp corners maybe blunt bent die or sharp bent die both can be used to check whether you know the material can be deformed or it can be bent to 180° using that particular die ok. But different materials like you can go for high strength steels or aluminum alloys or other steel to check whether different die radius can be accommodated for that bending ok. So, if you want to mitigate crack during your hemming operations ok. So, like this hemming operations are used to mechanically clamp two different sheets when you make a component is not it.

Suppose you want to make a soft drink can ok you can also check ok that the edges the two materials are actually hemmed ok. So, you will see that this type of bending characterization is important for that particular material. So, this is simple bending which you can implement where only moment is given ok you are going to give only moment to this. So, you want to give moment along with the tension. So, you can call that a stretch bend test stretch bend test look like this ok. So, here you can see that there is a punch ok I have shown a V shaped corner punch wedge like wedge shaped corner you can say like a wedge tape corner you know like angular punch you can say of a particular angle is maintained here and you can see that sheet is clamped in the blank holder on the die with a draw bead.

So, that does not move in and then you just push the punch inside the work piece. So, that the work piece bends like this at the same time a tension is generated in the unsupported region tension is generated in the unsupported region because you are clamping it because you are clamping it. So, that is why we call it as a stretch bend test. So, a rectangular strip of sheet metal is securely securely held using lock beads ok. So, it is deformed as shown in the figure using a punch. So, when you do this there are two type of punch you know one can use one is hemispherical test is a in which a punches are hemispherical tip and concentric circular lock bead is used otherwise you can use angular test where wedge shaped punch and straight parallel lock beads can be used ok.

So, in hemispherical punch one advantage is you can have variety of strain states like the way we have seen before, but in angular punch you can have plane strain state. Angular punch means wedge shaped punch and straight parallel lock beads. Plane strain state means it will be created by angular punch ok perpendicular to the plane of this diagram. So, perpendicular plane you can see that you can have plane strain mode of deformation ok. So, along the bend and in through thickness direction you may have some strain, but you know perpendicular to this you know the sheet or the plane of this diagram you can have a plane strain.

So, that can be used and fracture whether it is going to happen or not will be tested. So, the advantage the difference between the previous one and this one is here the sheet is actually clamped and then bend. So, it is actually stretched bending test the previous one is just bending only no stretching only bending is provided.

So, this is bend test. There are some stretching tests available. So, what are the stretching test one is a simple lab scale ball punch test ok ball punch test. This ball punch test we can categorize into Olsen test and Erichsen cup test. This Erichsen cup test is very famous ok. So, we can it is a commercially available test we can implement it in lab scale table top and then we can show demonstrate ok how formability changes for different materials.

Olsen test is also similar one only difference is going to be the test dimensions sample your tool dimensions. Olsen test you can check it is going to use 22.2 mm diameter hardened steel ball like this ok. This hardened steel ball is let us say attached to a punch and then you can see all the standard setups are available you have die holder everything material is clamped and it is going to push the sheet and the sheet is going to bulge like this ok.

Dimensions are given here the gap dimensions. So, you can use a 22.2 mm diameter hardened steel ball and a die with a 25.4 mm inner diameter ok and about 0.8 mm die profile radius you can use ok. And here main aim is you keep on deformed pushing the ball inside the sheet until fracture. So, this height ok the sheet is going to bulge like this is not it. So, this forming height is of important to us this forming height is of important to us.

So, let us say fracture occurs here ok this forming height is of important to us and we can characterize we can compare different materials ok. Instead of going for a lot of calculations like forming limit curve like that, but this test is very simple to understand. Ericsson captures similar one where you use a 20 mm diameter ball and die with 27 mm inner diameter and 0.75 mm die profile radius. So, evaluation of stretchability how do you do this cup height or this dome height and the maximum load at the point of fracture or measure.

So, if you can install this in UTM if you fabricate you can also get load versus displacement graph ok. So, you can get P_{max} which is nothing, but your maximum load ok. So, this height h and P_{max} are measures of formability it is easy to evaluate it. So, hemispherical dome test

LDH test this we already discussed ok little more more details if you want ok. So, then what you do is you can have bigger samples bigger dimensions in tool which is going to simulate what you actually see in industry level components. That level if you want to get more details then hemispherical dome test and LDH test can be used and in this test also you can forming height is important. Same way like for example, if you see fracture here this height this forming height is of important to us and for this test also if you install it in UTM you can get load displacement graph ok.

And this peak load ok is an indication of your instability in the material and this the displacement would be nothing, but this height only ok where this data is also going to be important for us one can get. Of course, other than that you can get a $\varepsilon_1^*, \varepsilon_2^*$ they are nothing, but forming limit strains and by changing the width of the sheet you can get forming limit curve. This all three load displacement graph forming height and limit strains all three can be obtained from this test we already explained it ok.

There is another important stretching test called OSU formability test ok. OSU formability test OSU is for Ohio State University and is introduced there. So, it is called as a OSU formability test it is called in short it is called as OSU-FT you can say OSU-FT. So, here the advantage is you can get forming limit strain ok in plane strain mode of deformation in plane strain mode of deformation, but sheet is going to deform in out of plane ok. Previously we have seen plane strain tension test, but that is like a like a uniaxial tensile test here the sheet is going to deform in one plane in vertical plane right. So, but in this particular test the tools are fabricated in such a way dimensions are fixed in such a way that you can deform the sheet like your limit dome height test, but the advantage is here your formability will be evaluated in plane strain mode of deformation ok.

So, you may get $\varepsilon_1^*, \varepsilon_2^*$ that means, forming a strain only in plane strain mode ok. So, this test is developed mainly to avoid certain demerits in limit dome height test where it is found that in limit dome height test repeatability is going to be a problem ok. Specifically in you know the limit strains are when they are conservative in nature like in plane strain mode of deformation it is difficult to repeat the data. So, though it is a standard test. So, it has got that particular problem then this one was developed where sheet is deformed only in plane strain mode of deformation and you can see the you know the sheet how it is deformed ok and tool sheet arrangement you can see.

So, you can see that sheet is clamped here and you can see that the sheet is actually deformed in this fashion ok. So, it is a plane strain ok in this fashion you can see that it is about 124 mm length and the draw bead to draw bead is about 65.3 and it is about 101.6 width ok. The methodology employs a punch and dies equipped with a log bead to systematically stretch a broad blank until fracture happens. So, you have to have fracture in the sheet. The test is easy ok the test is easy and straight forward execution needs only a single specimen width to achieve a plane strain failure ok. So, instead of deforming several you know strain paths the most critical one plane strain one plane strain deformation if you can get limit strain that will be good ok. And it is easy to do this in lab scale and you can characterize the forming limit strain in plane strain mode of deformation only with one sample dimension. So, throughout the test if you see the strain path is maintained in near plane strain or on plane strain enhancing the test consistency when compared to the LDH test.

So, that is the advantage here ok. So, this is called OSU formability test. In stretching test there is one more important test called hole expansion test. This hole expansion test will tell you about the sheet material during hole expansion. So, for example, here you will see that this is a flat bottomed punch as usual the sheet is clamped between die and the blank holder and you will see the sheet initial sheet flat sheet has got a hole flat sheet has got a hole here. And then you deform this using this particular type of punch or sometimes we can also use a spherical punch or conical punch also ok. And when you do this what will happen is the edge region is going to be little you know prone to your crack and it may fail in the edge region.

So, if you see from the top you if you see from the top you it is a sheet like this ok and there is a hole here and you are going to deform the sheet and you are going to stretch the hole ok. So, hole can crack anywhere in this location depending on its weakness ok. So, if you want to evaluate the hole stretchability of any material which is also an indication of in a way formability you can use this test. And hole expansion (%) $= \frac{D_f - D_0}{D_0} \times 100$ where D_0 and D_f are the initial and final hole diameters. So, initial hole diameter you know what is it let us say D_0 you measure it and keep it inside and then you keep on deforming it and just stop at which a crack occurs in the edge.

Take it out and measure the diameter you will get a hole expansion how much is a % ok. This is also stretching to this all basically involves a stretching component in the material to characterize its formability. Now, let us go to drawing test only drawing is involved ok like for example deep drawing. So, deep drawing test so simple examples I have shown here Swift cup test ok. Swift cup test is used to evaluate drawability of a material and you can see some typical you know tool dimensions given you can see standard punch is available it is a flat bottom punch and the sheet is clamped between the die and the blank holder, but there is no draw bead here you can see that.

So, when the punch moves in this direction if you give some displacement this movement is allowed this movement is allowed. So, that the flange region this is a flange region is going to become a cup wall region is going to become a cup wall region. So, you have flange you have cup wall and you have cup bottom we have seen this diagram the sheet as an example before also and you can see the punch is about 50 mm and you can see the die inner opening is about 52.5 mm only 2.5 mm gap you can see and this it is about 6.36 mm. So, what you do here is this particular test is used to evaluate LDR, LDR is nothing, but limiting draw ratio ok. Draw ratio we already seen draw ratio is nothing, but your sheet diameter initial sheet diameter to punch diameter punch diameter is constant ok. So, you can change the initial sheet diameter within a range ok and there will be one particular diameter at which you can get very nice cup without any defect. So, you call that as a limiting draw ratio we say maximum blank diameter divided by punch diameter is nothing, but $\frac{D}{d}$ that is one quantity which you can evaluate you can also evaluate % reduction ok.

You can also evaluate % reduction. % reduction means like in extrusion wire drawing also you use this ok % reduction means it is $\frac{D-d}{d} \times 100$. How severe is your deformation ok. So, how big is your D and how much you are going to push it inside this gap ok that is decided by $\frac{D-d}{d} \times 100$. You can also get cup height from this by equating the initial sheet volume to the new volume can if you can do that then you will get this type of relations also you can get. So, this limiting draw ratio is influenced by normal anisotropy and you know sheet thickness we will see some details later, but when you do this deep drawing test you need to be careful about blank holding force ok.

Too low blank holding force will create a wrinkling in the flange region because of your in plane compression ok in plane compression and too high value can create fracture in the punch profile corner. The punch profile corner itself it will fail before you form a cup ok. So, the die ring should be greased properly, but a punch should not be the amount of stretching that happens over the punch profile radius and the potential was putting to occur in this area are minimized by not lubricating the punch. So, you have to be careful when you use lubricant also.

So, this is a drawing test or deep drawing test you can say swift cup test ok. So, now you can have both stretching and drawing in the same test there are two important tests ok. One is you can call it as a Fukui conical cup test, other one is a Swift round bottom cup test. In these two test if you see stretching and drawing both will be there using a simple setup we can do I have just drawn one schematic here ok. So, you can see that the sheet is clamped and there is a ball in under which will come and deform the sheet. So, you will see that the sheet will be deformed in a conical fashion in the wall region at the same time this ball in under it will give you a shape at the tip and it can fracture here.

You can see this is the initial one initial work piece this red one is a deformed work piece, red one is a deformed work piece you can see that there is a fracture here ok. And you can see it is actually conical part which is actually sort of drawing in and then at the edge it is in the corner or in the uppermost portion it is going to stretch where fracture is going to happen. Because the punch top is semi spherical the specimen is stretched in the middle in addition to the flange being drawn in to create a cup wall. This is what I was telling you the end point of the test determined by observing fracture here I have shown you here.

So, this is it will be like this your deformed sheet will be like this. So, you will go like this and you will see some fracture here something like this. So, this is an indication of limit of formability. So, if you can do it in UTM you can say drop in you know punch load which is going to be indication of fracture. So, both your stretching and drawing involved in this. So, this can be categorized under stretch drawing test your Fukui conical cup test also like that ok.

So, only thing is like the dimensions are slightly different the details are given here using 12.5 to 27 mm diameter ball you can use it ok. So, diameter of the base of the conical cup is measured and divided by the diameter of the original specimen to give the Fukui conical cup value ok. And this punch travel at the onset of visible neck ok, which means that you get a load displacement graph ok. Suppose you see this load this displacement height or punch travel is also could be one parameter which you can measure.

Wrinkling and buckling test these are the last two test and then we will stop here ok. So, what you do here is you are you going to use this type of setup the setup is actually known to us. So, you have a punch like this and you have a die holder and it is actually held here and you will see that this punch is actually dimension is made such that it is much smaller than the die opening. So, that this wall region is little of conical in shape it is not straight like what you see here it is not straight like what you see here you can see it is straight wall is cup wall is straight here instead of that you reduce the diameter of the punch such that you can have a unsupported region here which is of this particular conical shape. As a result the cup wall is conical and does not come in touch with the punch it is basically a unsupported region.

So, you can see that the flat bottomed punch with the diameter equal to 75 % of the inner diameter of the die deform the circular bank. So, you can calculate accordingly ok. So, 0.75 into your inner diameter of this die is equal to the punch diameter you can imagine like that. So, what you do here is there is another important point. So, you can also change the blank holding force ok and check what is actually happening in the wall region ok. So, you can see that I have drawn a graph schematic forming height in Y axis BHF in X axis and there are actually 3 profiles here one is the red one corresponding to flange wrinkling ok.

Flange wrinkling is this part flange is this that wrinkling we know already. Then you can also have wall wrinkling ok wall wrinkling means this unsupported conical region can also wrinkle ok and then there could be a fracture zone ok. So, you will see that at lower blank holding force if you keep ok. So, there will be flange wrinkling that we already know ok that is why in the previous deep drawing case we said there has to be an appropriate blank holding force otherwise wrinkling will happen. So, if you increase the blank holding force beyond that you may have wall wrinkling wall wrinkling means here ok in the in the in the conical region ok in the unsupported you can wrinkle, but if you increase the blank holding force it may lead to fracture also.

So, you can get this type of profile and you will see that the forming height is going to be maximum where these two intersect. The wall wrinkling and fracture limits meet at the intersection of maximum cup height ok. So, one can characterize the formability in this fashion. So, the maximum height is reached when this wall wrinkling profile and fracture levels actually come closer to each other that is why you have H_{max} this can be characterized using this type of test. This test is actually called as Yoshida buckling test ok. Yoshida buckling test here you will see that you have a flat square specimen ok the specimen is of 100 mm side you can see here in this diagram and this actual sample is actually clamped in the corner.

In the corner region for about 41 mm width it is actually clamped and you are actually pulling it ok and you are actually pulling it. Gauge region is maintained about you can say like point to point is about 75 mm ok. And inside this 75 mm there could be one particular location of 25.4 mm you know width ok there you will have buckle this kind of buckling can happen you can see that the A-A cross section A-A if you section it and see you may have a buckle like this. So, you are going to pull in this direction to create this buckle in the A-A cross section within this small gauge region. A buckle develops in its center along the path of loading indicator of buckling is the height of the buckle at a specific elongation like let us say about 2 %.

So, you pull it to about 2 or 3 % and you will have a this kind of buckling height. So, that can characterize the buckling feature of this particular sheet whatever sheet you are going to deform. This is another way this is one way to characterize the buckling nature of a sheet. But the problem is this material should not fail before you reach this buckling ok. That is why you will see that low formable materials like aluminum alloys will have difficulty in completing this test because the specimen fracture before buckling that should not happen.

Otherwise probably you may have to reduce this % to characterize the buckling or buckling is not happen fracture happens before then you cannot test that material using this. So, for example, aluminum will have this problem. So, this many number of tests are available for us to characterize the formability of sheet or to characterize the deep drawability to characterize the hole stretching to characterize you know the drawing cum stretching ability of material in one test ok. And to characterize the shear deformation, shear formability of the material you can also characterize this kind of buckling, you can also characterize the limit of wrinkling ok. So, all this can be characterized using different types of test complexities change some need tools like punch, your die holder and blank holder like that some are actually can be done in UTM itself ok. So, depending on the case the complexity changes, but this many tests are available to characterize the formability of sheet and this particular one we will stop here.