**Analysis and Modelling of Welding**
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**Lecture - 10**
**Keyhole mode**

Welcome to the lesson on Keyhole mode, as part of the NPTEL MOOC on Analysis and Modeling of Welding.

So in this short lesson, we will be discussing on the transition from conduction mode to keyhole mode during welding. And what kind of process parameters are going to affect this kind of change, and how one can have a stable keyhole mode welding for a through thickness weld. And what kind of say parameters are going to play a role in this stability is going to be discussed at length, and we will get started by first looking at what is the definition of conduction mode and keyhole mode.

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So this is how the definition is. So, usually when you have the series of processing techniques welding processes, which we have looked at earlier.

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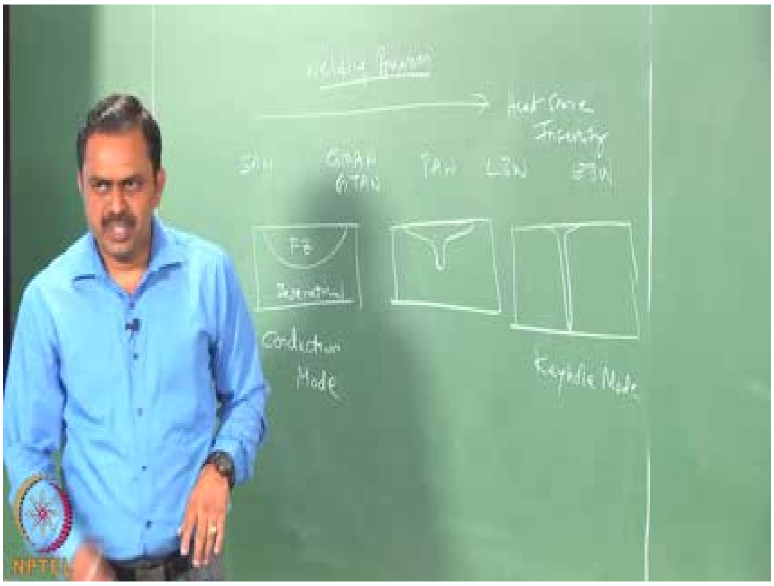


And if you look at how the heat intensity, heat source intensity is changing then you can see that at the lower end you have got submerged arc welding, and in the middle you have got GMAW and GTAW and then plasma, and then LBW, and then EBW. So, this is how the intensity of the heat source distribution is going to increase, and you would see that the weld pool shapes also change in the same manner schematically shown as follows.

So, broadly in two categories, it is going to look like this. Here, on this end of the spectrum or the heat source intensity, you would usually have a weld pool shape like this. The fusion zone and this is a base material, you are going to have like that, which means that if you were to make a very high thickness weld using these techniques then you would have multiple layers, because in each layer you have basically a wide and shallow weld pool that is coming in. This mode where the weld pool is wide and shallow is called the conduction mode.

And once you go to the other end of the spectrum, you usually have a shape of the weld pool as follows. This allows you to have very deep penetration, so that very large thicknesses can be weld in single pass. And this kind of a mode, you can see the shape difference, so at the very top the cup is going to resemble this shape, but then significantly it is a narrow and very deep pool that we are talking about here, and this mode is called the keyhole.

So, somewhere in between when the transition is happening, you may see shapes like this, you may see shapes like that, but you could see that it is perhaps a mixture of some amount of key holing happening; and rest of it is actually conduction mode. So these are two distinct modes that we are talking about what we referred to as conduction mode and keyhole mode.

What do we mean by keyhole actually is basically what is normally meant by in English as keyhole basically a hole that is drilled which basically contains a vapor and that is going to have an effect on the deep penetration.

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So, you can see that at what power density this is going to play role. You can see that the keyhole mode is effective only from the kind of heat source intensity that is available from plasma arc welding and upwards. So, 10 to the power of 8 watt per meter square is going to be the cut off; and by and large around that as you go increase up to 10 to the power of 10 or 12, then you would have the keyhole mode is possible. So you do not have this mode, for example, availability in the SMAW or submerged arc welding scenarios, and there the weld pool shapes is significantly only conduction mode.

And there is also a parameter even though you may have for example; laser beam welding where the heat source intensity is very high, it is possible to design it is the type by focusing the beam. You also need to know what would be the laser power per unit thickness that you have given and that is also plays a role. So there is again a threshold of the laser power per unit thickness above which the kind of key holing mode is also possible. So what is the reason why this happens that is basically a process by which step-by-step you are going to arrive at a keyhole; and the sequence is as follows.

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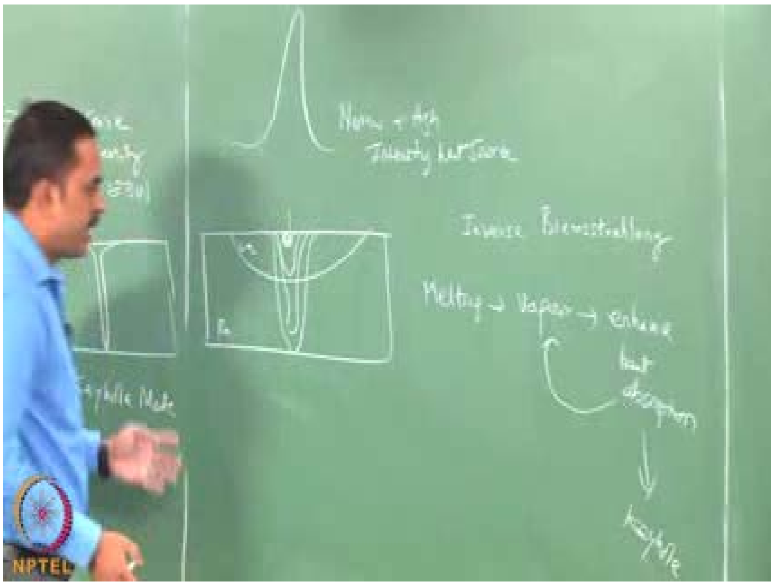


So, under the heat source, which is basically if it is narrow and high intensity heat source, so then what is basically happening is that you have a weld pool initially in the conduction mode, and then this is a liquid, and this is a base material. And you could see that it locations here the temperature is going to rise up several hundreds of Kelvin above the melting temperature of that material and soon there may be a situation where you have some amount of vapour that is formed is the temperatures are so high that evaporation as started.

The moment some amount of evaporation is happening then you can see that whatever is a beam, it is going to penetrate that much deeper because vapour column is amenable for complete absorption of heat. So, the views do have for example, the three sources of a heat. And for each of them, we can tell probably in the case of plasma arc welding, you can see that the constructed plasma torch is going to send the heat in the form of plasma and that can penetrate the vapour column and deliver heat throughout the thickness of the vapour column.

In the case of laser beam, the absorption is because of what is called inverse Bremsstrahlung this is basically a phenomenon in which the vapour is going to absorb the laser light completely and which is very different from the rest of the material. Because as we have discussed during the process over view that laser beam absorptivity in solids is very less, less than 10 percent. And it reach some reasonable number for liquid, but for vapour because of inverse Bremsstrahlung you have complete absorption of laser light happening in the vapour column and that means, that you have enhanced heat that is delivered to the beam.

And electron beam is the same thing again electron beam can penetrate that much deeper to deliver the heat to the vapour column. In other words, the moment as a small amount of vapour is going to have formed then it absorbs heat effectively and more and more vapours then going to form, and this can continue to happen until it has formed a through keyhole. So, we can see that this sequence of melting and then vapour formation is going to basically enhance heat absorption and this is going to be as a loop that is more heat absorption more vapour, and then further heat absorption further vapour, so that finally, you have basically keyhole that is forming.

Now, naturally this can initiate only when some amount of a liquid metal has formed a vapour for the kind of intensity distribution you have and that is what is absorbed from this process onwards towards the right hand side.

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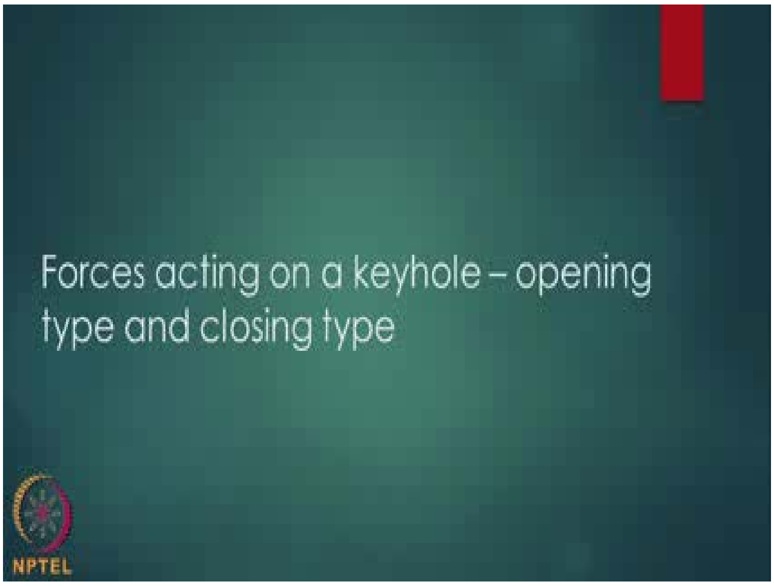


So, let us say that keyhole has already formed. And then analyze whether that keyhole is stable or not and that will tell us whether or not the keyhole mode welding is possible. For example, even in laser beam welding, it is only when the power intensity is crossing a particular threshold that keyhole mode welding is happenings; and therefore, we can actually see that the stability is going to play a role. And to understand this stability, essentially we are going to look at the domain containing the key hole, and look at what is happening around them.

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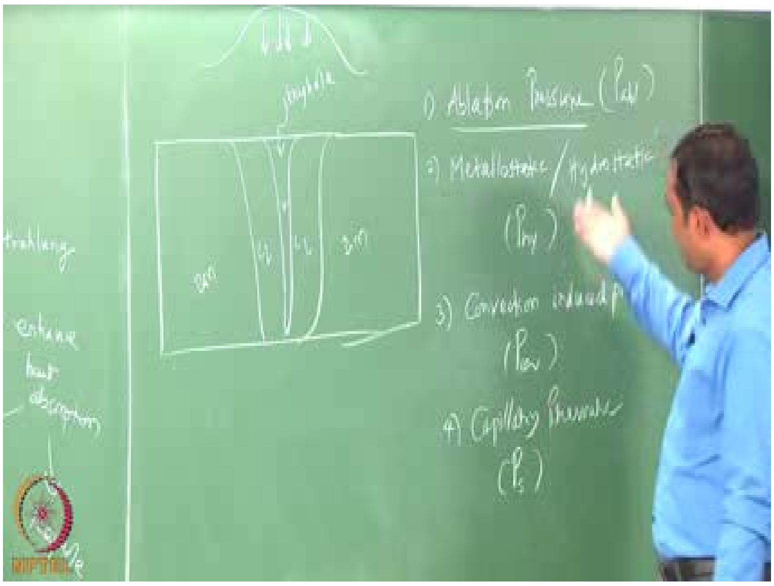


So, let us draw a schematic and see how it happens. So, this is the thickness of the plate, and the keyhole is looking like that, and this is the fusion zone. So this is liquid; this is the vapour, liquid; this is a base material; and this is a keyhole essentially. And your heat intensity distribution is going to give heat into this vapour column. So, now, if you see that essentially we have created an extra surface which the liquid would like to close, and there must be opposing factors, some factors that are going to open up the keyhole and some factors are going to close it.

So, let us see what are all the various factors that can come in; and I will just list them. One factor that would be coming in is ablation pressure. What we mean by ablation pressure is basically whenever there is evaporation that is happening atoms are going to leave the liquid surface into the vapour column, and when they are leaving they act on the reverse a pressure that is called as ablation pressure, and that is what actually is trying to basically open up the hole. So, ablation pressure is caused by evaporation flux; so the more evaporation is happening more is a ablation pressure, so that is one pressure that is going to happen in the vapour column.

Next pressure that is occurring is basically metallostatic and usually water is used as imagination for any fluid, so you normally refer to this as actually hydrostatic itself. So this is hydrostatic pressure that is acted upon by this column of liquid which tends to normally close also, so you have that pressure coming in. So, you can think of this as P ablation as a parameter, and this P hydro static as a parameter. And then you have got one more parameter which is basically whenever the liquid is actually convicting and that is going to also exert some pressure, so you would like to call as convection induced pressure, and you can think of it is P convection.

And then there is one more force that will be acting upon that is basically you have created a surface and that surface would have a cause associated which means that there must be some surface tension driven pressure that is coming up and that would be basically the capillary pressure. So, you could think of this as the because of surface tension, so you would just put it as P s.

So there are these effects that are all that are going to be there which are controlling whether the vapour column is stable or not, and whether the vapour column is actually going to survive and move ahead in the same way, so that a through thickness welding is possible. So let us look at each of these, what they would have a scaling analysis and how they would affect the vapour column stability step-by-step.

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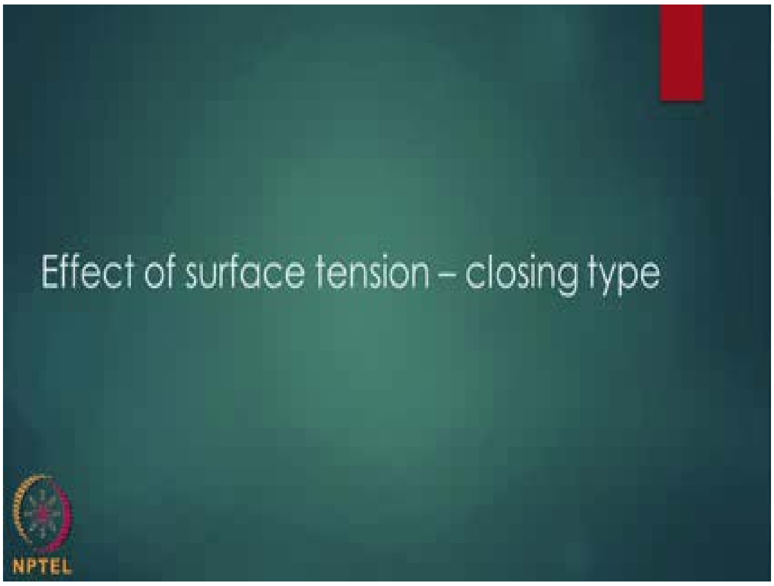

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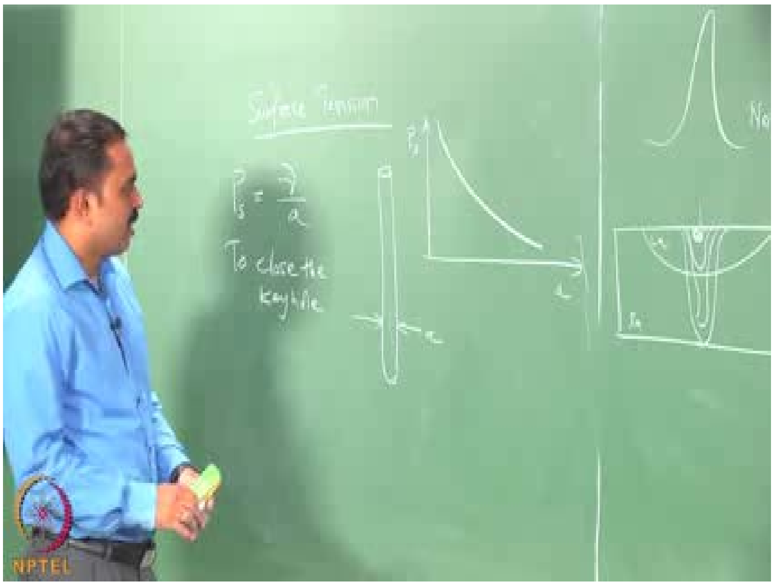


So, let us take this surface tension first. So, let me just erase this. Let us take the force because of surface tension, if the vapour column can be imagined as a cylinder of diameter a, then radius a actually, so you would actually then think of the P s gamma by a, so that you can think of a surface tension induced pressure that is going to act in a way to close. So this is the scaling and the way it is going to affect is to close, so which means that if you I want to plot the pressure due to the surface tension forces on the vapour column have a function the size of the vapour column, then it would look like this.

You can see that is basically 1 by a, so this plot should look like that, so that means, at as the vapour column is going to be wider and wider then tendency for it to collapse is going to be less and less. So when it starts of the tendency to collapse is very high, but as it increases the tendency to collapse is less, so this is one driving force for us to think that the vapour column has to be collapsed because of this surface tension.

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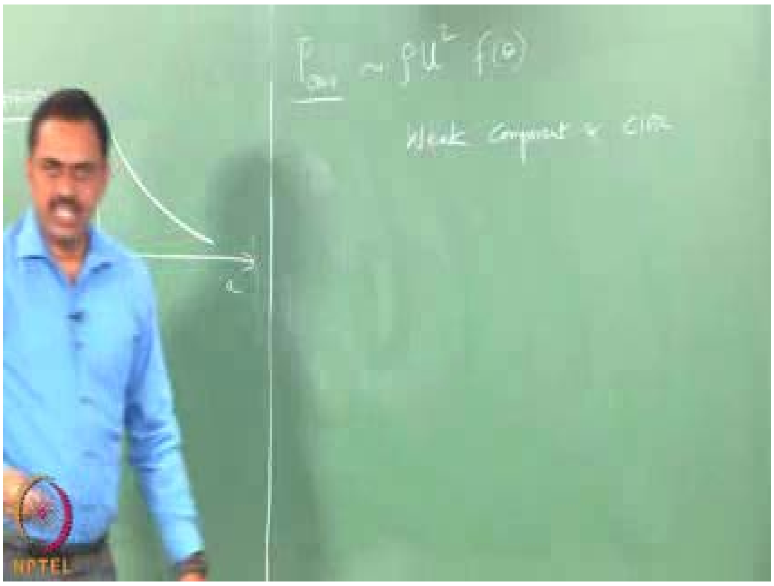

So, let us look at the next the driving force we have the pressure due to the fluid flow that is happening around the keyhole. The pressure due convection you can see that this is going to scale as rho into U square and some kind of a trigonometric function depending upon the geometry. And this is going to be as strong as a convection current itself. And you can see also that the vapour column if it is assume to be almost cylindrical, and the temperature is going to be same along the axis of the cylinder, then it implies that there are no strong temperature gradients along the vertical axis of the keyhole, which means that Marangoni convection is not going to be very strong.

So, under that assumption that Marangoni convection is not strong than the convection velocities are pretty weak, because other driving forces such as the buoyancy are not very strong, so which means that these numbers U is going to be in the order of few millimeters per second. And if you then square it and then multiply with the density of the liquid metal in the case of steel, it will be 7000 or 7500 into 1 millimeter of square then you can see that the convective pressure is not going to give much of pressure. So you can say that this is weak component and the modes it will active also too close.

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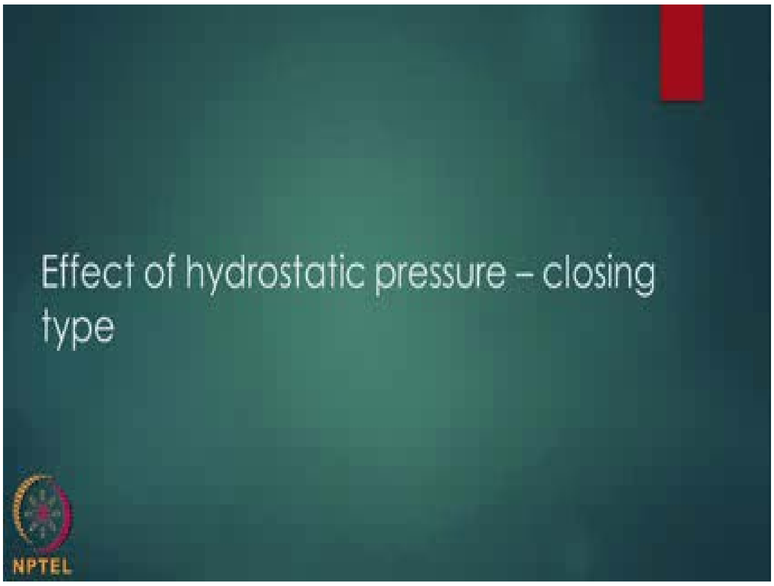


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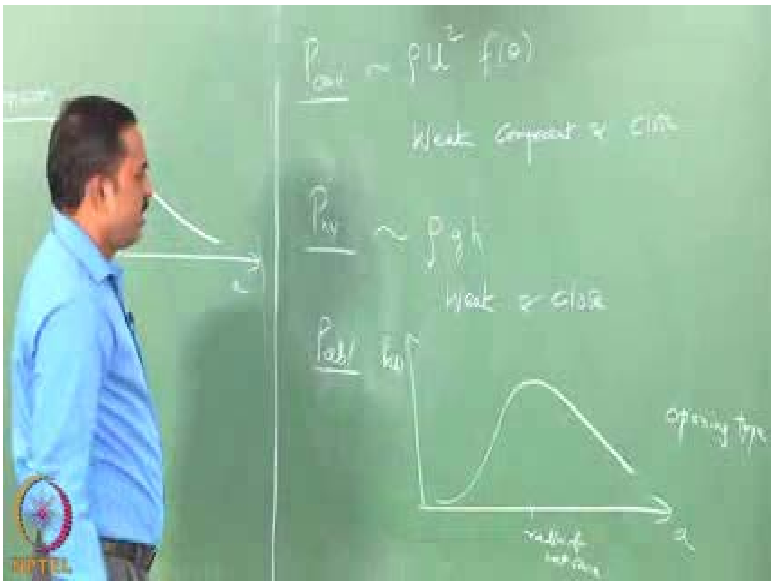

And let us take the third driving force that is going to be present that is a hydrostatic component. The hydrostatic pressure or metallostatic pressure to be accurate is basically going to scale as rho g into h depending upon the height, so which means that at the bottom of the keyhole the liquid is going to have higher pressure and at the top it is going to be lower pressure. But what are the heights that we are talking about we are talking about heights typically only in centimeters, so which means that again this number is not going to be very high, and this driving force also is weak.

And also, it is to have a tendency to close, the reason being that these hydrostatic component is going to actually act to close the vapour column as we increase a height, but then that tendency is actually quite weak, so one can actually ignore these.

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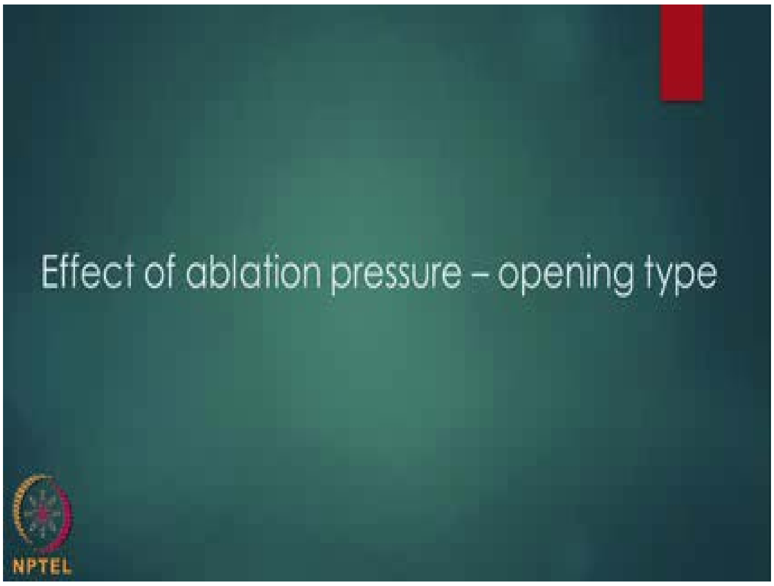


Let us look at the fourth component that is going to happen that is the ablative pressure so though how is the ablative pressure is going to be acting this relationship is fairly complex, so we would actually not look at that because it involves lot of calculations. But we can definitely get a trend for the ablative pressure as follows. So as you increase the diameter, what it happen is as follows, as we increase the diameter of the vapour column, the P ablation is going to go through a variation as follows. Initially, as you increase the diameter of the keyhole, then it is going to tap more and more of the heat source.

So imagine that the heat source is having a diameter of about 1 millimeter. Then if you start up with half a millimeter then as you go towards 1-millimeter diameter, you are capturing more and more of the heat source; so you should have more heat coming in, so more vaporization is possible and more vaporization means more ablative pressure. So, it means that initially you should have an upward trend so that the ablation pressure is increasing as we increase a vapour column.

And somewhere around the radius of the heat source, slightly beyond the radius of the heat source, you should see a tendency that even if we increase the keyhole to be much larger than the heat source, then the amount of heat source is anyway going to be the fixed one. So, it is going to actually fall in a vapour column that is going to be fully absorbing it, but the vapour column is now much larger. So which means that the ablation is happening in a much larger area than earlier which means that it is going have less and less pressure so which means that eventually it has to come down.

So, you imagine a situation where you have got a very large keyhole diameter, but then the total amount of heat here compare to here is going to be the same. So, same amount of heat is falling on a larger keyhole, which means that ablation is happening over larger area, but the same amount of a molecules are coming out of the surface of the vapour column exerting basically smaller amount of pressure, so it is going to do this way.

So, if this is the variation of these four components, then what is the mechanism by which the stability of the keyhole is going to act? You can basically see which way is opening and which is closing. So, the three factors are closing type, this is opening type. So, essentially, we take a sum of the closing types and equate to the opening type and that should tell us about the stability.

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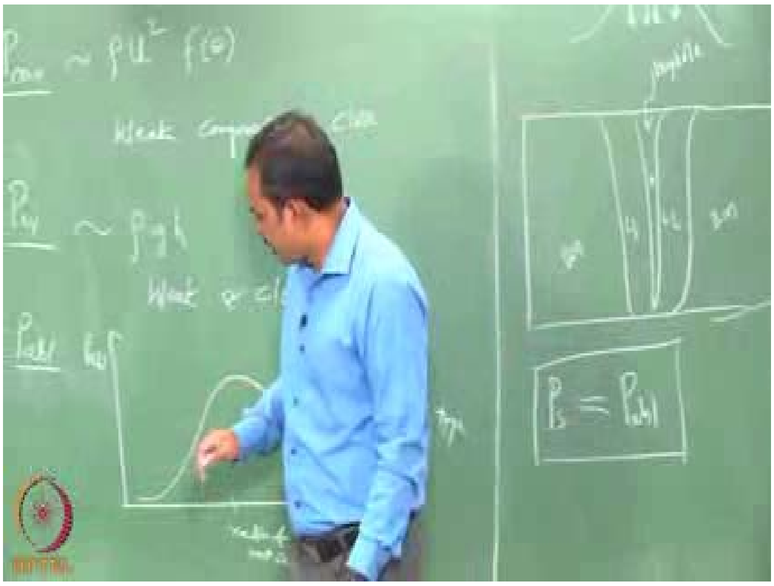

So, we would write that as an equation here as follows. We can say that ignoring these two components, which are very weak. We can say that under conditions where these assumptions are reasonable, these opening pressure for ablation if it is equal to the closing pressure which is for the surface tension and that is exactly where the keyhole is just about balanced. So, this is the condition. And let us just look at this condition by looking at the plots essentially what we are meaning by this condition is that super position of this plot with this plot. We can then superpose and see what would happen to the matching between the two values.

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So let us look at the competition between the surface tension forces that are to have the keyhole to be closed and the ablative pressures that we are wanting to keep the keyhole to be open.

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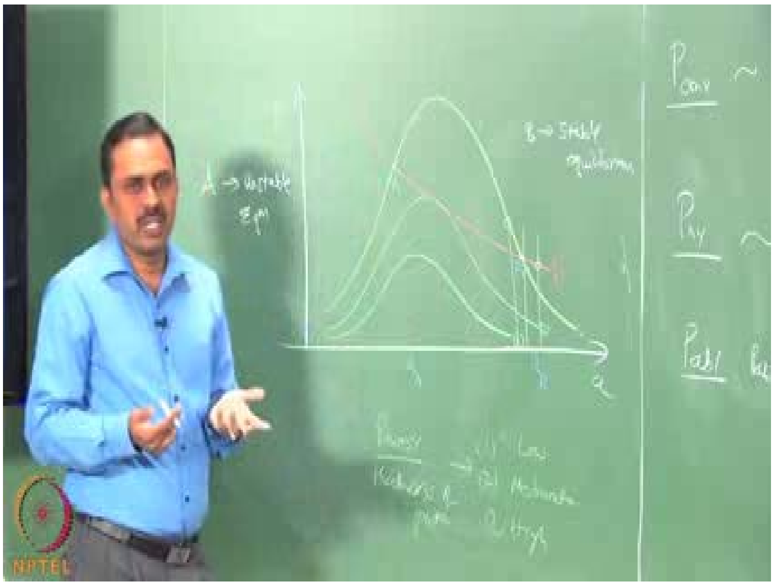

Let us look at the competition between them. So, I will just superpose them as one plot here. The size of the keyhole as a function of the pressure, and I will draw with red chalk which is for the surface tension one, and I will draw the ablative pressure. So, I can actually choose this ablative pressure to be at different levels of the intensity of laser so let us say you have intensity of the laser not very high. So in you may have this plot happening only like this; in which case, this is first situation P - power at low value which means that the ablation pressure is never going to match the closing pressure; that means, the keyhole is always going to be closed which means keyhole modeling welding is not possible.

And if you keep increasing the wattage of the laser or the electron beam welding then you can see that you reach a situation where there is at least one point that is common with the other curve which means that it is just about matching. There is one choice of parameters that would make the two pressures match. But, if you increase the wattage further, then you have a situation of this kind. So this is for situation three. So, you can say that the power per thickness of plate is for 1 - very low; 2 - it is low, moderate; and for 3 - it is high.

So, when the power per unit thickness of the plate is high then you intersect the red curve two locations. And those two locations let us designate them as A and B. Now what happens at A, and what happens at B is what is going to tell us whether keyhole is stable or not. So, which means that as the vapour column is forming and the column is growing then the moment the where vapour column is having a size that is here or here, what is happening is what is going to be discussed.

Let us take the ‘A’. What happens for example, if the vapour column happens to be slightly less than A, then what happens is that the closing pressure is high and which means that the vapour column will then get closed and it will just die off. And if it happens to be slightly high then what happens is that the opening pressure is high. So, it keeps on opening up because the opening pressure is higher than closing pressure till it reaches B, which means that at a small fluctuation in the diameter of the vapour column on the lower side will close it off, and on the higher side it will take it to the B point, which means that A can be designated as an unstable equilibrium between these two driving forces.

So, A is unstable equilibrium for the two driving forces to match each other. If you have less than the diameter as A than the closing forces are high so that will let close completely, keyhole will just get shut off; and if it is higher than a then the opening forces are high and that will just go on up to B.

Now once you are at b then we can let inspect what will happen. Let us say the keyhole is at B, and a small fluctuation in reduction of the diameter would see that if it is slightly smaller, then you see that it is the opening pressure which is high; that means, when the keyhole happens to be slightly small, the opening pressure is high which means it again it will open to make it again come back to the B value. And if it grows beyond B value, then it is a closing pressure that is high which means that it just again comes down to the B value which means that at b you have basically is stable equilibrium of the keyhole size.

So, in other words, when the keyhole is just about starting to form, it basically undergoes certain variations where it may just get shut off, but the moment it reaches a critical size of this value intersection here given by a b, then you normally have a stable keyhole mode welding. And you can see that this point is on the right hand side of the peak. And we saw that the peak should correspond roughly to the diameter of the heat source that means, at this value is going to be slightly more than the heat source; that means, the stable diameter of the keyhole, and during the keyhole mode welding is going to be slightly more than the diameter of the heat source.

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And this is going to happen when the critical power density is going to exceed a particular value because when only at high values, you start cutting at two locations and you get the stable way; and if it is lower than that you see that it does not have any match at all the closing forces are significantly higher. So for very low threshold power density or power per unit thickness then the keyhole is not at all possible. So you can see that there is a threshold value you have to cross; and in the threshold value once it you cross you must come up to this point so that you can have a stable keyhole mode welding.

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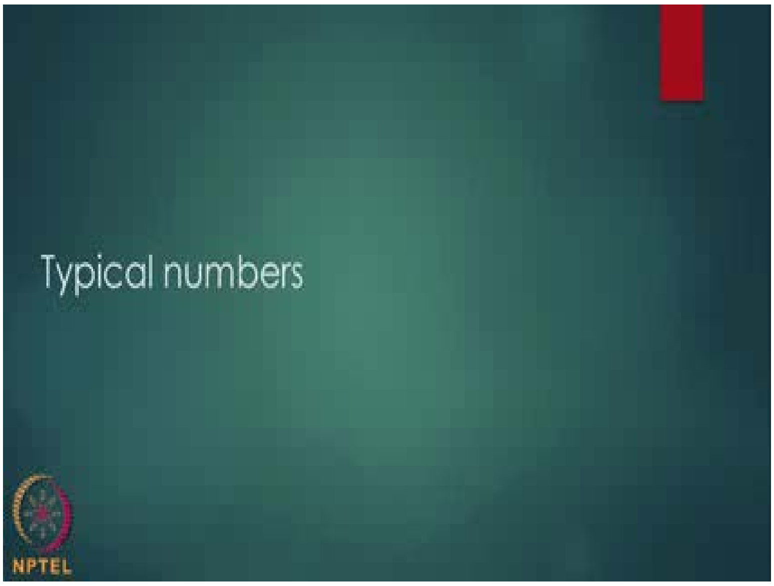


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And what kind of a number we have looked at in the literature this stability is corresponding to - 1.7 r naught, it comes too roughly about 1.7 that is about roughly 70 percent larger than the heat source diameter is this size of the keyhole that has been absorbed by numerical studies.

Obviously, we have made this analysis extremely simple; we have not considered the fluid flow in the liquid zone very extensively, and we have also not considered if the keyhole is going to be tended an angle to the vertical direction, and we are not considered the trailing of the weld pool during this process. But still we are able to come to some conclusion which is rationalizable with respect to the experiments, namely there are low heat inputs for which you do not have keyhole and there are stable regimes and unstable regimes.

And the stable regimes are giving a particular number, which also seems to be reasonable with respect to the observations. So, by this kind of an analysis we can understand how the keyhole mode welding is happening. And we can see that it is will it is going to happen in high heat intensity processes such as plasma, or electron beam welding or laser beam welding.

So with this, we close this lesson on a keyhole mode welding. I hope it is now clear to you how the transition from conduction to keyhole mode is going happen. And it is important for us to keep it in mind that these are possible only in the right hand spectrum of the heat intensity distributions for the laser for the various welding processes. And one can take advantage of this key hole mode welding to avoid multiple welding sequences, so that a thing will pass welding is possible.

Thank you.