Analysis and Modeling of Welding
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Lecture - 04
Heat sources - Part 2

We come to the part-2 of the lesson on Heat sources, we will continue from where we have left.

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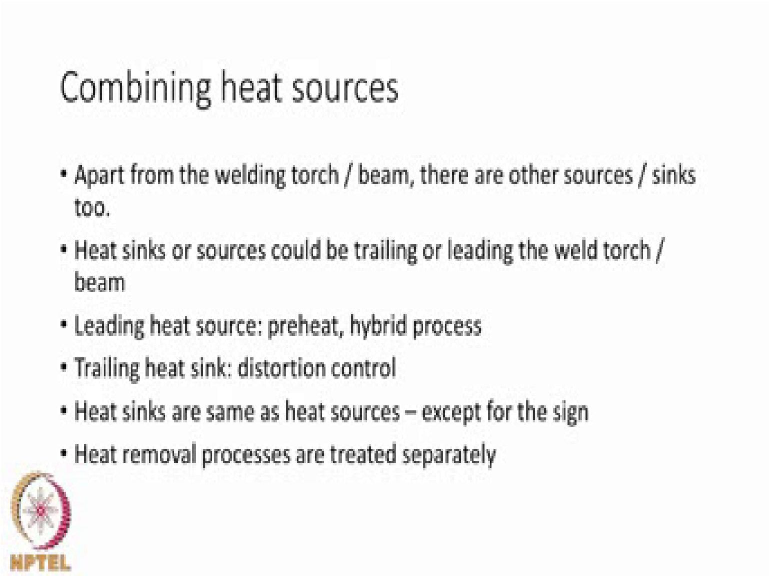

We have the situations; we have discussed where we will be combining a multiple heat sources. So why would we need to combine heat sources or sinks is as follows. So apart from the welding torch or the beam, there are other heat sources as well as heat sinks that will be present in the welding. And we have heat sources apart from the welding torch for preheating conditions, for example, or hybrid welding conditions.

And then we may have heat sinks that could be either trailing, because we want to remove the heat to control the distortion for example. So in situations like this, we have the possibility of multiple heat sources and sinks that have to be combined. And then we also need to remember that heat source and heat sink mathematically is just one and the same except for the sign. And the heat removal processes will be separately taken, so we are only going to look at the heat sources and sinks together in the rest of the lesson.

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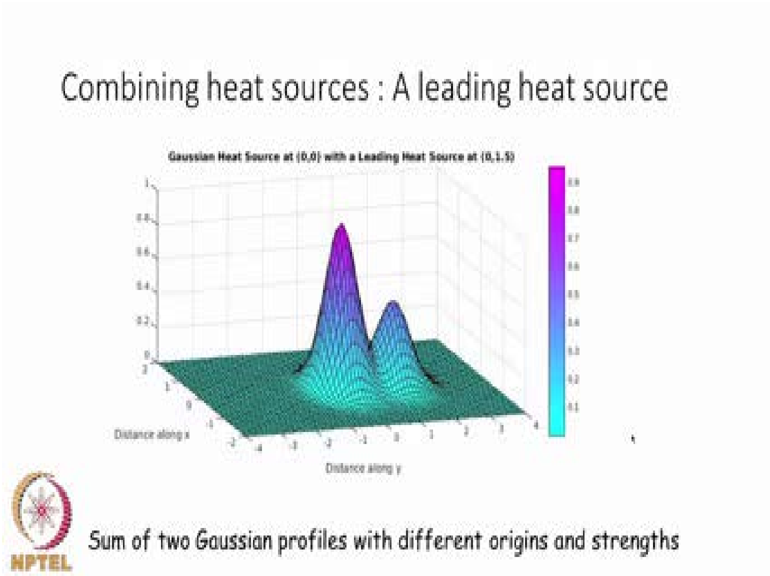

So, here I have shown you two heat sources that are being joined; and the one with the taller appearance is the welding heat source and the one ahead of it is the preheating heat source. So you may have two torches that are doing this job. And you could combine two Gaussian functions to achieve this; essentially, we have taken two Gaussian functions with different intensities and then shifted the origin of one of the Gaussian functions and then added the values and then plotted this. So it is possible for us to now make such a complicated appearance of heat source in just one combination of a function.

And, as you can see from this combination that if the leading heat source is little too close to the torch, then it may appear as only a shoulder for the first heat source, which means that it may simulate an asymmetric heat source. And if it is far away then in between you will have a situation when there is no heat, in other words the heating that is given by the leading heat source is a lost by the time the welding comes.

So you could actually play with the positioning of the two heat source as in the computer using a matlab script for example, and adjust the spacing in such a way that the amount of heat in the trough between the two peaks is adequate to maintain the preheat that you want to have in the welding setups. So, it is very important to be able to analyze the heat sources in this manner before we actually tried to implement and fabricate a very complicated nozzle for our welding setup.

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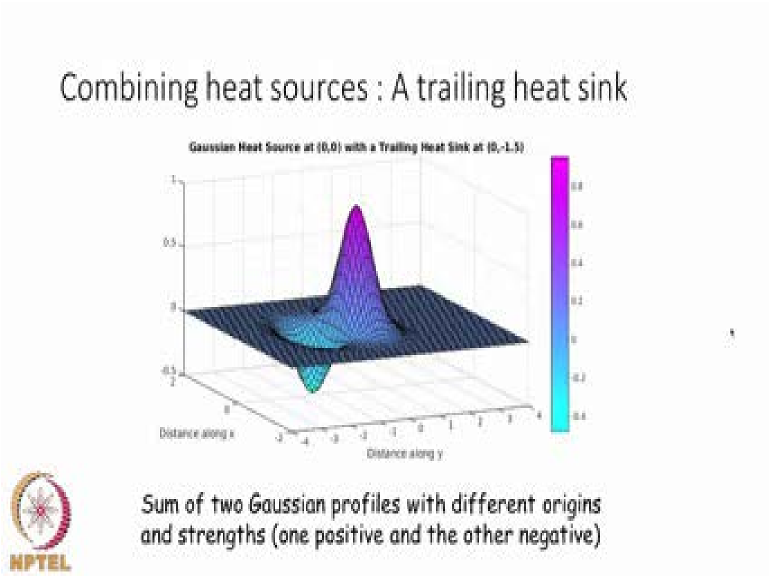

And one can combine a heat source and a heat sink also the same way, except for the sign of the second Gaussian that we are going to add; here in this situation, we are taking it as a negative. So as a result, you can see that here we have plotted a heat source, which is for the torch and then a heat sink which is behind the torch. And the heat source is moving in the y-direction as I have plotted here. So you can see that the heat source and sink together would like what is shown in the schematic; and then in the region between the two, you will have a cancellation of some of the heat by the welding torch because of the sink.

So, if you have the heat sink too close, you may lose the heat behind the torch; and again you may have a significantly asymmetric heat source that is coming up. And if it is too far way, then the heat sink may not be effective, because it is trying to remove heat from the material when most of the heat is anyway already gone. So again even in this situation, where we have a heat source and heat sink identifying the distance between the two to have appropriate heat transfer is important.

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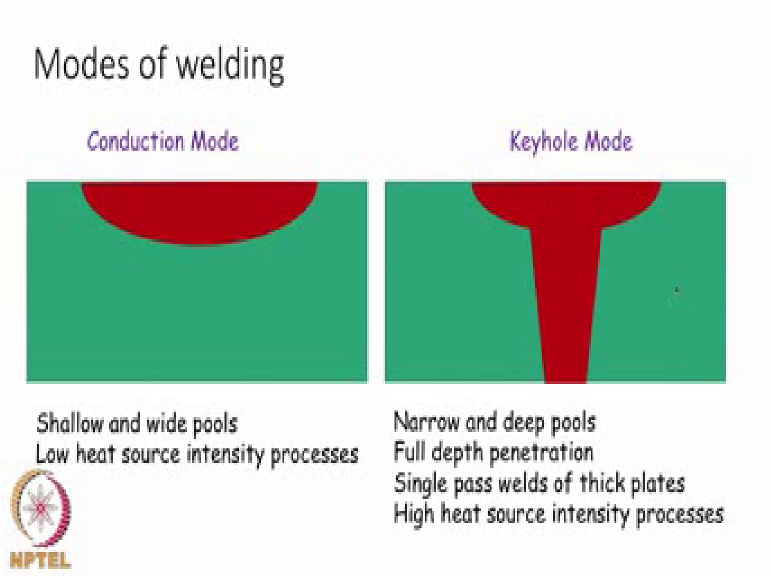

And further discussion of how different heat sources have been modeled by different researches across the world will be meaningful, when we understand that welding is generally done in two very different modes. The two modes are called as conduction mode and keyhole mode. By conduction mode, what we mean is that the weld pool happens to be shallow and wide; and then it is normally achieved when we have a weld heat sources which are of low intensity of the heat source. And these are processes which are like GTAW and lower than that.

And in situations like plasma welding, laser welding and electron beam welding, we have a mode of welding that is possible which is called as a keyhole mode. And keyhole mode is achieved when the heat source intensity is very high; and this mode is very attractive, because you could join very thick plates using a single pass because of the deep penetration of the heat source through the thickness of the weldment. And you normally see narrow and deep pools, but at the very top of the weld pool, the weld pool has a shape that is very close to the conduction mode. So you could actually imagine the keyhole mode as conduction mode plus a vertical column which is forming the keyhole.

And it is not as if these two modes can be chosen a priory, these are basically coming because of the heat transfer phenomena, that are taking place during the welding; and the heat intensity variation achieves the transfer between one mode to the other. And we will later discuss, how we can pick a heat intensity value such that the keyhole mode is stable and the conduction mode is preferred, when you have lower heat intensity and what would be that value also we can design. And we will look at the discussion in a later section.

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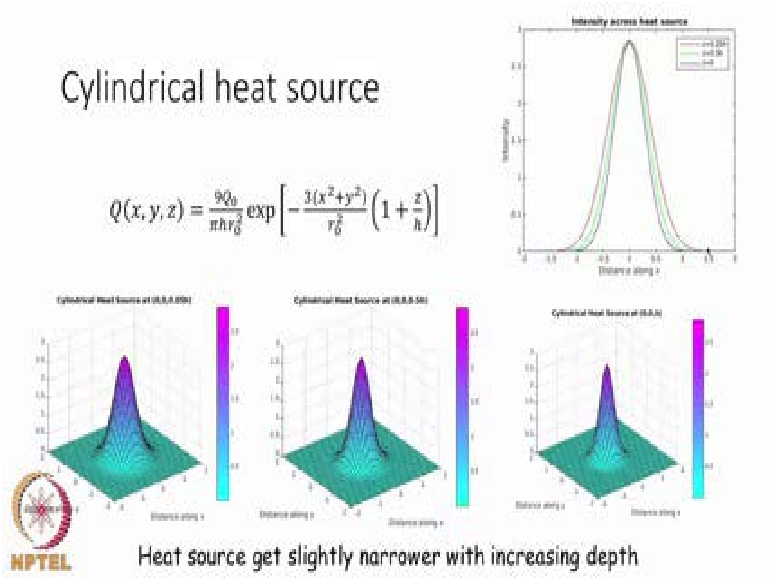

So, the kind of heat sources that would be applicable for welds which are showing a keyhole mode are going to be very different from the Gaussian. The reason being that the Gaussian heat source though it does show a high heat intensity at the center of the weld, it is not adequate to be able to capture the fact that in a keyhole the vapor column actually absorbs heat right through the thickness, and the Gaussian is only a surface heat flux. So very often a volumetric heat source is used to capture the weld pool shape evolution using keyhole mode welding. And we are going to look at the heat sources that cover this kind of a method and I am listing one after them here.

So, a cylindrical heat source, for example, is a very simple extension to the Gaussian heat source; you could see that the first part of the function in the exponential is looking exactly like a Gaussian. And there is a multiplicative factor which depends upon the thickness; so z is the height from the sample surface, and h is the thickness of the entire vapor column. So as you go from the top surface to the bottom, you can see that the thickness is being used to tell you that there is a heat source that is available even in the thickness direction.

You can see that the heat source is no longer x, y function, but it is a x, y, z function. So how does that cylindrical heat source look like I am showing them at three different heights; and you can see that at the very top surface, it is a bit wider; and at the bottom, it is a bit narrower. And as you go down, it is actually having the same peak value roughly, but the width is decreased. And the plot here also shows you from the top surface to the bottom surface, how the width of the heat source is changing. So cylindrical heat source can reproduce the keyhole shape mode of fusion zone evolution and people have used it to simplify the heat source distribution.

However, this may not reproduce entire keyhole mode in all the welding processes and that is why people have gone for other heat source models as well, so we look some of them now.

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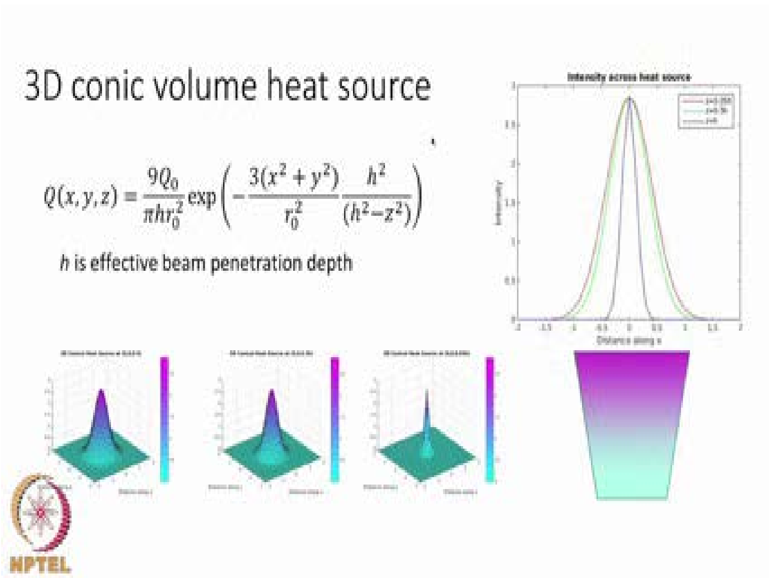

A 3D conic volume heat source has been shown to be quite good in reproducing the shapes; and here I am showing you that the conic heat source is essentially the Gaussian heat function multiplied by a factor, which is not just a simple ratio, but a square function. So you can see that when you go from the top to the bottom of the keyhole, you can see that the intensity variation is much, much larger than in cylindrical heat source.

A conical heat source that way a lowers the amount of heat distribution variation at the bottom of the sample compared to at the top. So the conical shape is shown here, shows you how the volumetric heat distribution is done; at the top, it is wider; and at the bottom, it is narrower. So, such a function actually can be used to capture how the keyhole mode welding will be done to show you the heat transfer difference between the top and the bottom due to the heat source.

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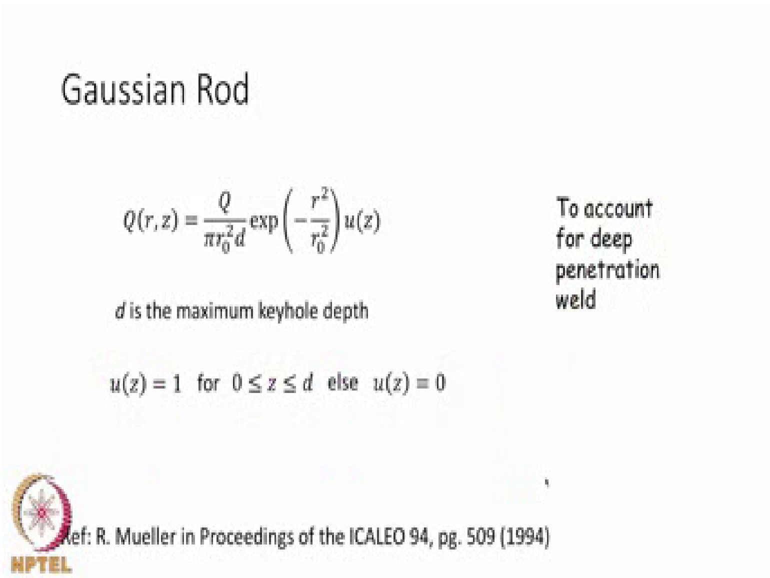

A Gaussian rod also can be used in other words basically a Gaussian function multiplied by a z function; so, such a function also can be used it is a very, very simple kind of a function where the heat source is centered at 0, and then multiply a function u of z. And then that value can be chosen from going from 1 to 0; and it is just a rod which means that it is a perfect cylinder; and that also can be used to model the heat source which is volumetric in nature.

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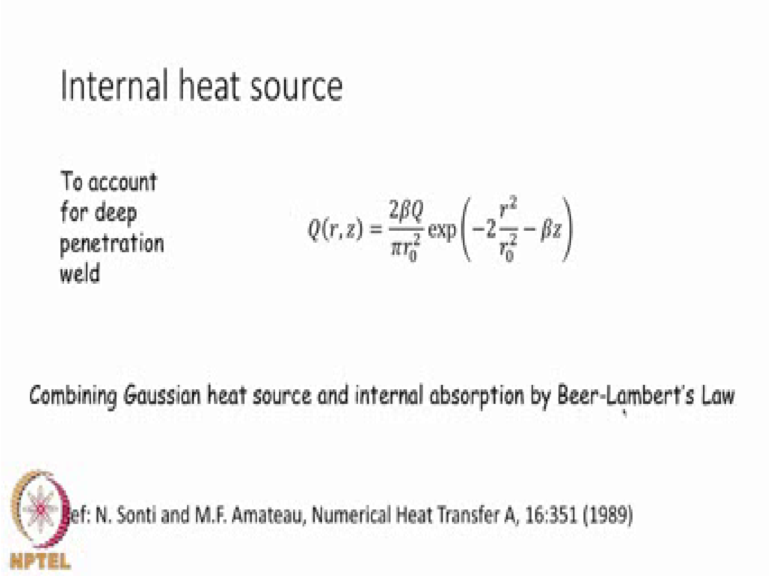

One can also use the fact that for laser welding particularly, the absorption of the laser by the material depends upon the thickness through which the laser is supposed to pass through. And as you know for solids and liquids, the density of the material being very high, the absorptivity is also very high, and the attenuation distance is very, very small. So in very often, it is in just microns. Whereas, in the vapor column the absorptivity is not that small and because of the lower density of the material, and very often you have Beer-Lambert's law that is applicable, so that we can see how the laser light is absorbed as it goes through the vapor column.

And that can be then merged along with the Gaussian heat source to combine to get what is called as the internal volumetric heat source for deep penetration welding in a laser keyhole mode welding. And this is shown here as an illustration, you can see the Gaussian component and the Beer-Lambert's law irrespective of minus beta z, and beta is the absorption coefficient which is shown here which is also coming out. And this kind of a function can be used to capture the keyhole mode welding in lasers. And the reference at the bottom, it shows you one implementation in the recent open literature that uses this particular kind of a heat source.

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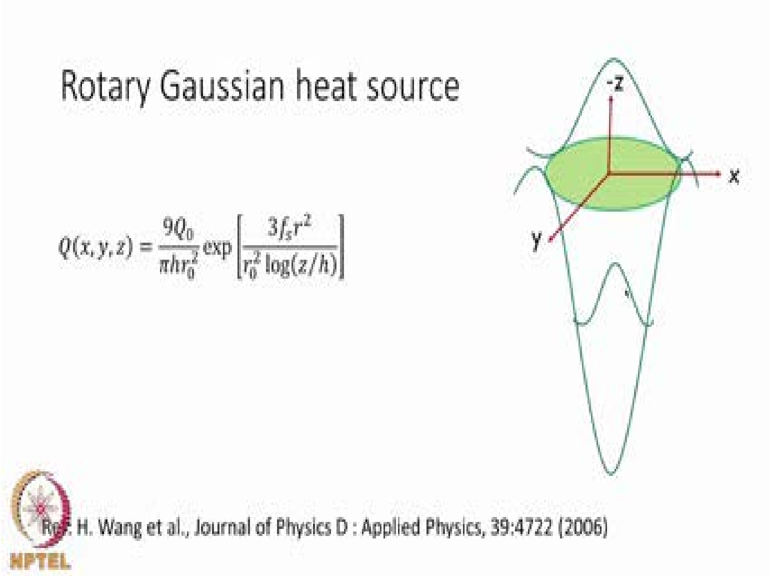

One can also use what is called as a rotary Gaussian heat source that is basically a heat source that looks quite similar to a conical heat source; however, it is not a function that is going as 1 plus z by h or h square minus z square, but it is actually 1 by log of z by h.

And which basically changes the way, the heat absorption is changing from the top to the bottom of the keyhole, and that function is shown here for illustration. You can see that the rest of it actually is looking like Gaussian, and there is a fatigue parameter f s, which shows you to control how fast or how slow this attenuation of the energy change from the bottom to the top can take place it. So by using more parameters in the heat source, you could actually fit the heat source to the reality as close as possible.

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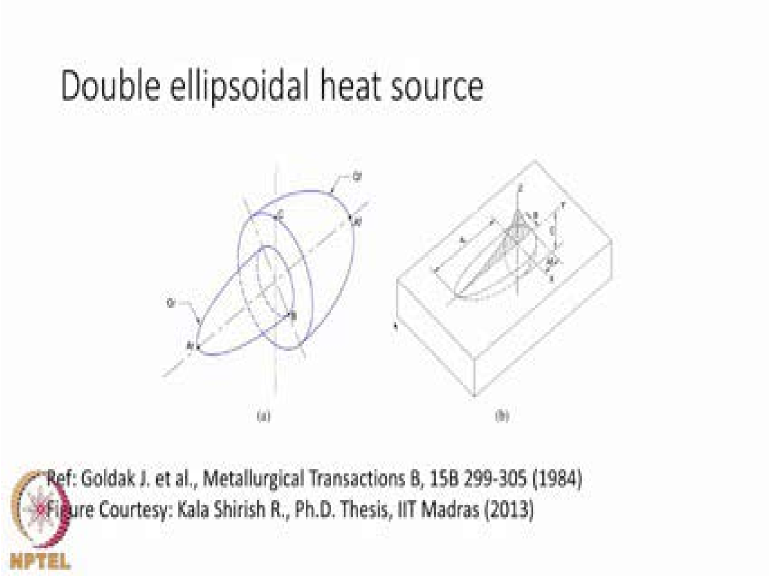

And the most popular among the heat sources that are used by the commercial welding software is the so called double ellipsoidal heat source. So, essentially we have got two ellipsoids and half of both will be taken together and then we have a double ellipsoidal heat source. And this has been one of the very highly sited publications in the welding literature almost more than 950 times by Goldak. et al., and the heat source also goes by after his name, it is also called as Goldak double ellipsoidal heat source.

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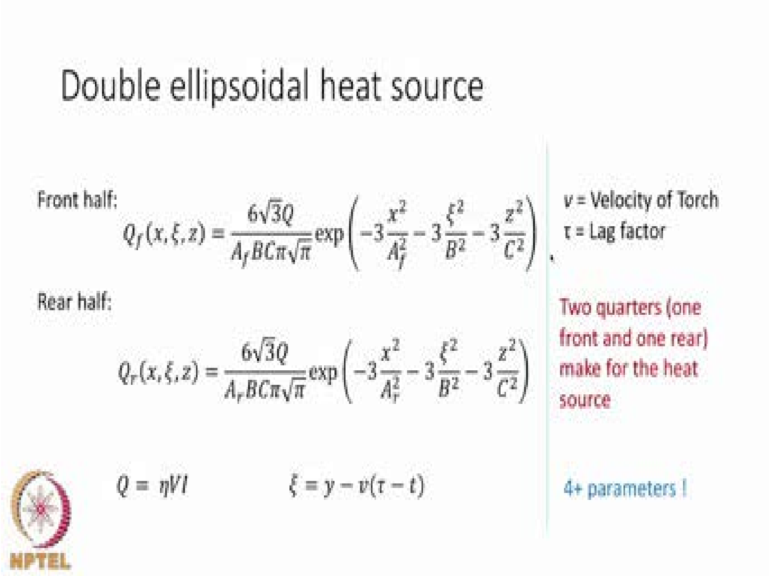

So how does it look like, it looks like this, you have ellipsoidal function of that is indicated by this three squares that are added. And then the minus sign to show you that the heat source is going to be attenuated as you go away from the center; and then you have these coefficients that will tell you which are different from each other showing you that it will be ellipsoidal in nature.

So, you have what basically four coefficients A f, A r, B and C that will tell you, how to change the shape of this heat source depending upon the actual welding process that you are doing. And you would normally choose A r and A f that is the shape of the heat source in the front and the rear directions to be different, because of what is called as a weld pool trailing effect. As the weld source is moving then the weld pool tends to get trailed and which means that it is the going to the look like a tear dropped shape on the location behind the center of the weld pool, the distance is far away to the fusion line compared to a head of the center of the fusion zone.

And in materials that have high thermal conductivity such as aluminum the trailing effect is not so significant so which means that a f and A r can be chosen to be different from each other when the material has low thermal conductivity; and similar to each other when the material has high thermal conductivity. And B and C can be chosen by looking at how the actual welding process is done and Q r and Q f are the heat sources in the forward and rear directions. And whether they are 50-50 or they are going to have a proportion that will be different in the front and rare half is also a choice that is to be done by taking feedback from the simulations to see whether this kind of a heat source is replicating the heat transfer profile correctly or not.

The Q value, which is in front of the exponential shows you the nominal heat input that is given V I - voltage and current, and then eta which is the efficiency of the heat transfer. And the three distances are not given as x, y, z, but in terms of y we have got another variable here which is modified with the time; and v is the velocity, and t is the time, which shows you that this heat source is written in a way that it is moving with time.

And there is a value here tau which can tell you whether there is a lag factor that can be used while using this kind of a heat source. So as you can see that there are large number of parameters that are available in a double ellipsoidal heat source which means that perhaps it can fit most of the welding heat sources with the exception of the keyhole mode welding, and then it can actually match the weld pool shape quite accurately. However, how do we go about varying these four coefficients to fit the heat source is a different exercise, which we will discuss at a later point of time.

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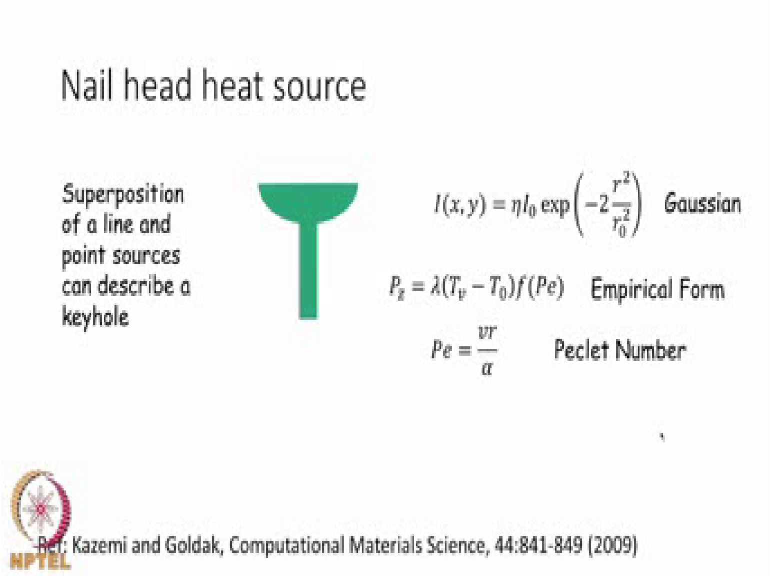

There is also what is called as a nail head heat source. This is actually inspired by the shape of the keyhole itself. The top of the keyhole is going to be looking like a conduction mode and there the Gaussian heat source is applied, and the rest of the keyhole is going to be almost cylindrical in shape, and then there we can apply an empirical form that depends upon the vaporization temperature and the ambient temperature of the material.

And one can fit these profiles that are going to give you the power distribution in the key hole, and use a combination of the Gaussian and the power distribution to achieve a heat source that looks like a nail head. And such a nail head heat source also seems to reproduce the keyhole shape quite accurately and the number of fitting parameters is not much accepts for the empirical form, and so one could also use this in the software to simulate the keyhole mode welding.

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Summary of heat sources

Profile	Number of parameters	Comments
Gaussian	1	Radius
Cylindrical, 3D Conic body Gaussian Rod	2	Radius, Depth
Internal Heat Source	2	Radius, Absorption Coefficient
Rotary Gaussian	3	Radius, Depth, f_s
Double Ellipsoid	4+	A_f, A_r, B, C
Nail head	?	Radius, Pz(Pe)

So, here I am going to summarize now all the heat sources that I have discussed till now. So, on the first column, we have the heat profile; and then the second column, we have got the number of parameters that have to be chosen; and in the third column, we have got the comments. So, the Gaussian profile is the simplest of all, and it has only one parameter which is the radius. And there are other profiles such as the cylindrical heat source, 3D conical body heat source, and Gaussian rod heat source, which have two unknown parameters, which are basically the radius and the depth of penetration of the heat source.

The profile of the penetration of the heat source is already determined by the choice of the heat source; whether it is cylindrical or conical etcetera, only the depth needs to be identified, and there are two unknown parameters for this heat source. And for the internal heat source, the absorption coefficient becomes the fitting parameter apart from the radius. And in the case of rotary Gaussian, we have got an additional fitting parameter, where the radius the depth and the f s parameter that is to be fit to calibrate the heat source.

In the case of double ellipsoid, you have got a number of unknown parameters that have to be identified; it can be four or more depending upon the asymmetry of the heat source that we are choosing. The nail head it is a bit difficult to tell, how many parameters are unknown, the reason being that the empirically made fit for the power absorption as a function of the depth, we will tell you how many parameters are involved. It could be as small as one, in case you choose a linear profile and it can be more than that if you choose a complicated profile.

However, radius also is one of the parameters that have to be identified. So in this summary, we can see that we have an ability to go from a very simple heat source to a very complicated heat source, so that the heat source is matching the experimentally known one as close as possible.

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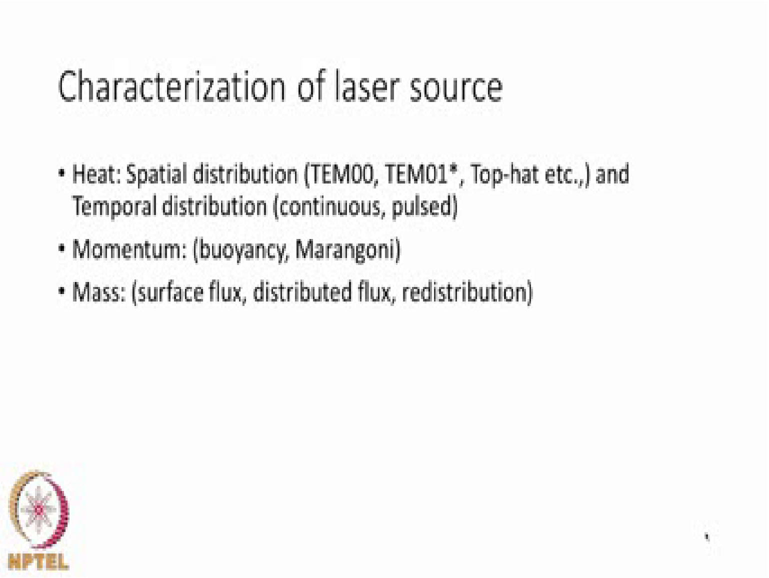

And in the case of lasers we have some more variety of heat sources that are possible. The reason being that unlike the plasma or arc welding setups in a laser source, the light can be then made into a multiple beams and those beams can be then shaped by the lens actions. So, it is possible to have a variety of heat source distributions in laser that are not possible, for example, in arc source. And therefore, I dedicate one or two slides on how laser heat sources can be chosen.

Very often, the laser heat sources are known by a designation that is going by TEM - transfers electromagnetic wave representation, and we have got TEM00, TEM01, top-hat etcetera, all these kinds of names are popular when we read literature in the laser ah welding and laser cladding kind of a topic. The reason why the laser sources are very important is because they affect not only the heat that is given to the body, they also effect, for example, how the fluid flow is going to happen.

So, the how the momentum of the liquid pool is going to be changed through the buoyancy and Marangoni convection also depends upon what kind of a heat source profile you have; and the effect is why are the temperature. And it also affects the mass flow, because the laser is going to melt the filler powder in the path while the powder is reaching from the powder feeder into the base material.

The kind of heat source you have will tell you how much of powder is molten in the path and will get mixed with the liquid melt pool. So, therefore, it is going to affect the fluid flow as well as the mass transfer, and therefore, one must identify the laser heat source description quite accurately. And there are direct measurements that are possible for the experimental facility to know what kind of a heat source distribution you have for a given lens. And, this equipment may not be available all the time, so one must always look up the lenses that are used to know what kind of a laser heat source is emerging out of that.

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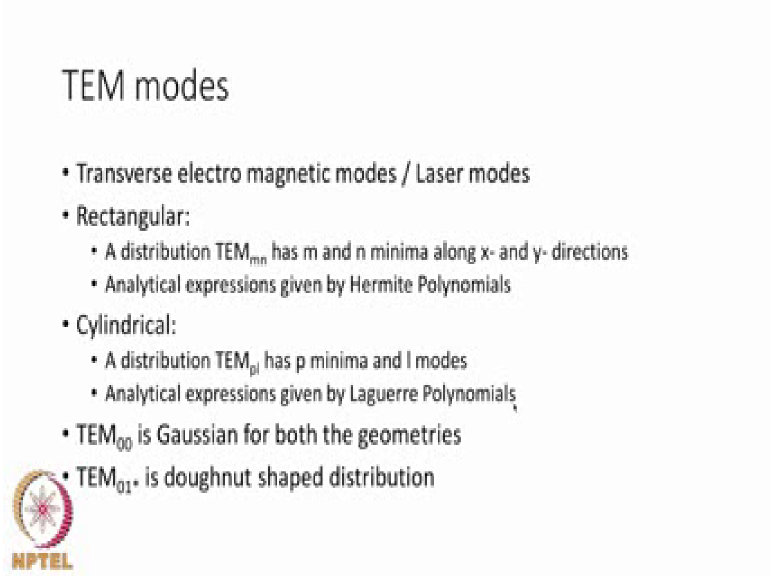

The TEM modes are as follows. You have two ways of describing the TEM modes one is using the rectangular mode; and other is using a cylindrical mode; that is if there is an axis symmetry, you can use a cylindrical mode; and if there is no axis symmetry, then you can use a rectangular mode. And usually you have TEM, and then there are two numbers that are coming after it; and the two numbers are basically the number of minima along the two different directions.

And these can be also modeled analytically by using what are called Hermite polynomials, where m and n go as parameters, so that we have a analytical expression that is available, so that we can produce the heat source distribution that we have for any combination of m and n in both rectangular and cylindrical. And the polynomials that are to be used for the cylindrical heat source are basically Laguerre polynomials, and these also are available in the open literature.

TEM00 is the most common heat source description and that is basically the same as Gaussian. So, we have seen for the arc welding Gaussian is the most popular heat source description; and in the case of lasers, it is a TEM00, which is the mode that is used for cutting and for welding. TEM01 is popular in the case of surfacing applications and that is a doughnut shaped distribution that is also quite popular. There are other modes that may not be popular for welding applications, but I will just show them to you just for the curiosity.

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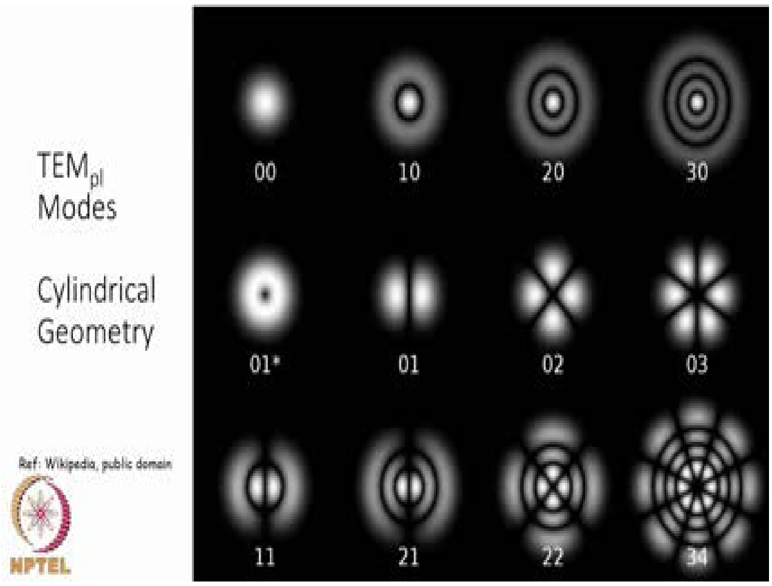

So, here is how the modes are looking like. So, you could see that the way to interpret these images has as follows; where you have a brighter white light, that is where the intensity is high; and where it is dark, the intensity is low. So, you can see that the TEM 0 means that the maximum intensity that the center, and as you go away from the center the intensity is going to 0.

And TEM01, for example, at the center, you have got dark which means that it is a low intensity at the center, but as you go away there will be a toroidal space where you have got the intensity being high. And then much, much farther away, again the intensity goes to 0, so which means that you have got a doughnut shaped heat source that is available in TEM01 mode. And there are other modes that are possible and you can see how these are looking like for different values of p and l.

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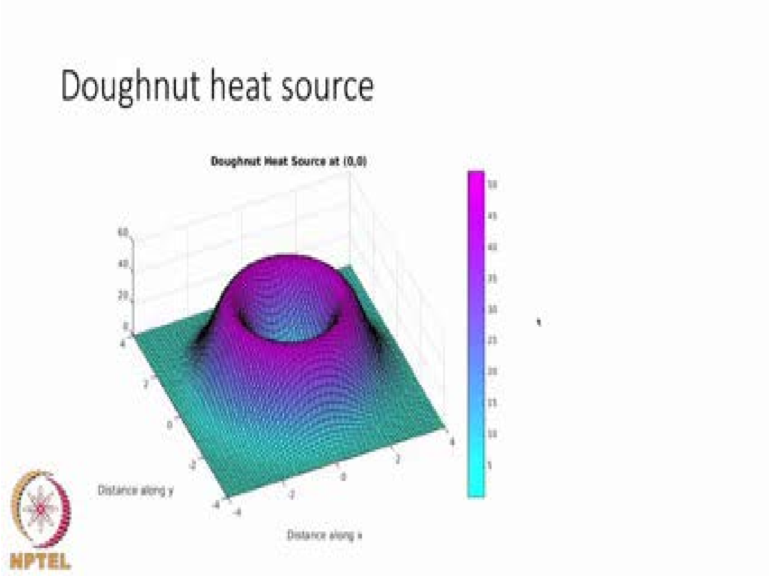

And how does a doughnuts shaped heat source look like, I am just plotting it here to show you. And this is basically of interest, because the maximum heat source is not at the center of the heat source, but is at a ring shaped region that is away. So, which means that the peak temperatures achieved in the heat source, when the heat source is falling on the material is not going to be as high as in a Gaussian mode.

And very often, in a cladding application or surfacing application or surface modification application, you do not want to heat the materials so that it actually melts, so we have a situation where the maximum heat source intensity has to be limited and a doughnut shaped heat source can achieve that and this is how it looks like.

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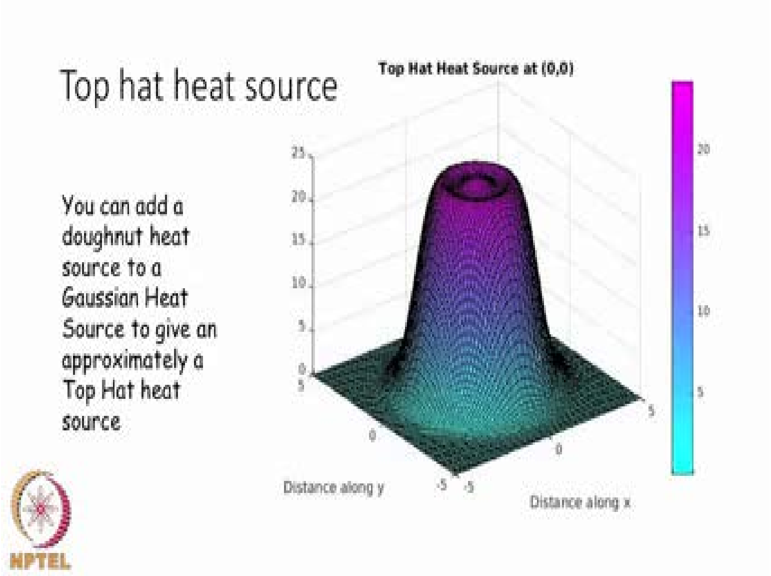

And you can also see that you can combine a doughnut shaped heat source distribution and a Gaussian heat source distribution to see what is called a top hat heat source distribution. Top hat means that there is a circular region where the intensity is almost flat and then out of the circle it almost 0, so it is like a very sharply changing the heat source and this is used, for example, for surface applications. So if you want to model, for example, if the experimentator says that he has used or she has used the top hat heat source then while modeling it, we do not need to construct new functions.

We can just take two functions - one for a top hat, and another for Gaussian, and then add them to proportionality to achieve this kind of a heat source. So we have seen how to add the heat sources earlier for leading heat source and trailing heat sink, but they can also be merged at the same origin location to get different shapes.

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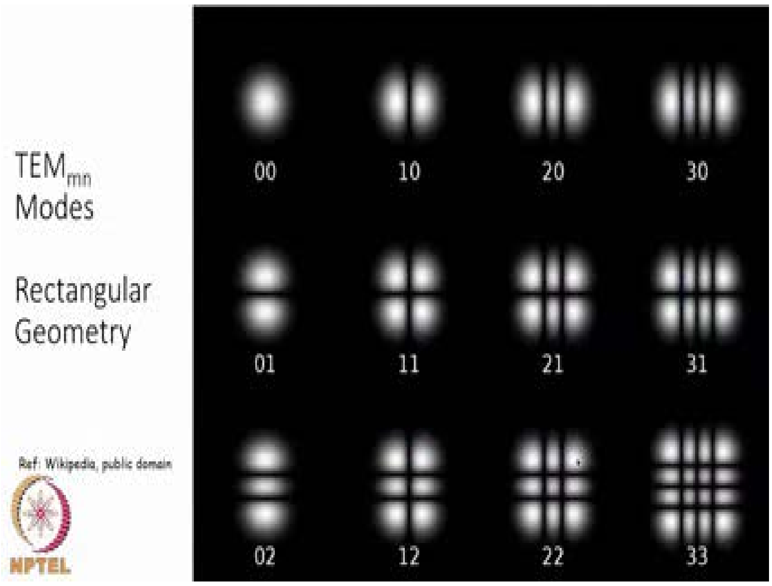

And the rectangular geometry, the modes are shown here; and you can see that the doughnut shape is not there, but then you can see that there are various loops that are possible. And these loops are not directly relevant for welding applications, but just for curiosity, how do they look like I am showing it to here.

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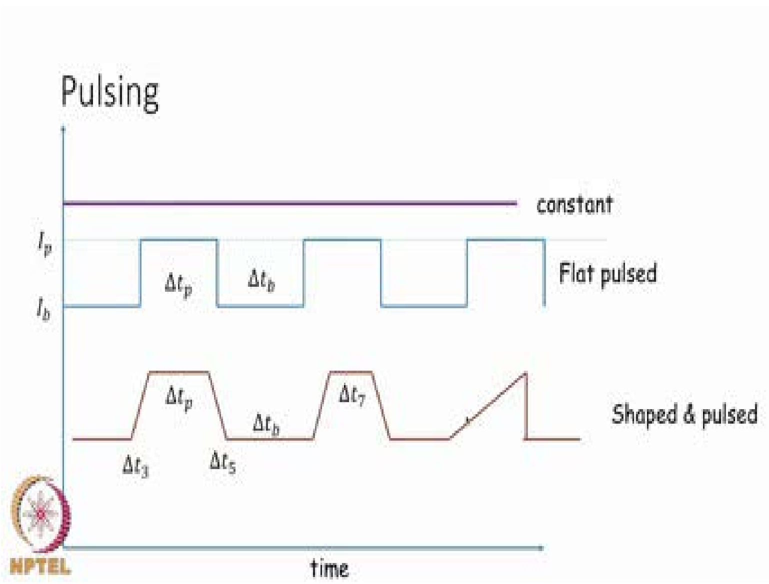

Apart from this spatial distribution for laser electron beam and for the arc welding, it is also possible that you have a pulsing effect that is possible as a function of time. So, when you do not have any variation in the heat source that is coming from the weld supply or the power supply then you have what is called as a constant power source which is constant with time, but you may have also a possibility to go towards what is called a pulsed heat source. So, what it implies is that you may have the variation of the heat source from a low value to a high value for two different amounts of time. And the pulse frequency will tell you how many times we change as a function of time.

So you can see that I am indicating in the axis here for the intensity of the heat source I b as in the base value and I p as in the peak value. So we go from the base value to the peak value, and again back to the base value after regular amount of time. And then delta t p will tell you how much is spent at the peak value, and delta t b tells you how much time is spent at the base value. So, these two times are required so that you can calculate what would be the frequency of this pulsing.

And the heat source in description should include this information; because the way a pulsed heat source is going to affect the weld pool is going to be a very different from a constant heat source. Particularly, it affects the convection that is happening inside the weld pool and then the solo distribution and then the microstructure therefore, though the thermal processes may be approximated by an average value, but the fact that there was a pulsing should be captured and then used in the modeling effect.

The way the intensity is changed from the base to the peak value can also have an effect; in the case of lasers, it is very common to have what is called as a short-tooth kind of a heat source. And you can see that you can take delta t 3 amount of time to go from the base value to the peak value, and then again from the peak to the base, you can take a different amount of time delta t 4. So these details on how much time is spent at the base value, how much time is spent to go ramp up to the peak value, and then again how much time is spent at the peak value, and then how much time is spent to ramp down to the base value as a cyclic manner. And then how many cycles, we have in one second, so this information should be known.

So, in other words, if there is a known fact of pulsing in the weld heat source, then we must know what is a pulse frequency, what is a pulse shape, and what is a way that the pulse shape is then mixed and matched with different ones to arrive at the total distribution as a function of time.

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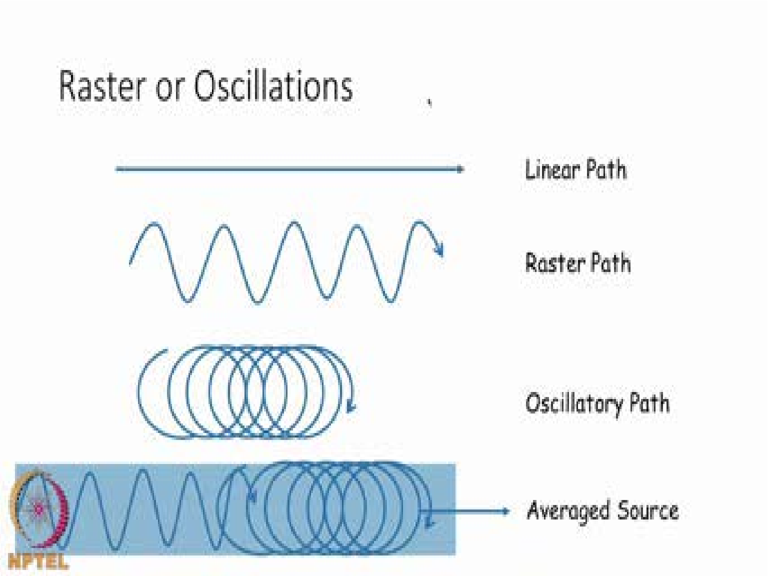

And the path that is taken by the heat source as it moves along is also important. In the case of most of the welds, the path is actually linear, so which means that it is very simple and you can programme it with just one variable velocity and with that we know the path. And sometimes, it is possible that the weld heat source may be taking a raster path it may be going back and forth between two different positions. And this kind of a rastering is used for example, for surface applications, surfacing applications using laser or to do weld overlay etcetera.

And the raster path will have as you can see a wavelength of the distance and also the frequency at which it is changing from left to right etcetera, so the raster path information must be known to be able to capture the path of the heat source accurately. It is also possible, for example, in a very fine beam that can be controlled by lenses such as electron beam welding an oscillatory path can also be taken. So, in the case of an electron beam, you can actually deflect the electron beam with very high precision and accuracy. And you could actually achieve an oscillatory path so that you may have for example, a top hat kind of a heat source that is achieved effectively, but then with a narrow beam that is being made to go in oscillatory path.

And it also enhances the connection between the weld pools and mixes the weld pool, and then avoids micro segregation and other things. So there are situations where you may want to actually capture that information. And one can average all these paths to have an average value that can be used. However, the fact that there was a raster path an oscillatory path with certain kind of a frequency and wavelength should be known, so that that information can be used to analyze effects that are caused by these kinds of changes in the heat source.

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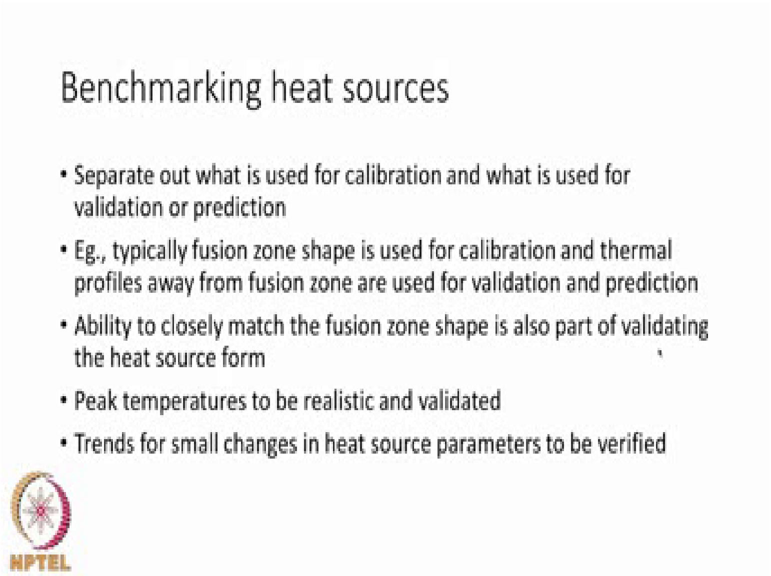

And these heat sources must be always bench marked. So we must know actually whether these heat sources are been calibrated; and we must know what information is being used for the calibration, and what information is used for the validation. And we may not do the same information for both, because then there is no purpose in actually doing the modeling.

So typically, for example, what is done is the fusion zone shape is used for calibration and then the thermal profiles away from the fusion zone are used for validation and prediction. And you must then not claim to have reproduced the fusion shape, because fusion zone shape itself was input to calibrate. So it is very important to delineate what parameters are used for calibration, and what are used for the validation. And we must be able to validate to know that the heat source we have chosen is an accurate one and a reasonable one. And closely matching the fusion zone using a particular heat source function is also a confirmation that the heat source is reasonable.

The reason is as follows; you could not for example, match a keyhole shape mode profile using a Gaussian heat source which means that it is not an appropriate heat source for keyhole melt welding. So you may change the radius; however, you may not match the shape. So, like that, you must also look at the fact that you could match a shape for calibration itself is a indication that that particular heat source is actually reasonable. And when you do these fittings, you may also see that the peak temperatures are sometimes unrealistic, and sometimes realistic. So we must also keep an eye on what are the peak temperatures that are calculated using modeling using these kinds of a heat sources, whether they are reasonable and whether the experimental evidences support such values have come out or not.

And then when we make small changes in the parameters for the heat source, then how does a weld thermal profile change, so that is also a trend that must be observed to know whether the heat source has been chosen correctly. And how many heat source parameters are there will also limit the ability of the scientist to change and then verify. So if you choose a double ellipsoid heat source model then there are so many parameters that you may not be able to make a rigorous systematic change of all the parameters to know the sensitivity. But for example, for a Gaussian it is very trivial to see whether the changes are realistic or not, and to capture the trend being correct or not.

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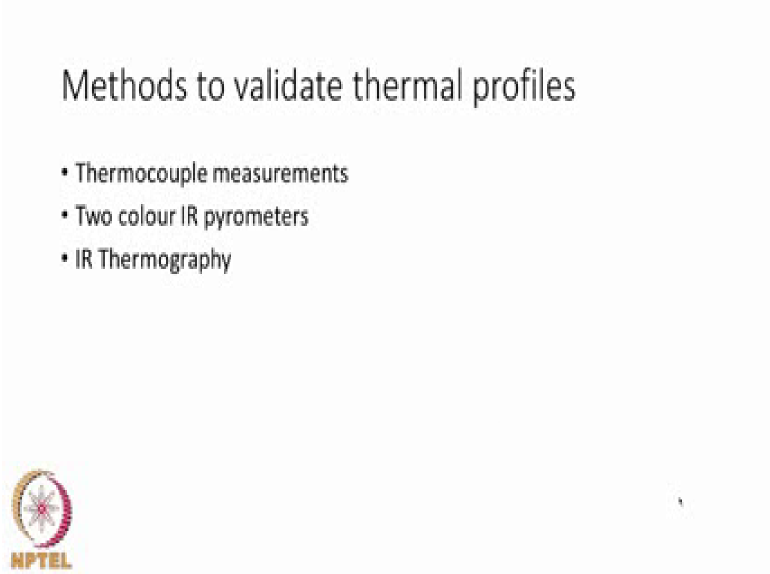

And what are the ways to validate the thermal profiles; there are three different ways. The first and the simpler one is thermocouple measurement; and then the two color IR pyrometer that is infrared pyrometers; and then infrared thermography. So these are the methods that are readily available today to validate the thermal profiles.

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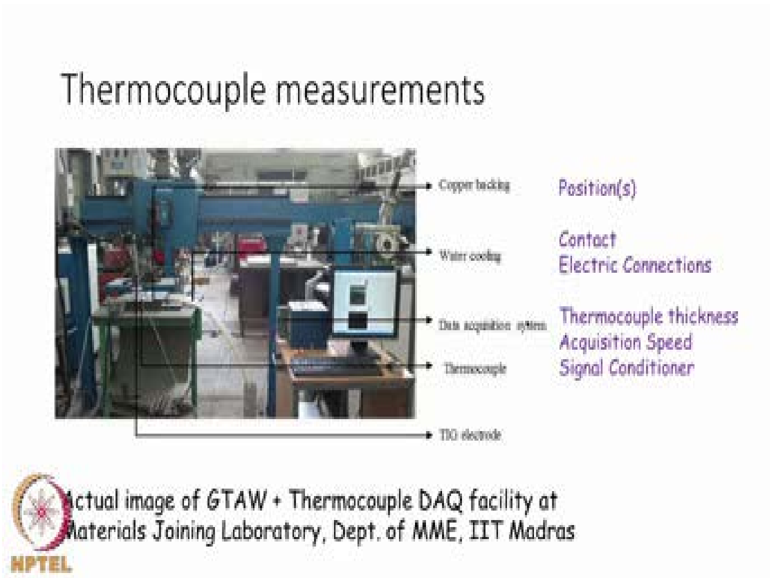

And the thermocouple measurement validation is shown here using a welding setup that is in our lab in the materials joining laboratory Department of MME, IIT Madras. And the facility shows you a GTAW welding setup along with data acquisition facility. And you could see that in the facility you have got a monitor, where the weld thermal profile is being recorded; and behind the monitor you see a box, which is basically signal conditioner that enhances the accuracy with which we are measuring the thermocouple signals. So, you know the thermocouple signal is going to be in milli-volts and to be able to measure that at very high rate, for example, in several hundred samples per second then you need to ensure that the signal conditioner is going to play a role there.

And therefore, the design of the thermocouple data acquisition setup is important and that can be used with multiple thermocouples, so that you can get the thermal profile measurements at given locations. So, it is important to note down where are the positions where the thermocouple is placed, and then whether they are also not too closely spaced, so that they may disturb the thermal field itself. But again they are not too far away placed, so that they are also being useful for the thermal profile measurement.

And the contact between the thermocouple and the sample must be always intact during the welding, because if the contact is lost then you do have a signal loss. And then whether the electrical connections are provided properly, because if the earthing or the neutral is not correct then you may have situation where the measurement of the thermocouple reading may be erroneous. And you must also pay attention to the thickness of the thermocouple wires, the finer the wire the better it is for you, because the signal is going to be stabilized quite quickly for very, very thin thermocouples.

And the acquisition speed at which you are going to measure depends upon how thin the wires are. And usually for welding, if you are able to acquire at 100 samples per second or more then that would be adequate for you to capture the complete profile by taking into account the various slope changes during the heating and cooling cycles.

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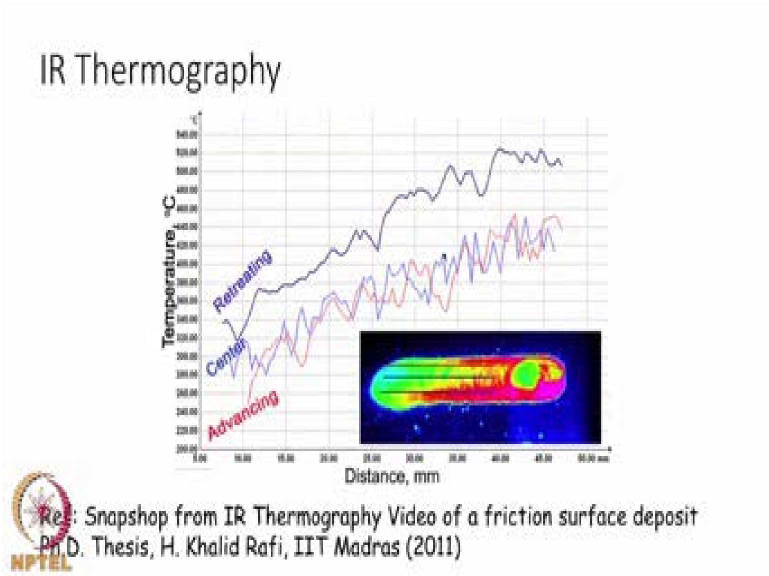

A thermography using IR cameras is expensive way of doing measurements, but it also provides a lot of information in just one single run. So, in this schematic plot, we are actually showing you a snapshot from the IR thermography done on a friction surface deposit which is a weld overlay kind of a technique, and the work is taken from the Ph.D. thesis of ah Dr. Khalid Rafi from IIT Madras, 2011.

And once you have a snapshot or a video then you can actually look at the history of the temperature of a particular location, and then plot it as a function of distance or as a distance as a function of time. So, in other words, one should take one video then you have a plethora of information that is available from the thermography; and you could then use it to benchmark your thermal profiles that are calculated using the heat sources that you have modeled. So, it is important to choose the thermocouple and thermography, so that it can be validated against your thermal modeling and whether your heat source choice has been correct or not.

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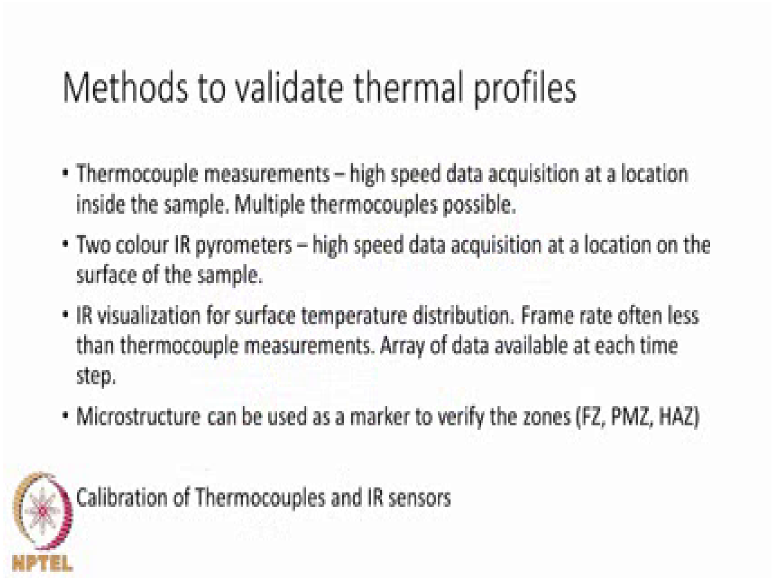

So, we now summarize the various methods of calibrating and validating the thermal profiles that we have obtained by choosing the heat source distribution. So, the heat distributions must be validated and we have looked at how thermocouples and IR visualization setups can be used. In the case of thermocouple measurements, we must take precaution that when we are taking the data at high speed then the thermocouple wire thickness must be low, so that it can be acquiring the data at a high speed without any loss of information.

Multiple thermocouples are possible up to 16 very easily we can make; however, each thermocouple requires you to drill a hole in the sample and each such hole will be disturbing the thermal field around the fusion zone, which means that we must draw a line between the accuracy of the measurement and the number of points at which we want to measure by choosing an appropriate number of thermocouples for the measurement

In the case of the IR pyrometer, because only one point can be used for measurement using one pyrometer, and each pyrometer is quite expensive, they are not very popular in validating exercises. And in the case of IR visualization videos that can be made then frame rate is increasing with technology advancing now; however, it is still less than what thermocouples can be providing. And when crucial information is that the IR thermography is only if a surface information whereas the thermocouple measurement can be giving you information from inside the sample at a depth from the surface. And thermography can give you array of data, which can be available or in each time step which means that we can reconstruct the history of a thermal profile of a location and also validate what would be comparable with the thermocouple.

And we can also use microstructure as a marker to know whether these zones namely, the fusion zone, partially melted zone and heat affected zone are having widths that are validated against the thermal profile that has been calculated. And the choice of heat source is accurate only when these kinds of zones are also a reproduced accurately. And it is also important that when we are validating the thermal profiles with thermocouples or IR sensors we must also keep in mind that thermocouples and IR sensors also need calibration themselves against standard samples; and without calibration, the temperatures reported by these two experimental facilities could also be erroneous.

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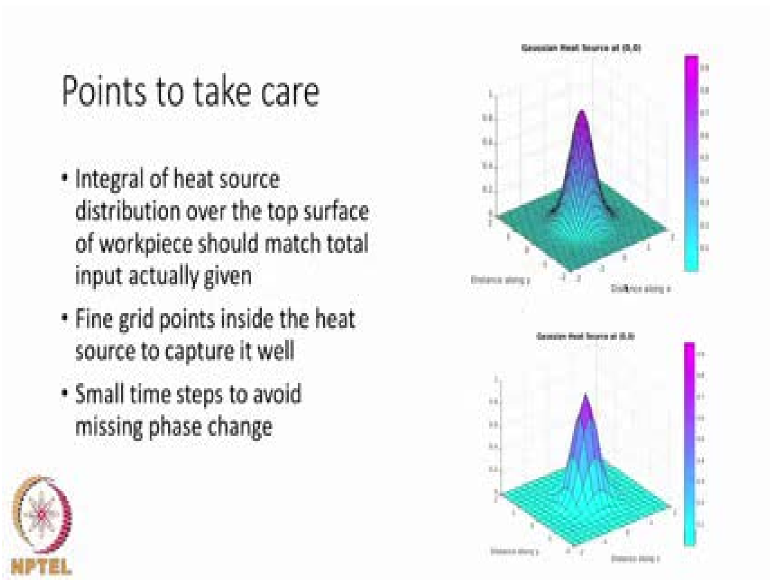

So, before we wind up, I will just give you couple of points to pay attention to; one important information is that, when we choose the heat source distribution and then we want to use it to calculate temperature profile at different locations on the surface of a weldment. Then we must know that the integral of the thermal profile distribution that is when we sum up the amount of heat source that is dumped at each location, in each square millimeter of area and then add it up in all the area of surface then we must get the same amount of heat that is being given by the heat source.

So we must not have a distribution which is not calibrated against this kind of an integral, because then again we are making a mistake in the amount of heat source. And the number of locations where we are want to estimate the heat source distribution in a model that also must be high finer grid points must be kept, so that we can actually capture the entire variation of the heat source.

If you have very small number of grid points then the variation is not captured completely and that is evident from the plot below. You can see that the plot above has lot of grid points capturing the smooth variation of the heat source in a Gaussian, and the plot below actually is looking quite faceted, the reason being the number of grid points is very small. So, it has one information that must be kept in mind, because later on when we use this information to calculate thermal profiles, we may get erroneous information when the number of grid points within the weld zone is not adequate.

And we also must ensure later on that the time steps also must be small to do any calculation, because no location on the surface should miss the phase change that will account for some of the heat. So the heat source is important in the choice to model the thermal profile and it also affects the results that you get out of them. So adequate information is available in this lesson, and we must then use this to choose the heat source distribution appropriately.

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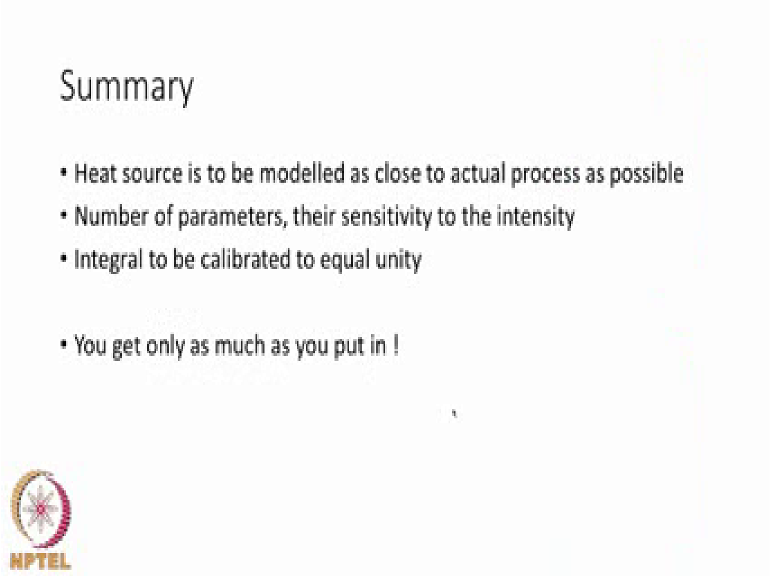

So, I would then now summarize by saying that the heat source is to be modeled as close to the actual process as possible. And there are maybe a number of parameters, we must know their sensitivity to the intensity distribution; we must have a way to calibrate each of those parameters. And then we must also ensure that the integral of the entire heat source distribution must be calibrated to equal unity, so that we get as much of heat that is dropped on the surface as that is drawn from the weld heat source. And at the end, we must only expect to get out only as much as we put; in other words, the simpler the heat source the less variation in the output that we may expect. The more complicated the heat source the more variety of results we may able to match.

With that, we close the lesson on heat sources and we will continue with thermal modeling from where we left off.