Analysis and Modeling of Welding
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Lecture - 03
Heat sources - part 1

Hello, welcome to the second lecture in the online course on Analysis and Modeling of Welding. This lesson is titled Heat sources.

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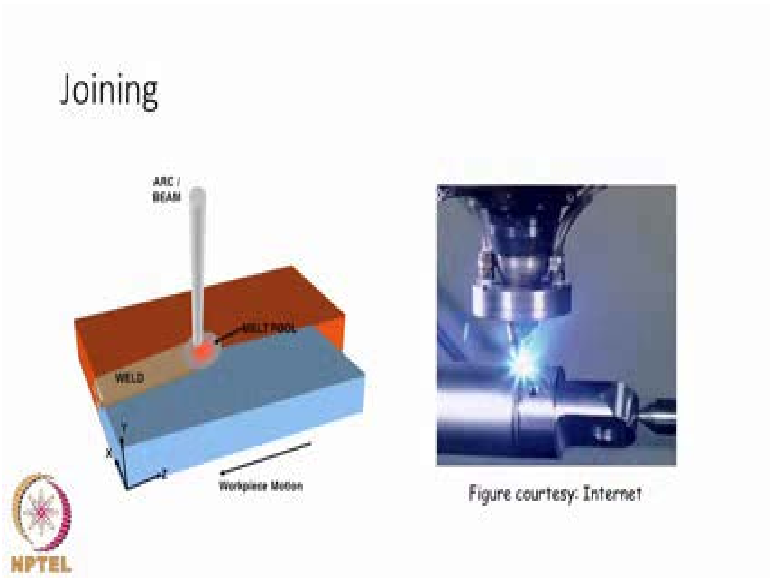

The heat sources that we have going to discuss will be applicable for both joining and cladding. In the case of joining we are seeing in the schematic to base materials are being joined and then you can see the arc or beam which is the heat source that is giving the heat to the joint between the two pieces and then as the heat source moves or the base material moves in the opposite direction, we have a bead that is made and we have labeled it as weld in the schematic.

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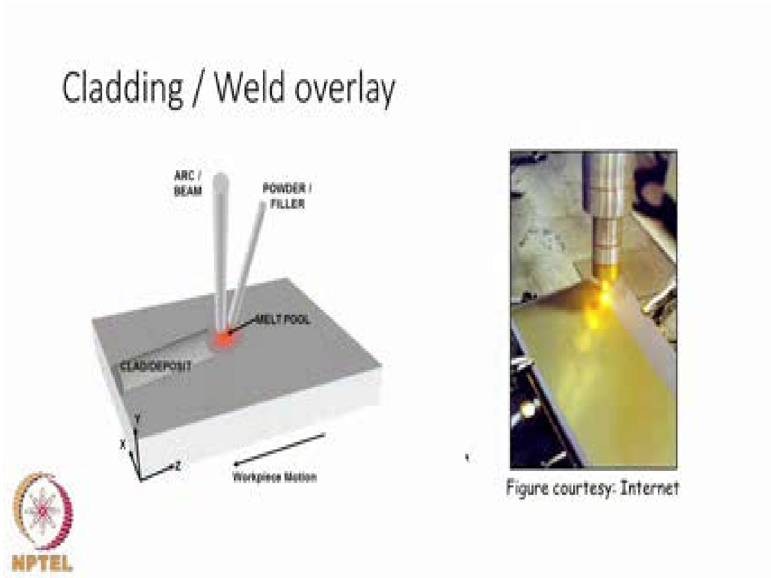

And in the case of cladding or weld overlay a very similar process is taking place except for that there are no two different pieces that are being joined, but only a material is being deposited as a track on surface of a base material.

So, we do have again the arc or the beam that is giving the heat source and then in the base material the heat is actually falling on a location and then as a beam moves forward or the base material is moving backwards, we have the melting of the powder or the filler material which can be given in the form of a wire for example, and then a deposit is made as a track and then these tracks can be overlay on the base material side by side so that we can make an entire layer coverage on the surface of the work piece. So, both the joining and cladding processes use heat sources and we are now going to go in depth on how these heat sources can be modeled and analyzed.

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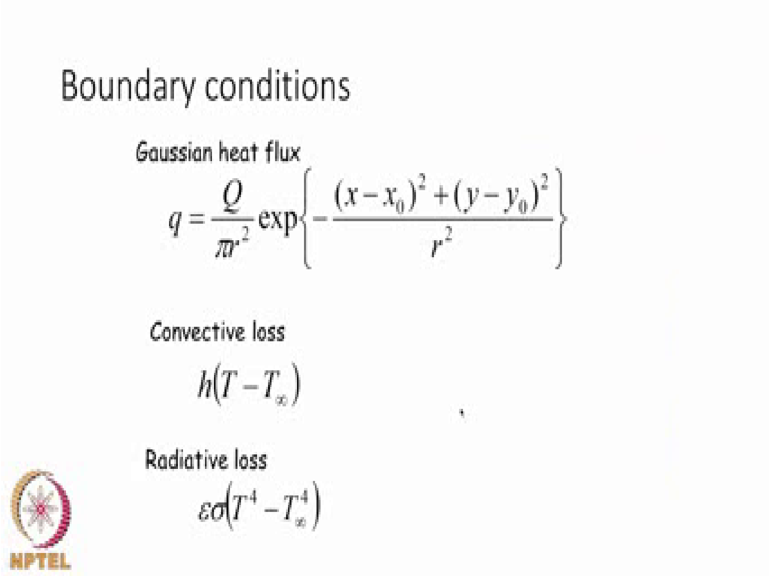

So, very often when we read a general article which looks at the analysis of joining and welding, we look at boundary conditions which they have used to understand how the heat transfer has been modeled. So, usually we have the heat source boundary condition, the heat loss boundary conditions and we normally encounter a Gaussian heat flux as an input condition for heat on the surface and then we have convective losses being taken care by use of a heat transfer coefficient edge and then the radiative losses are also taken care, some of these may be extended with different terms or different sides of the material that is being joined or clade.

It is important for us to ensure that these conditions are understood very well before we apply to a situation in industry and therefore, we are going to go in depth one after other. So, in this particular lesson we are going to look at the first aspect namely the heat flux to show that Gaussian is while being most popular is also not adequate for many of the situations that we encounter in real life industrial scenario.

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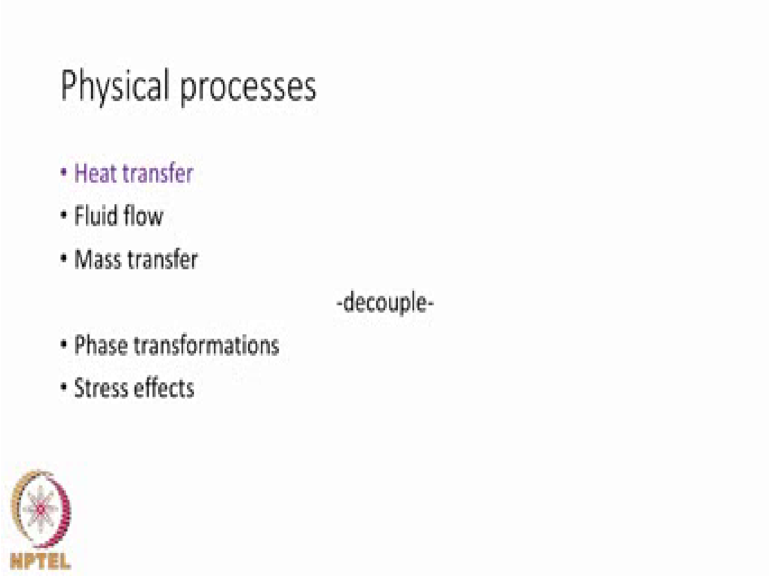

The physical processes that take place during welding I have listed here they are like heat transfer, fluid flow, and mass transfer and so on and then during welding, the materiel usually undergoes phase transformations and then there are also effects due to stress. So, it is very important for us to understand that all this processes are taking place simultaneously; however, it is difficult to solve a problem with taking all these processes simultaneously into account.

So, what we normally do is to decouple these processes in other words we understand each of these analyze and then we will see how the information from one effect can be taken as an input to the other effect and then sometimes the loop can be closed completely and then we can proceed to have the solution of the particular welding problem we are looking at.

So, in this particular lesson we are going to looking at the heat transfer alone and while it is being affected by the rest of the things, we are not going to look at them at this point.

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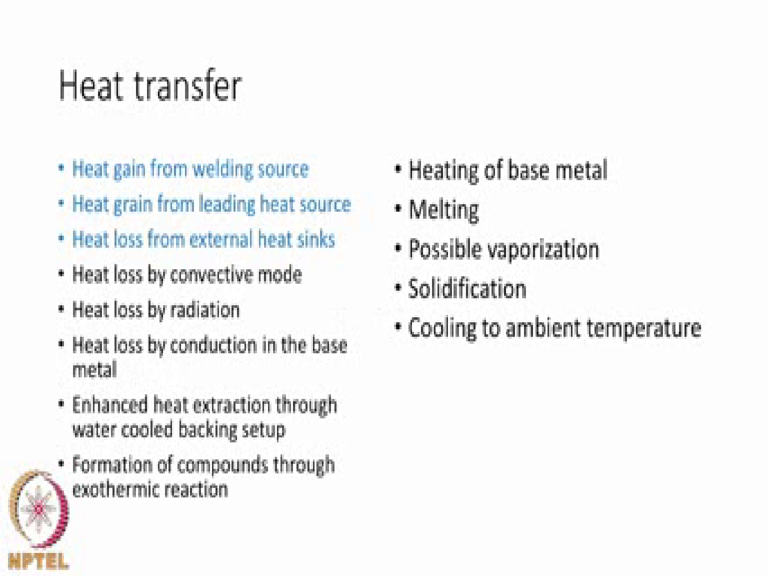

So, the heat transfer when we look at; it is a very extensively understood process; however, we are going to limit the scope for this lesson as follows. Heat transfer to a weld will be basically from a heat source from the welding source and then we also have additional heat source sometimes with a leading heat source that is, in front of the welding torch we may have another torch which gives a preheating locally which can be for example, in tandem we also have what is called a tandem welding where we have two torches that are doing the process simultaneously and we also have situations like high bread welding where there may be a for example, arc welding and laser welding simultaneously being done on a sample one torch behind the other beam etcetera.

So, you also have situations like external heats sinks to remove the heat so that the thermal distortion can be controlled. So, you could actually look up the source and sink as just two aspects of a focused and localized heat transfer either positive or negative in sign and I have given in blue the three which we will be covering in this lesson as a one module under heat sources.

The rest of the things that happen for example, heat loss by convection mode, by radiation or by conduction to the base material and extensive heat loss through the water cooled back up setup etcetera these are going to be looked at in the thermal modeling lesson later on and we also have situation where there will be heat released in the weld pool because of exothermic reactions that could take place when there is a powder that is being fed into the liquid melt so that it can form some special layers on surface so such situations are also not considered in this lesson.

And during heating what normally happens is, we have the heating of the base material and then eventually the melting point will be reached and then we have the melting of the material forming the liquid melt pool, and then sometimes the temperatures could be reaching high enough that locally evaporation can also take place and then eventually when the torch moves ahead then the liquid melt will solidify to form the solid material behind the torch and then eventually that gets cooled to the ambient temperature. So, this is a cycle where the heat is given so that the material is heated up and then is cooled back to the ambient temperature and these are dependent on the heat source very crucially and therefore, understanding the heat source in depth is important.

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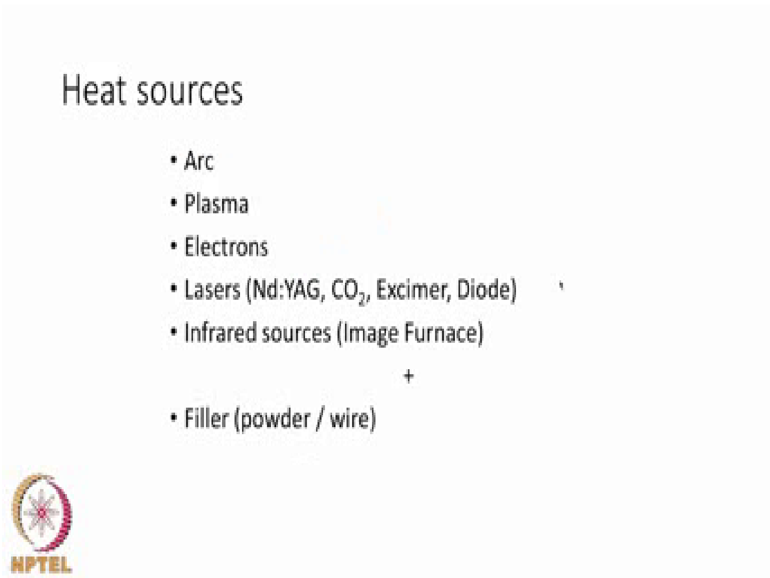

So, the heat sources in welding processes we have already seen a list of welding processes in the previous lesson and we are only going to take out the heat source alone for the purpose of this lesson and the lot of heat sources that we are going to look at. The most important heat source would be arc, electric arc and then we also have plasma as a heat source and electrons are heat source for example, in the case of electron beam welding and then lasers different types of lasers are there which act as a heat source and we have generally observed in industry environment such as Nd YAG laser, carbon dioxide laser, excimer laser etcetera and we have sometimes also infrared sources as heat sources.

We have not looked at infrared source as a welding source; however, we do have the possibility for surface treatment and surface coatings which form as an allied process welding, so infrared sources also form one of the heat sources that we are looking at and sometimes we have the filler which is being added so it can generate heat by exothermic reactions, it can also consume heat because it needs to heat up and melt and then mix with the liquid melt pool. So, you could also choose to have the filler wire or filler powder as a heat source or sink, but in our lesson we are not going to look at that. So, we are going to look at the top five items that I have listed here.

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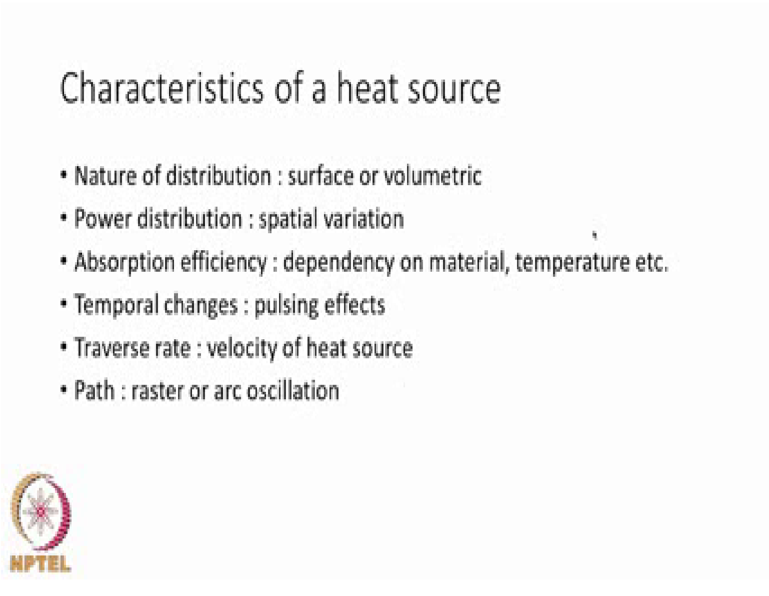

So, what are the various characteristics of heat source that we need to analysis it? So here, I have listed some of those characteristics. So, the nature of distribution that is the spatially how is the heat is distributed on the surface of the base materiel is important and most of the times the heat source will be taken as a surface heat source in other words it is only acting as a boundary condition on the surface of the base materiel that is being joined or molten locally. Sometimes as a situation may warrant in the case of say key hole welding you do have what it is called as a volumetric heat source also possible.

So, it is important to know whether the heat source that we are looking at is a surface heat source or a volumetric heat source and then the power distribution in terms of the spatial variation should be available to us, in other words it should be a function of either x y or x y z as the case may be for surface or volumetric heat source and it is also sometimes possible that the variation may be with respect to the material also. So, there are situations where the absorptions of the heat source on the material depend on the material, the temperature of the material etcetera. So, you may actually have power distribution that may come as a function of many other parameters apart from just being spatially varying.

Sometimes it is also possible that the heat source is changing in time, in other words we may have pulsing effects the lasers are examples are very popular in that sense, you do have a pulsed laser to be used for a welding and surfacing or surface treatment, so where the heat is given in a short pulse and a number of such pulses are given one after other to the material. So, it is important to know for example, what is a pulse width, how much time the pulse is on and then how much time the pulse is off between two pulses and then how many pulses are we giving in a given amount of time per second for example,. So, like that we need to understand the temporal changes; that is the variation of the heat source as a function of time also to understand how the heat source will affect the thermal processes that take place during welding.

But traverse rate is essentially refers to how fast is a heat source moving on the surface of the material that is being welded. So, it is nothing, but the velocity of the heat source because the heating is happening just right under the heat source. So, you would actually look at it as a traverse rate of heat source and sometimes the heat source cannot be moved and it may be the material that will be moved in the opposite direction. So, you may have a situation of the traverse rate being referred to as a heat source motion or the base material motion as a case may be and which way does it move, does it move linearly or does it move in a zigzag manner is also something that is going to play a role.

So, very often the path that is taken by a weld heat source is linear and it can be programmed by a single drive, but there are situations where you may have a rastering action for the heat source by rastering what we mean is moving back and forth to cover a wide area. This is often practiced in situations where, a very wide pool is required; however, the heat source is focused that cannot be extended to that much of a width.

Oscillation also can be coming in reality for example, magnetic arc oscillation is sometimes used to avoid central and cracking and therefore, we may also want to look at the heat source whether it is moving in oscillated manner across the path during the welding process. So, we need to observe all these quantities and then capture them in the model that we are choosing to represent the heat source.

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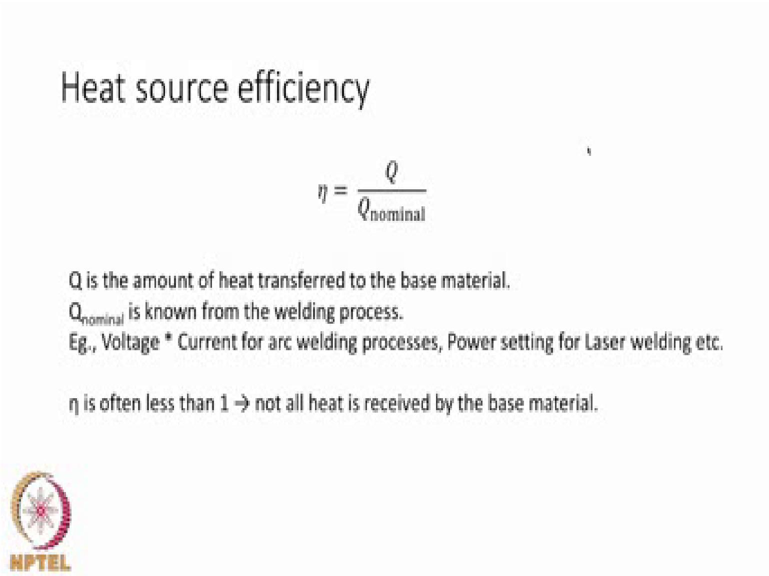

So, we often refer to the efficacy of how the heat source is able to deliver the heat to the material using a parameter called as heat source efficiency. Heat source efficiency is nothing, but a ratio of two quantities on the numerator you have basically the amount of heat that is actually transferred to the base material and the denominator is amount of a heat that is nominally provided by the welding process, so very often the nominally heat is drawn from the socket in the case of electric arc or it is a setting on the laser welding set up etcetera.

And the ratio is very often much less than 1 to indicate that the heat is not completely transferred some of it is lost. So, we have lot of ways to understand why the heat is lost; however, we have to appreciate the fact that, heat source efficiency is very important because it is going to tell you how much of actual heat is transferred and that is what is going to used in the model. The nominal heat is only an indicative factor, but the product of nominal heat and the efficiency is what goes into the modeling effects of understanding the welding.

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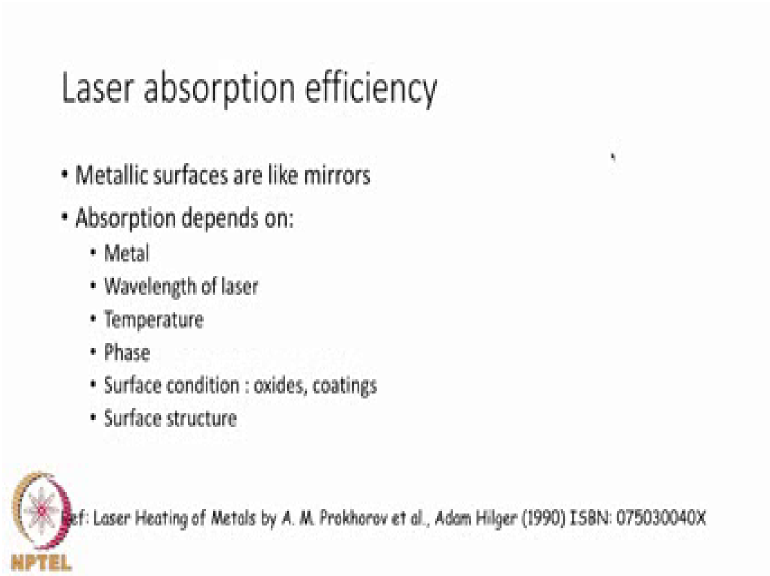

For the lasers the absorption efficiency is going to very very (Refer Time: 13:02) the reasons are as follows. First of all most of the lasers are very inefficient in transfer in the heat to metallic materials, the reason being that metallic surface are like mirrors, they reflect light very easily. So, most of the time at room temperature the kind of metallic materials we have in the industrial alloys that we use like for example, copper based, aluminum based etcetera, the surface absorptivity is less than 3 percent which means that most of the heat is actually reflected back and is not being used for the welding purposes.

So; obviously, we need to take into account that while choosing the process and also and modeling the same and the absorptivity depends upon a number of quantities it depends upon; obviously, the melt, the metallic material that is being molten and being joined. So, there are materials like copper which are acting like a mirror, so they do not absorb much of the laser light and there are materials like for example, steel which absorb slightly better amount of laser light.

The absorptivity is directly proportional to the frequency of the light that is being sent or other words inversely proportional to wave length of the laser which means that between Nd YAG which has a wave length of about 1.06 micro meters it and compared to for example, carbon dioxide which as a wave length of 10.6 micro meter, you can see that the absorptivity with Nd YAG is better than with respect to the c o 2 laser. So, wave length of the laser is also very important, shorter the wave length better is the absorption on the metallic surface.

The temperature of the material also plays a role in absorptivity, as you increase the temperature you expect the laser light to be absorbed more so that by the time we reach the melting point, the absorptivity will come to several percentages and when the temperature rises to the extent that there is a some amount of evaporation that has taken place and then there is a vapour column then the absorption reaches nearly 100 which means that the vapour state of a material absorbs all of the laser heat, where as the liquid absorbs only a few percent and solid will absorb less than 2 percent.

The phase that is the liquid state or vapour state or the solid phase is to be known when we are applying the absorptivity of the laser. In other words laser absorption parameter is going to be a function of either time or temperature as which use to modulate. Surface condition of the material also plays a role in the absorption of laser, so in the case of solid materials the presence of oxides on surface will enhance the absorption and surface coatings also can be given so that we can enhance the absorption. So, very often a thin black coating of graphite layer is put on surface of metallic materials, so that it can enhance the absorption.

Surface structure also can improve the absorption and surface structures can be induced again by lasers or any other manufacturing process and the surface roughness for example, allows for reflection of light locally and then provides more opportunity for the laser light to get absorbed on the surface.

The solid materials while they are being heated, the surface roughness and the surface structure do play a role. However, these are all only binding the materiel in this solid state and as a temperature increases to the liquid state then most of these are gone and then we now see how it is depended on the temperature. And there is a whole book on only one topic that is the laser absorption efficiency and you could, if you like read it in the book title laser heating of metals by Prokhorov and the book is published by Adam Hilger. I would advise you to look at it if you want to know more about how the laser light is absorbed by metallic materials and even in general I would advise you pay attention to the literature from Russian side because they seem to have done a lot of work in welding area.

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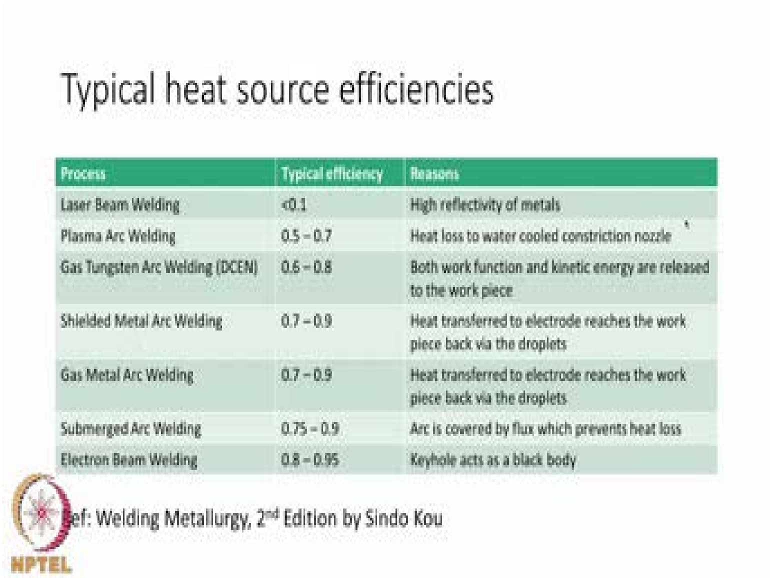

Typical heat source efficiencies

Process	Typical efficiency	Reasons
Laser Beam Welding	<0.1	High reflectivity of metals
Plasma Arc Welding	0.5 – 0.7	Heat loss to water cooled constriction nozzle
Gas Tungsten Arc Welding (DCEN)	0.6 – 0.8	Both work function and kinetic energy are released to the work piece
Shielded Metal Arc Welding	0.7 – 0.9	Heat transferred to electrode reaches the work piece back via the droplets
Gas Metal Arc Welding	0.7 – 0.9	Heat transferred to electrode reaches the work piece back via the droplets
Submerged Arc Welding	0.75 – 0.9	Arc is covered by flux which prevents heat loss
Electron Beam Welding	0.8 – 0.95	Keyhole acts as a black body

So, here is a summary of the heat source of efficiencies including laser and arc and these are actually organized from lowest to the highest efficiencies values that we have found in the literature and these are available with lot of discussion in the book by Sindo Kou and I am presenting here a summary. So, laser beam welding as we have just now seen as here efficiency much less than 10 percent and that is the reason is because of high reflectivity of the metallic materials and then comes the plasma arc welding, which has the absorptivity between 0.5 and 0.7 and the reason why plasma arc welding has slightly on the lower side the efficiency is because there is a water cooled construction nozzle that is surrounding the plasma jet which is present in the plasma torch.

So, because some of the heat is lost to this water cooling jacket that is surrounding the plasma torch then we have some loss of heat and therefore, the efficiencies slightly on the lower side and then when it comes to rest of the arc welding facilities normally you do have a good value between 0.6 and 0.9 going from GTAW in the electrode negative mode to shielded metal arc welding and gas metal arc welding.

The reason why in the electrode negative mode we do have a higher efficiency is for both the two reasons which is the kinetic energy of the electrons being absorbed by the material the electrons that are accelerated towards the base material or stopped suddenly and all the kinetic energy is then left to the base material which an takes it and converts into heat and that is one reason another reason is also is the work function, as we know when we want to remove an electron from a metallic material then we need to provide some amount of energy that is called as work function and the reverse happens whenever electron is then given into a metallic material. The work function will then be released and that will be also one part of energy that will be released.

So, in other words when the electrode is negative electrons are going towards the base material and than that gives a lot of the heat to the base material and therefore the efficiency of the GTAW process is on the higher side. And we do have also GMAW showing you very good efficiencies and normally GMAWs are with electrode positive polarity and the reason why efficiency is considered high because the electrode actually melts and those molten droplets of liquid at high temperature are again reaching the base material and giving the heat.

In other words the heat that is given to the base material and also to electrode, are both reaching the base material eventually and therefore, the efficiency of GMAW is very high reaching up to 0.9. Submerged arc welding also as lot of efficiency, the reason is being that the arc heat is not lost to the environment by radiation because the arc is covered by granular flux which hides the arc and therefore, prevents some amount of radiate to loss.

And electron beam welding is known to show efficiencies reaching nearly 95 percent and the reason is as follows, the keyhole mode of welding that is normally taking place during electron beam welding has a vapour column and the vapour column acts like a black body to absorb all the energy that is given by the beam and therefore, the entire heat will be dumped into the material and that sense the efficiency of electron beam welding comes to be the highest in all the welding processes.

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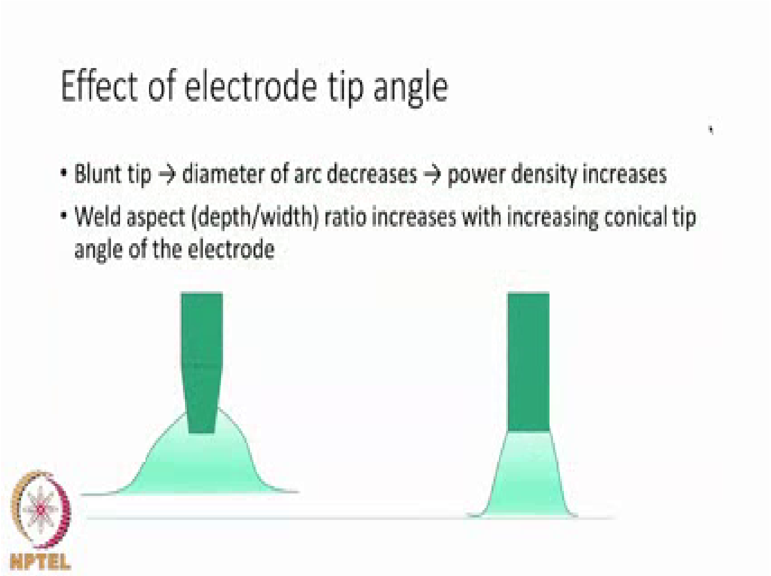

How does the heat source appear and how do we then modulate. So, this is the extensive discussion that we are going to have now and we can actually see the shape of an arc with naked eyes it is not recommended because there is lot of ultra violet rays that also coming, so you would actually see the arc with your eyes by placing a filter and looking through it. And then you can see when your eyes that the shape of the arc looks like a decreasing nature with the maximum value under the electrode and going towards 0 away from the electrode and the width of the arc is generally slightly more than the electrode may be up to about two times the diameter of the electrode.

So, it is also possible the for the electrode to be either sharp end to be a tip or like a conically tapered just blunt and what kind of a in electrode tip shape would give you what kind of a heat source distribution is evident from this schematic image that I have shown, it is seen from here that if you have a blunt tip, then the diameter of the arc is decreased and which also means that the power density is actually increased. In other words, the entire arc is restricted to a smaller width and the intercity of the power is going up which means that when we have electrodes we must pay attention to the shape of the tip before we identify what would be the power density that would be applicable for that particular process.

And then, the aspect ratio of the weldment also is affected by the conical tip angle and this has also been studied experimentally very extensively and people have shown that the weld aspect ratio increases with increasing conical tip angle and it will be the highest at 180 degrees which means that when the electrode is blunt that is completely flat.

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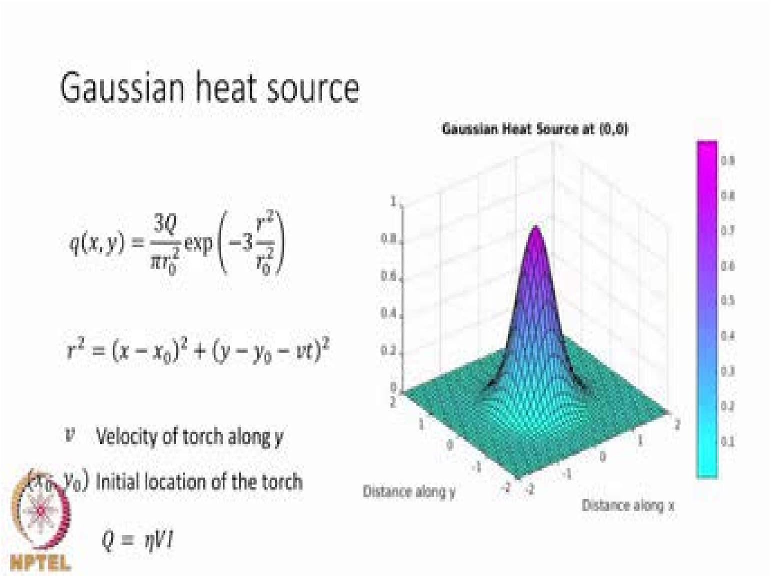

And as you can see that we can actually mathematically represent the heat source that we have seen in the previous slide by using what is called as a Gaussian function. So, the function itself is shown to you here showing you that is exponentially written in a form that goes as (Refer Time: 23:15) to the power of minus x square where x is the length and in 2 d, you have not just one length, but you have in the two directions so you use the radius as a parameter r, so you have (Refer Time: 23:30) to the power of minus r square as a general nature by which the intensity is decreasing as you go away from the center of the heat source.

And we have those numbers like 3, that are given to ensure that the variations is as sharp as what is normally seen in the actual arc and the distance variable r is returned not just as a function of distance away from the origin of the heat source which is at x naught and y naught, but as was a function of time. The reason being that the torch is moving and as you can see from the expression written here, the radius is changing with the y distance as a function of time which means that the torch is moving in the y direction that is the meaning of the second expression we have given x naught and y naught is the location of the heat source which is at the center and then the q value is nothing, but the nominal heat source that is being given multiplied by the efficiency of the absorption of heat by the base material.

So, eta V I, where V is the voltage and I is the current; that would be the power that is given and that power is then distributed in a Gaussian manner. So, the appearance of the Gaussian heat source is shown here, it goes down like a hill going from a high value at the center to 0 away from the center.

I have made this plots using setup MATLAB scripts, I will be showing you a various such heat source distributions and those MATLAB scripts will also be uploaded into the course site and you could then plot them yourself and explode those nature of the heat source distributions and if you are not familiar with MATLAB. Then perhaps you may want to also join the online course on MATLAB offered by Dr Niket Kaisare from our institute on the MOOC in the same semester as this course is going on.

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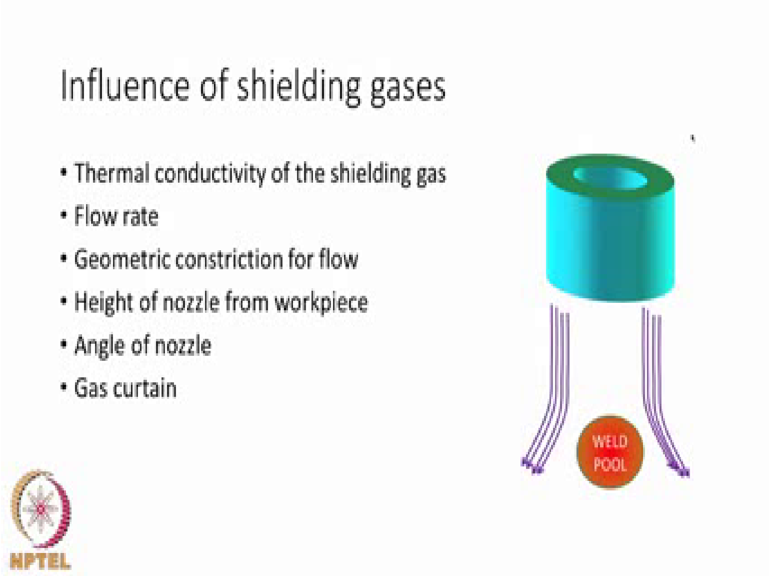

So, there is also one more aspect that we need keep in mind, what happens normally is apart from the Gaussian nature of the heat source that is coming from the arc. We also have a situation where the shielding gas that is used playing a role with respect to the heat source distribution. So, I have shown here a toroidal space from where the gas is coming through and at the center of the space is where the weld pool is located. To keep the schematic simple, I have not shown you the welding torch which will be actually at the center of the toroide that I have shown.

So, basically in the annular region, the gas is coming out and then going on around the weld pool, so that it is protecting the weld pool from contamination. So, we must understand that the shielding gas that is being used to protect the weld pool also as thermal conductivity, which means that it also can remove the heat and therefore, we had to also pay attention to what is the shielding gas that we are using.

So, if it is going to be for example, argon versus helium, then we know that the helium has higher thermal conductivity which means that the heat loss is going to be more, if helium is going to be used as a shielding gas and that information should reflect in the heat source formulation by a change in the efficiency or a change in the nature of the distribution and information. Such as what is the shielding gas if it does not enter the heat source distribution at all then; that means, that actually we are neglecting some of the realities of the actual welding.

The flow rate of the gas plays a role, the reason being that if the flow rate is high then it is taking away through convective heat transfer, quite a bit of heat from the arc and that should also play a role and usually the welding processes are such that the flow rate is not valid much because the purpose of the gas is only to shield and it will be kept constant for most of the welds; however, if there is a change in a flow rate then we must know and then keep that information also handy to modify the heat source as the case may be.

The geometrical construction for flow also plays a role, if there is no geometrical construction; that means, if the gas is flowing freely and then expanding as it goes away from the weld pool then its velocity also goes drops and; that means, that the rate of heat loss from the weld pool to the environment will be at a particular way and in case if it is constricted then we would see that the velocities of the gas going through the nozzle will be higher and; that means, that the heat loss will be slightly higher than the previous case you just mentioned. So, geometrical construction is there or not is in information that we need to know.

And how far is a gas nozzle from the work piece that also plays a role, the reason being that as the gas is expanding and mixing in the ambient air, then you see that its velocity also goes off and then, if the nozzle is very close to the base material then it has significant amount of momentum and the heat loss will be more and if it is very far away from the base material then it may not be taking away much of heat. So, we must also know what is the height of nozzle from the work piece.

The angle of the nozzle also plays a role; it may induce asymmetric in the heat source distribution. So, if the welding torch along with the gas nozzle is kept perfectly 90 degrees to the work piece then there will be a symmetry that will be expected from the heat source distribution, but if is that in angle then you may not have that symmetry if the shielding gas is going to play a role in significantly altering the heat source.

And there are situations where you may have a gas curtain separating the nozzle and anything else that is behind the nozzle. So, you may have a situation where you may want to remove the heat through liquid nitrogen jet behind the welding torch and then if you do not want the nitrogen to mix with the weld pool then you may want to have a gas curtain made of again argon in between. So, such gas curtains also remove heat and then play a role in the heat source distribution, so you must also know whether gas curtains are used or not and whether they have play a big role or you know it can be neglected, but we must be conscious of all these influences, but shielding gases will have on the heat source distributions.

With that we conclude the first part of the heat source description, and then we will move on to the second part. We will be going to further details on combined the heat sources and other formulations.