Analysis and Modelling of Welding
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Lecture - 02
Introduction - part 2

Welcome back to the second part of the introductory lecture in the online course on Analysis and Modeling of Welding.

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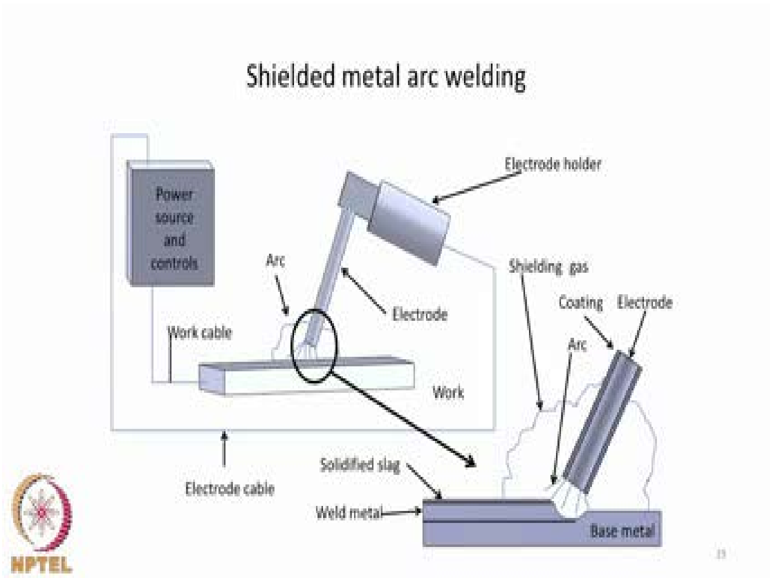

So in the second part, we are going to go through a list of processes, a brief description of each of these processes, and then come to a summary of all the processes relevant for the analysis and modeling aspect of these welding processes. So first process, that we are taking up is shielded metal arc welding; and this is also called as a stick welding or manual metal arc welding. So, in the schematic, we are seeing that there is an electrode; the electrode is usually about 20 centimeter long and it is a wire of the material, typically compatible with the base material that you are going to join, and it has a coating on surface of the electrode.

And the electrode is then gripped by an electrode holder, and then the polarity is then applied to the electrode using a power source. The power source has respective controls; and the worktable also will be earthed and connected to the power source. And in the schematic here you are seeing how the welding process will be taking place; typically, when the arc is struck then you have the arc between the electrode and the base material. And as the electrode is moved along a line; in our case, it is going from the left hand side to the right side then you would see that the wire that is part of the electrode would be melting and then forming what is called as a deposit, so there is a weld metal deposit that will be forming.

And the coating is going to then also a form a thin layer and usually it is less dense than the weld material, and it will be forming a solidified slag layer on the surface of the weld metal. And the entire fusion zone is then covered with the shielding gas that is also generated during the arcing process, and this is aided by the coating material and that is going to protect the welding process that is happening under the electrode. And the shielding gas is going to play an important role in the stability of the arc as well as in protecting the material that is being deposited.

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So, let us just look at some of the further details. What kind of a flux is used on the surface of this stick to make it as a useful material for the process? So as you could see from the repair shops that are there in the daily life, you could see that this is perhaps the cheapest welding process that is because the flux has a multiple role, and it avoids the usage of any inert gas attachment.

So, normally a flux is a combination of a lot of materials. And here we are seeing a table that shows you the constituent, and the role that is played by the particular material. So, the flux has actually four roles; they supposed to protect the material; and it is supposed to help in deoxidization of the material; and then stabilize the arc; and also add material to the weldment, so that the composition can be modified locally as required.

So various constituents are there so iron oxide is present and that is going to help in the formation of slag and also in stabilizing the arc. Titanium dioxide rutile is also present and it will help in forming the slag as well as stabilizing the arc. Calcium fluoride is present to help in slag formation and also making the flux, a low melting surface layer that would be protecting the liquid metal. And potassium silicate is used to stabilize the arc; and it is also used to bind the different oxides and fluorides silicates that we are seeing to form adherent coating on the surface of the electrode wire.

Magnesium oxide is used as a fluxing agent. And we have cellulose which is used to form the gas; and this gas is then going to protect the liquid metal by forming a shroud around the arc. Calcium carbide, also used for the same purpose to form the gas that would be protecting the material; and it also helps in stabilizing the arc. And then we have certain other powders such as ferromanganese, ferrochrome, ferrosilicon etcetera in joining the steels; they cause the alloying changes that are required for the welding joint to be stronger.

And ferrosilicon also plays a role in deoxidizing the surface to help in the weld joined to be stronger etcetera. So, you can see that the flux is very important and this flux will not be effective, when it has picked up moisture. So it is important that the stick welding or the a shielded metal arc welding is performed when the electrodes are all baked, so that there is no moisture because when the moisture is present, you would have hydrogen entering the liquid metal and causing defects later on that are not desirable for an engineering component.

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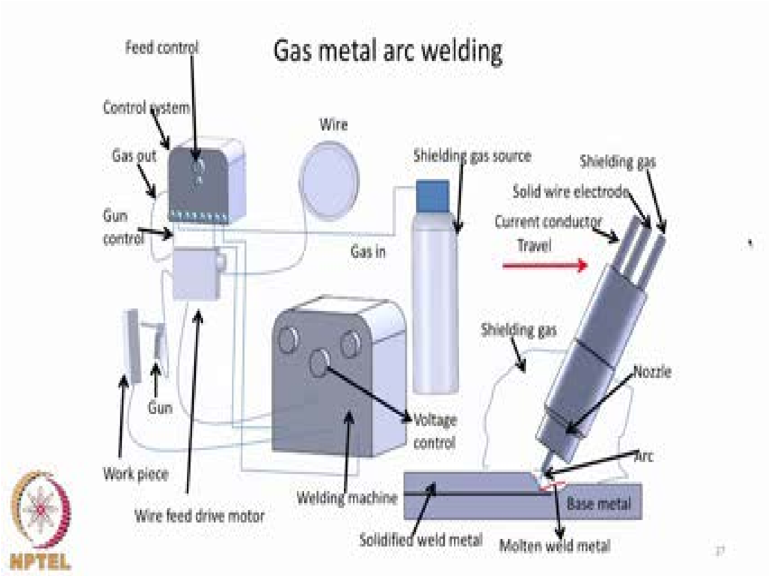

The second process that we are going to look at is gas metal arc welding. And this is again a process in which you have electrode and base metal and the power source; however, there are some minor variations. So let us just go through the system here. So, gas metal arc welding or MIG welding as it is called uses a wire, which is basically the fare wire which is in a pool; and the wire is then going through a control system, which would be coming out as a an electrode wire.

And the process involves protection of liquid metal using a gas, which means that you also have an argon gas cylinder that has to supply the gas at the same location as the wire is going to come and strike the arc. And then you would have a power source that would be playing a role in changing the polarity and passing the current as required.

So here in the right hand side, we have got a zoomed in schematic to show you that in MIG welding we have a nozzle and we have a wire that is a consumable wire that is acting as an electrode, and also as a filler simultaneously, and striking an arc with the base metal. And as the torch is now moving in the direction from the left to the right in the screen, then we would see that the solidified weld metal will be formed on the base material leading to the joining of the materials that are being processed here through MIG welding. And you have the electrode assembly having possibilities to pass the shielding gas, the wire electrode and any other requirements that are there.

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This is a photograph of such a welding machine in our lab in the materials joining laboratory in the Department of Metallurgical and Materials Engineering, IIT, Madras. And the building power source is shown on the left hand side along with the argon cylinders. And on the right hand side, we are seeing the torch in a closed inset. And you can see that the wire is sticking out, and this is the plate that is going to be now joined with this MIG welding.

And you could also deposit the filler wire material on top of a flat surface using this technique. And because the wire is coming from pools, it implies that you could make lot of welds without interrupting the welding process. An interruption in the welding process is generally happening in a stick welding, because the electrode wire is getting exhausted during the welding process, and after the 20 centimeter long electrode wire has reduced itself to about 4 centimeters or so, it has to be discarded and a new electrode has to be assembled. And such interruptions are not there in a GMAW process, which means that it is admirable to robotic welding in automobile component manufacturing.

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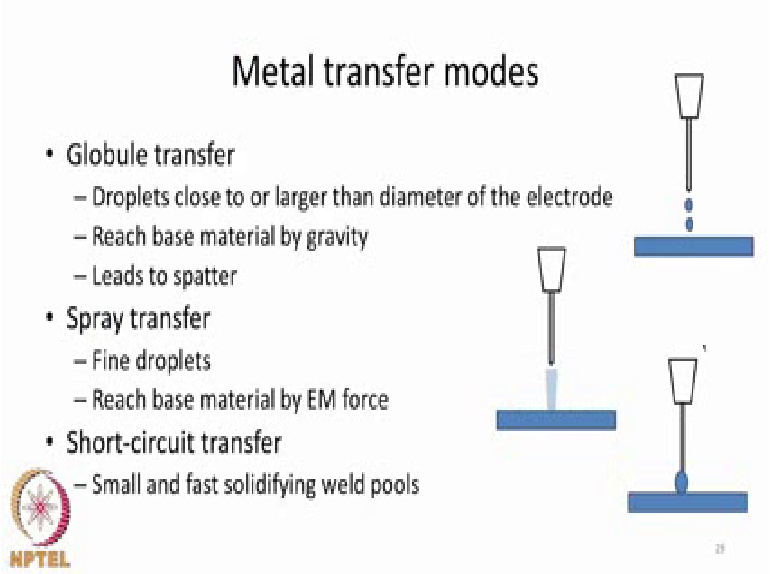

And there are certain differences in the parametric space that is used by the MIG welding. And the most important of them is what chooses the transfer of the liquid metal from the electrode onto the base material. And this is generally done in three different fashions. So, what is called as a globule transfer that occurs at relatively low voltage and current and spray transfer that occurs relatively at high values of both these parameters; And then a short circuit transfer, which occurs at again a low voltage and it is a specialized process. So, the reason why these three processes are important is as follows.

The globule transfer basically makes the electrode wire melt and form droplets which are having a diameter either equal to or larger than the electrode wire. And these large droplets then reach the base material by the action of gravity which means they fall on to the plate. And very often such an action also leads to what is called as a spatter, which means that excessive material that is deposited in the vicinity of the weld on the base material, and not desirable for the weld and it is a defect. So you could see that global transfer leads to a defect, and it is not desirable; however, because of the deposition is happening in large droplets it may be useful for large deposition on a flat plate.

Spray transfer occurs when the current values are high. And in this case, the droplet is actually in a very fine form and several small droplets are actually coming from the electrode onto the base material. And these fine particles are moving towards the base material by the electromagnetic force that is acting on them within the arc, and which means that this kind of a transfer mode is suitable where the direction of gravity does not match the direction of melt deposit that is taking place.

Short circuit transfer is a third process, where a large droplet of a metal is formed at the bottom of the electrode, and then it gets into contact with the base material. And upon contact then there is a short circuit that is happening and at that junction if the electrode is retracted then you could have the deposition that will be occurring on the base material.

And because the droplet is not heated to temperatures much higher than the liquidus temperatures, usually you would have a small and fast solidifying weld pools made with this kind of a transfer mode. And we will be later discussing about what is called cold metal transfer process, which uses this particular method with some more interesting changes to the weld current cycles that makes the process one of the lowest heat input processes among the arc welding processes.

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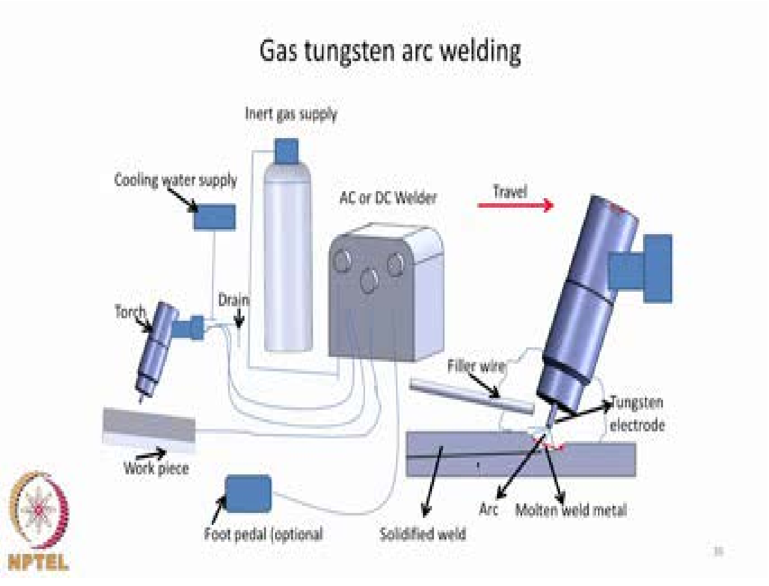

So, here is a schematic on the GTAW process, which is also called as a TIG welding process. So, this is one of the most popular manual welding processes that can be done when there is no deposition of material involved; and this is also the welding process of choice for aluminum alloys. You can see that the welding setup contains a work piece and a torch the torch is connected to the power supply. And then there is also in an inert gas applying to the torch.

The tungsten is usually picked up as thoriated tungsten, so that the electrode can withstand high amount of currents and then it is also not-consumable and the electrode is connected to the power supply. And as a torch strikes an arc with the work piece and is moved then you would see that a molten track will be made on the base material. And if the welding process requires then a filler wire can also be added along in the arc, so that it can melt and make the deposit.

So please note that the filler unlike in the earlier processes that we discussed is not coming from the electrode, but it is separately headed. And the liquid metal is protected by the inert gas that is being supplied; typically, it will be the argon gas that is used. And in the schematic that is shown where the torch is moving towards the right hand side you would see that the solidified weld is on the surface, and the arc is then protected by the shroud of argon gas that is around them.

There is a food pedal that can be attached to the power supply to change the parameters such as the current value, during the welding; and usually if it is done manually one would change the position of the food pedal to adjust to the different arc lengths that might be changing as the welding process is going on. It is also possible to operate this in an automatic manner.

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And here are some images to show how TIG welding setup would look like. So what is on the screen is showing you a torch attached to a linear drive, which makes a torch go along a particular linear path at a given velocity.

And in the zoomed in picture, you would see a ceramic container that protects the electrode and has the argon gas going in the inner side of it, and then you have the power supply here from one of the popular companies in the world. And these are the kind of setups are also available in a smaller scale, so that it can be made also portable. And this particular image is taken from our materials joining laboratory in the department of MME - IIT, Madras.

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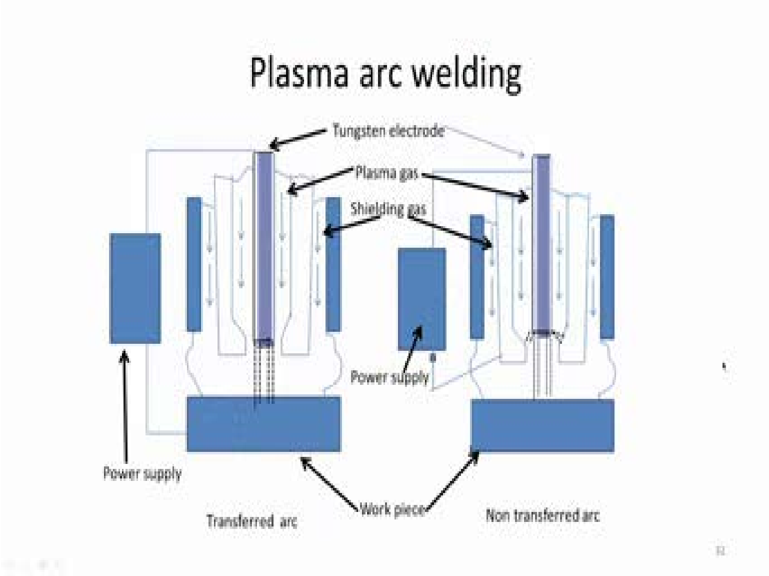

So, here is the schematic of a process called as plasma arc welding. So plasma arc welding, the process is going to be shown here, you have basically a two streams of gas; so there is one gas that is supposed to form the plasma, and there is another gas that is going to act as a shielding gas. And what happens is very similar to the TIG welding, here also you have a tungsten electrode which strikes an arc, but then the arc is then constructed and then is fed with the plasma gas at a high flow rate, so that a constricted long supply of plasma is then supplying heat to the work piece. And the power supply is shown here.

And this arc if it is initially struck with the outer container and then transferred on to the work piece then you would call it as a transferred arc welding; otherwise it would be just called as plasma arc welding, which means that there are two variants PTAW and PAW that are possible in this particular setup. So, as you can see from the constriction that is possible for the arc, it means that the heat source is going to be more intense, and the rate of heat input is going to be higher.

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And here is a setup that shows how a plasma arc welding setup would look like from our materials joining laboratory in Department of MME - IIT, Madras. And you could see that the torch assembly is little bit more involved compared to a TIG welding torch, and then the torch is then mounted on a drive that could make the torch move along a path at a given velocity.

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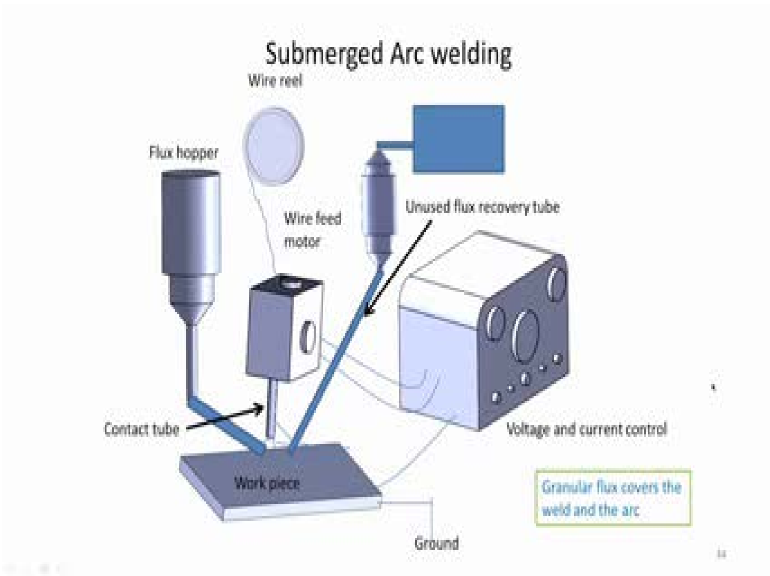

Here is a schematic of what is called as a submerged arc welding. Submerged arc welding the name as it implies, what is submerged, in this case, it is the arc assembly that is submerged. So what happens is that, they flux that is supposed to protect the arc and also perform other functions such as adding material etcetera is actually taken in course grained form, and there is a hopper that supplies the flux on the surface of the material.

And there is electrode that strikes an arc and the electrode is often a consumable electrode, and which is coming from a pool. And as the arc is then traversed along a path on the work piece the flux hopper also is moved along and the flux is then deposited on top of the arc. And arc is actually submerged under the granular form of the flux, which means that the flux will actually protect the arc environment, and leads to the arc being stabilized compared to a situation, where the arc is struck and the gas is freely flowing away from the arc in an open environment.

This particular process is meant for lower traverse rates and higher deposition thicknesses, and the advantage being that large thicknesses can be weld in one single pass. The disadvantage being that the amount of heat input is large and very often you would have course grain size, and lack of impact toughness of the parts that are joined using this particular process. However, it is a process of choice for creating the surface layers on other pieces of different materials.

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And here are just images of an old submerged arc welding facility that we have stopped using, and how the electrodes and the power supply look like is shown here.

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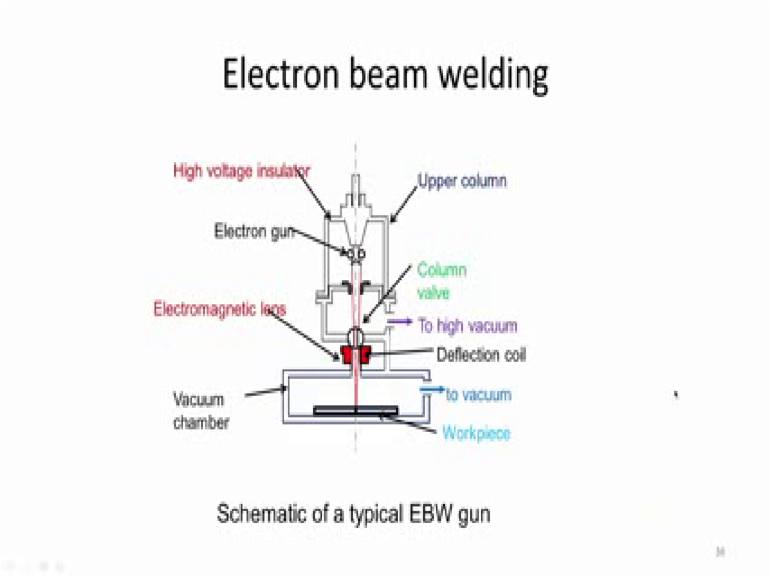

The last two processes which are basically high power beam processes or electron beam welding, and laser beam welding. So electron beam welding process is shown here as a schematic.

Here the welding source the reason why the material is going to melt is basically electrons which are generated by using an electron gun. And as you would imagine that electrons cannot traverse in a coherent fashion, if they are exposed to air because then they would go on ionizing the gas on the way, and then get scattered. So you normally need evacuated chamber, so that the electron beam can arrive on to the sample surface. And you also have coils that would guide the path of the electron beam, so that it can be precisely located on the work piece.

And one of the important aspects of an electron beam welding is the vacuum chamber. A high vacuum is created in the chamber, which means that the entire part that has to be welded must be sitting in a vacuum chamber and this often means that the vacuum chamber is a large chamber involving a TDS evacuation setup. And the electron gun also plays a role here and you would see that the electron gun has assembly where there is a insulator and a separate column with higher vacuum where that is being generated.

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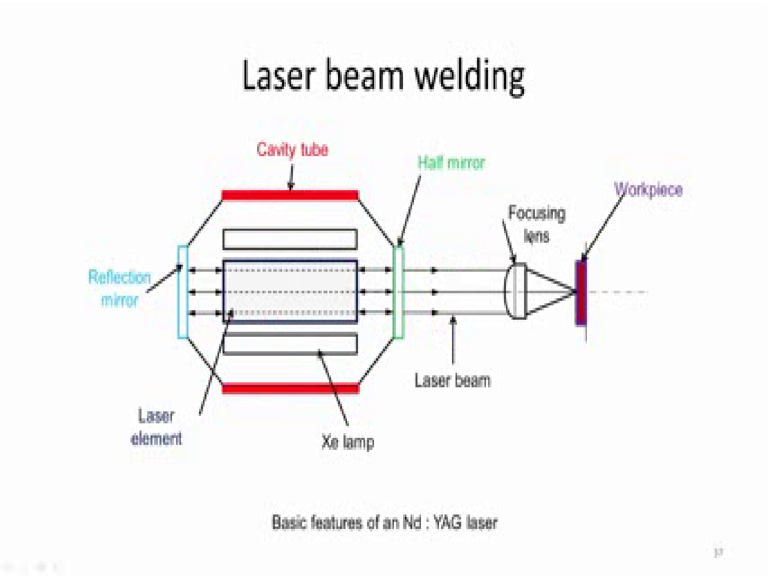

Here is a schematic of laser beam welding. And here we see that light is fed into a cavity, where internal reflection is then going to happen, and then a coherent beam is going to emerge out, and then it is focused by a set of lenses to form an intense beam on the work piece. And the lenses can then make the beam come in a particular distribution, and the work piece can then be moved along to create the path for the welding process to take place.

So there are situations where the delivery of the laser is fiber delivered in which case the torch or the laser focusing lens assembly can move; and in the case, it is not fiber delivery then the lens is fixed in space, and its work piece that is moving to create the path where the welding is going to take place. And both electron beam welding and laser beam welding are situations, where the heat source can be focused significantly, so that the heat energy density distribution is very sharp, which means that you could have extremely high amount of rate of heat input to the material.

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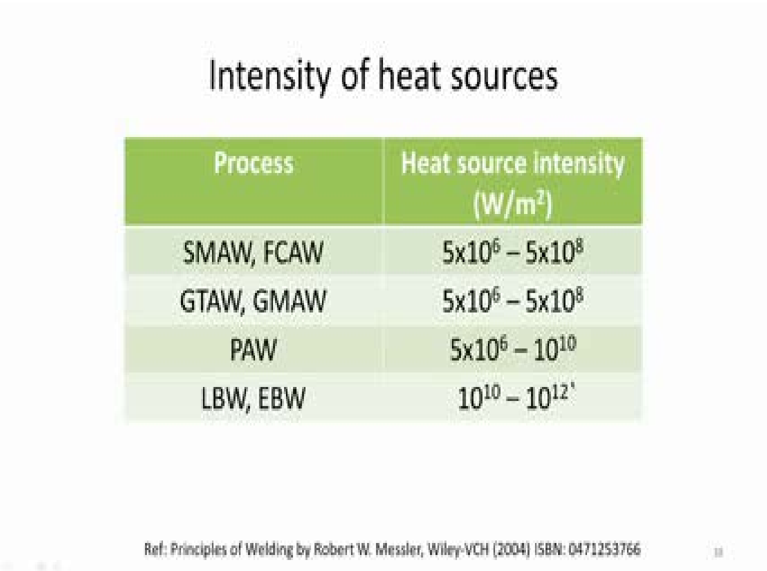

Intensity of heat sources

Process	Heat source intensity (W/m^2)
SMAW, FCAW	$5x10^6 – 5x10^8$
GTAW, GMAW	$5x10^6 – 5x10^8$
PAW	$5x10^6 – 10^{10}$
LBW, EBW	$10^{10} – 10^{12}$

Ref: Principles of Welding by Robert W. Messler, Wiley-VCH (2004) ISBN: 0471253766

And I am just giving you here how those numbers look like; this is a large range that is given here because that much of flexibility is available with these processes. So, the intensity of heat sources is as follows in the case of shielded metal arc welding and flux code arc welding etcetera, you have the range going from 5 into 10 to the power of 6 to 5 into 10 to the power of 8 watt per meter square.

And for GTAW and GMAW, the range would be very similar, but may be the operating values generally on the higher side. In the case of a plasma arc welding, then you can see that a significantly higher amount of heat source intensity can be explode that is when 5 into 10 to the power 6 to 10 to the power of 10 watt per meter square.

And in the case of laser beam welding and electron beam welding, this is even higher so up to 10 to the power of 12 watt per meter square can be achieved, which means that the very fine focusing capability for the beam is going to make us achieve such a high amount of intensity on the surface of the base material.

It also means that the base material that is going to be molten can be extremely small in dimension, so that you can have welds that are very precise size and very small. And usually such high source intensity also means that you could also use it with lot of flexibility to join both very thin as well as very thick samples; which is not the case for example, with TIG welding where the lowest thickness and highest thickness that is possible in a given range.

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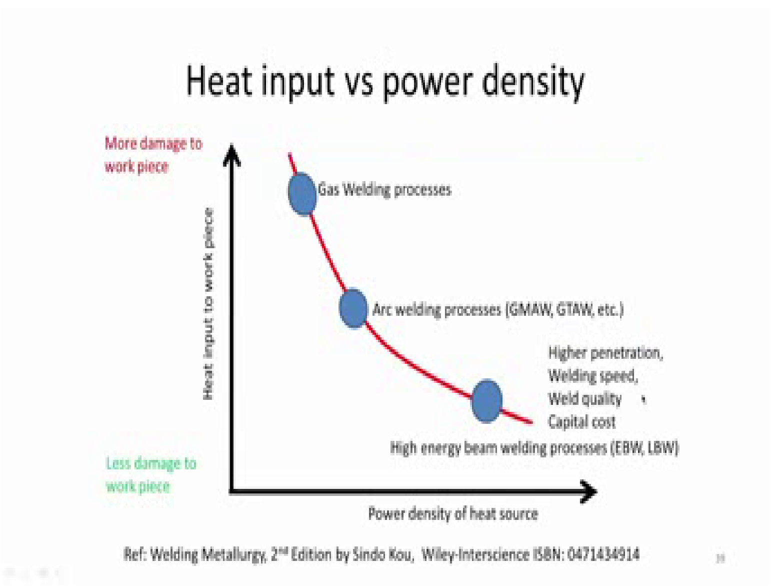

And how would these processes line up in a sequential form is shown here; along the x-axis, we have the power density of the heat source; and along the y-axis, we have the heat input to the work piece. And we see that the gas welding processes and arc welding processes generally tend to have high amount of heat to the work piece. And processes that have high heat intensity, generally give a total amount of heat input to the work force which is much smaller. So you can see that there is a an exponentially falling curve as you go from the gas welding to arc welding to electron beam and laser beam welding thing.

And you could see that when the heat input to the work piece is large, it means that the work piece is going to be damaged more that is because the entire work piece will be getting heated up, and then there will be significant amount of distortions that will be coming in. And if the heat input to the work piece is small then the total amount of damage that is done to the work piece is very limited.

And it also means that very precise control that is available in electron beam and laser beam welding could be used to fabricate a complicated part, from separate parts without causing the damage to the rest of the parts. So this is how you could see that facilities that are having a high capital cost also tend to have a good weld quality and are capable of a large variation of welding speed and are also able to give both high penetration as well as very low heat input to the sample.

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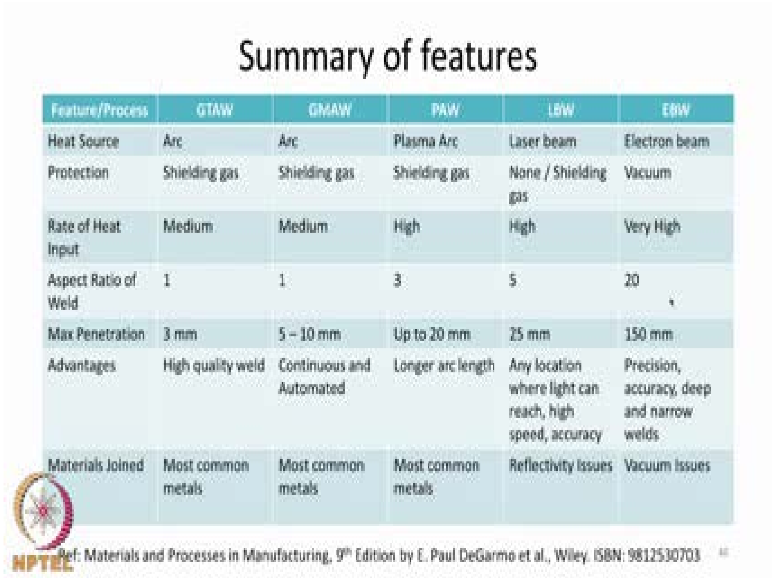

Summary of features

Feature/Process	GTAW	GMAW	PAW	LBW	EBW
Heat Source	Arc	Arc	Plasma Arc	Laser beam	Electron beam
Protection	Shielding gas	Shielding gas	Shielding gas	None / Shielding gas	Vacuum
Rate of Heat Input	Medium	Medium	High	High	Very High
Aspect Ratio of Weld	1	1	3	5	20
Max Penetration	3 mm	5 – 10 mm	Up to 20 mm	25 mm	150 mm
Advantages	High quality weld	Continuous and Automated	Longer arc length	Any location where light can reach, high speed, accuracy	Precision, accuracy, deep and narrow welds
Materials Joined	Most common metals	Most common metals	Most common metals	Reflectivity Issues	Vacuum Issues

Ref: Materials and Processes in Manufacturing, 9th Edition by E. Paul DeGarmo et al., Wiley. ISBN: 9812530703

So, here is a summary of all the processes that we have looked that. And I have taken five of them for comparison. And the processes are being compared with the following features a heat source, the way of protection, the rate of heat input, the aspect ratio of the weld, maximum penetration that is possible, the advantages that are very specific to that particular process, and what kind of materials can be joined.

So you could see that as we compare, so we would see that for example, for GTAW, the heat source is arc, the protection mechanism is by the shielding gas, and the rate of heat input is moderate, and the aspect ratio of the weld is 1. Which means that you cannot make very deep welds, the width and the height of the weld are roughly the same and maximum penetration is given as a 3 millimeters, which means that these are meant for thin to thick sheets, but not very thick plates.

And one can increase from 3 mm to about 10 mm by modifying the GTAW process, which we will be discussing later on; however, the maximum penetration is very limited. And the advantages are that it is a very high quality weld that we will get and most of the common materials can be joined using TIG welding process. In the case of MIG welding, you have what very similar kind of characteristics except that the maximum penetration is slightly on the higher side; and the advantage of continuous and automated operation using a robotic welding appliance is also there.

In case of plasma arc welding, as we have discussed, there is a constricted that is giving you high heat intensity, so which would mean that the arc source that is used for the welding is called as the plasma arc. And the rate of heat input is high. And the aspect ratio of weld is then higher that is about 3, which means that you can have welds that are more deep than wide.

And up to 2 centimeters thick plates can be joined using just one pass of plasma arc welding. And this also supports longer arc length; and longer arc length would actually mean that more agility in the welding process. And the weld assembly can then be decided so that the plasma torch can move around, and make the joints possible which may not be for example, possible using the GMAW or GTAW processes. And most of the common materials can be joined using the plasma arc welding. What are the disadvantages, it is slightly more expensive facility compared to the MIG welding facility.

In the case of laser beam welding, the heat source is the laser beam; it is a light basically; and the protection is not given by a shielding gas unless you necessarily require it. The reason why one would normally not think about a shielding gas in the case of laser building is because the amount of duration when the liquid metal is exposed to the environment is very less.

And therefore, the amount of contamination or formation of oxides etcetera is very less and therefore, one normally does not choose to have a shielding gas, but one can habit if it is required. And the rate of heat input is high and the aspect ratio welds is 5, which means that you can have fairly thick plates that can be joined with very, very narrow weld widths; and the maximum penetration given is 25 millimeter which means that it can then join a very thick sheets in a single pass.

And the very specific advantage is there for laser beam welding, it can be done wherever light can reach; in other words, the physical proximity of the welding source to the base material or the plate is not a constraint. So as long as the laser light can be focused even interior parts that are inside a vacuum chamber for example, can be welded as long as light can go through the windows, and be focused at a location where the melting is supposed to take place. The only disadvantage of the welding techniques using laser is a reflectivity issues. So there are metals which are highly reflective which means that the amount of heat that will be absorbed for the welding process is limited, and these can be then overcome using surface coatings.

Electron beam welding has very similar characteristics as laser beam welding the heat source is electron beam instead of a light source. And there is no protection mechanism that is required to be provided in electron beam welding the reason being that the entire assembly that has to be joined is physically placed in a large vacuum chamber, which means that there are no gases that are present which can contaminate the liquid metal.

And therefore, there is no requirement to provide any protection environment. The rate of heat input is very high, the reason being that electrons can be focused to extremely small dimensions, so that the heat intensity is very high. And aspect ratio of weld is highest among all welding processes which mean that in a single pass, the highest thickness that can be welded is using a process using electrons. And a maximum penetration is also very high 150 millimeters is a typical number that is possible for many of the high power electron beam welding.

And the one of the specific advantages of electron beam welding is a precise nature with which you can position the electron beam further path it should take so that it can do the welding. And it also means that it has less tolerance to the deviations of the weld path which means that the edge preparation and the joint preparation are also quite critical, and it can make very narrow welds.

And what kind of materials can be joined using EBW, most of the materials except those that will have a problem when you place the liquid metal in a vacuum environment. So those materials which have elements that could vaporize very easily, they may face some problem in the electron beam welding; otherwise most of the common engineering materials can be welded using electron beam welding facility. The capital cost of EBW is very high, and that is often the limiting factor why one would choose any other process over EBW.

So, with this we summarize, the various welding processes and I hope you have got a fair overview of different welding processes. And in the second lecture, we basically move on to analyze a heat source the distribution and how we can understand the thermal processes that take place during the welding.

So, I will back up the introduction section by giving you videos on how these welding facilities would look like, the actual videos of some of the welding experiments that could be done in our own lab. And then one page writes ups of each of these processes for you to read further about these processes. And I will also give you a set of links from where you can read more information about these processes. A broad overview of all the processes would be useful in understanding how the modeling technique that we are going to take up in the set of lectures would be applicable to most of these processes.

With that, I would close the introduction lecture for this particular course.