Analysis and Modeling of Welding
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Lecture - 01
Introduction

Hello, welcome to the first lecture on the online course on Analysis and Modelling of Welding. My name is Gandham Phanikumar. I am a faculty member of the department of Metallurgical Materials Engineering - IIT, Madras.

In this first lecture, we are going to introduce the different welding processes, and then look at how the heat input and other specific aspects of the process will be differing across the different welding processes.

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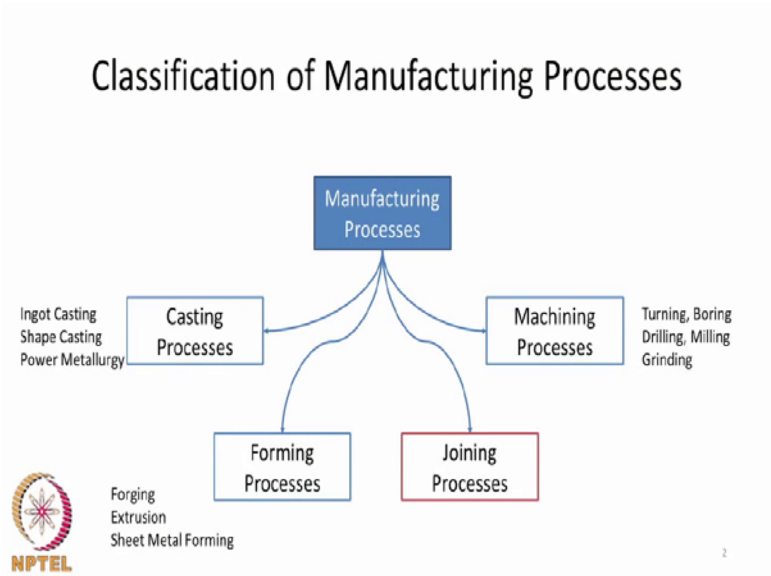

Let us first look at under what over view does the joining on welding processes come under. We have basically a large number of manufacturing processes, which can be categorized broadly as casting processes, which are the primary manufacturing processes, such as ingot casting, shape casting, powder metallurgy etcetera. And then forming processes, where we a change the shape by using processes such as forging, extrusion, deep drawing, sheet metal forming etcetera.

And then we have machining processes, which are somewhat like material removal processes, which include turning, boring, drilling, milling, grinding etcetera; advanced processes such as abrasive jet cutting, and water jet cutting etcetera also fall under the machining processes. And it is in this broad category that joining processes also come; and they can be called as fabrication processes, because they are used to fabricate a large part from several small parts.

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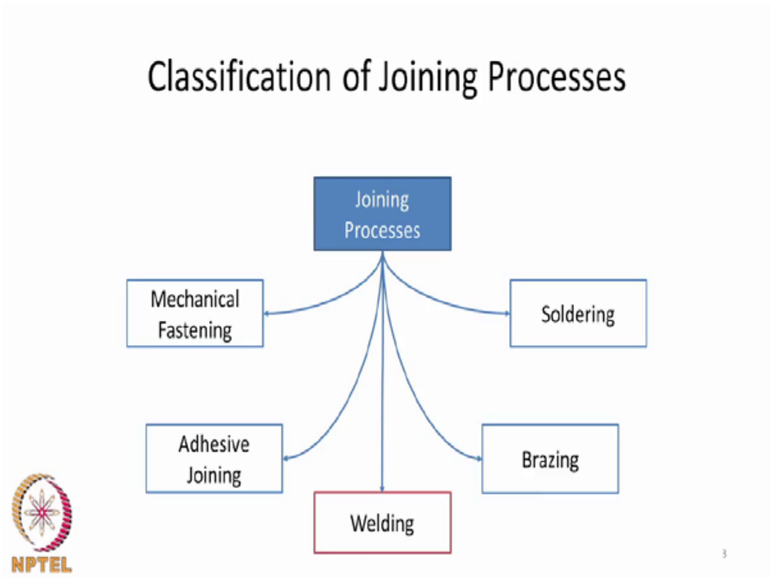

So, the large number of joining processes exits, and they can be categorized broadly again into the following categories. A mechanical fastening is a fabrication process, where a different parts are joined together mechanically without a metallurgical bond between the two parts that are been joined. We also have adhesive joining, where dissimilar parts can be joined using epoxy and various polymeric materials. Brazing and soldering are joining processes that are of importance to materials, where the melting points are very different, and it is the filler which will join these two meeting parts or rather than melting of the two meeting parts.

The difference between brazing and soldering is basically definition of temperature 450 degrees centigrade is arbitrarily chosen as a cutoff, so a process that works below 450 degree centigrade can be called as soldering; the process that works above can be called as brazing. So, welding comes under this broad set of processes. So welding is one of the fusion processes that come under this broad category.

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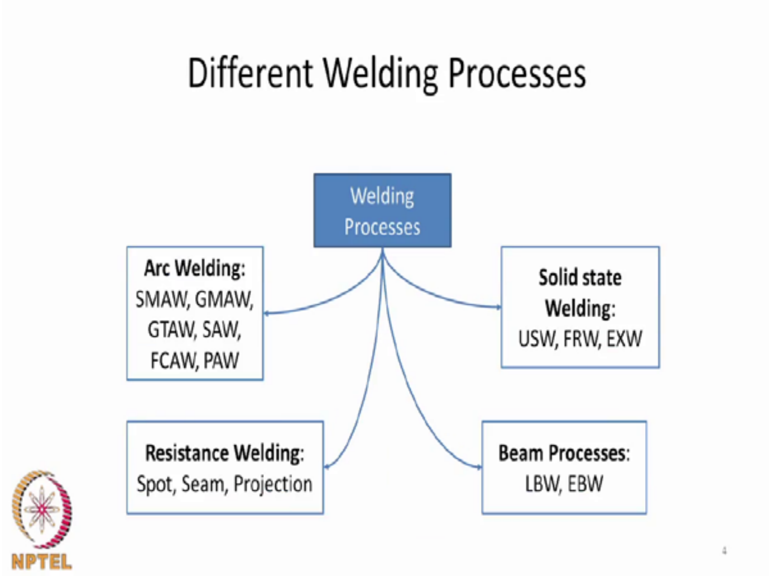

And welding processes again can be categorized by a different source of joining. The first set is by arc welding, where there is an electric arc that is used to join the two materials. I have given the acronyms here as per the AWS - American Welding Society specification.

So there are several arc welding techniques such as shielded metal arc welding, which is also called as stick welding or manual metal arc welding. Then GMAW - Gas Metal Arc Welding which is also referred to as MIG Welding - Metal Inert Gas Welding, which is an automated process; GTAW - which is also referred to as stick welding, Gas Tungsten Arc Welding, and SAW - which is Submerged Arc Welding; FCAW - Flux Code Arc Welding; and then PAW - Plasma Arc Welding. So there are so many different varieties that are possible using electric arc as a heat source.

We have also processes that use a resistance - electrical resistance to join the materials. So we have a spot welding, seam welding projection, welding etcetera. The welding does not require actually the materials to be completely molten, so solid state welding also is possible. So we have processes such as ultra sonic welding, friction welding, explosive welding etcetera, where the fusion is not explicitly caused. And then we also have specialized processes, where the melting is initiated by using a beam of high energy. So, we have LBW that is laser beam welding and EBW that is electron beam welding as processes that use in high energy beam to lead to the welding process.

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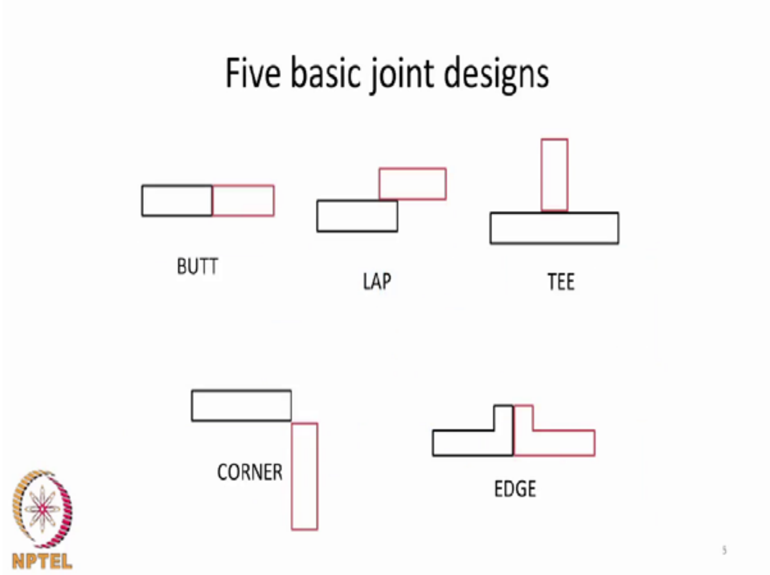

And these welding geometries can then be looked at by looking at the type of joints. So here are five joints and that are usually refer to this is essentially to make the terminology familiar to you as we use these names later on. So what is normally refer to as a butt joint is essentially when the two meeting parts are just opposed beside each other and then the joint is made. Lap joint is where the two meeting parts are kept on top of each other and then the joint is made. A tee joint is where the meeting parts are configured to look like a T.

And then, a corner joint where they are kept at an angle to each other and then at the edge, they are then joined; edge joint is basically again a joint where the two meeting parts are initially kept in the butt geometry, but then are folded up so that they can be joined along the edge rather than along the plane.

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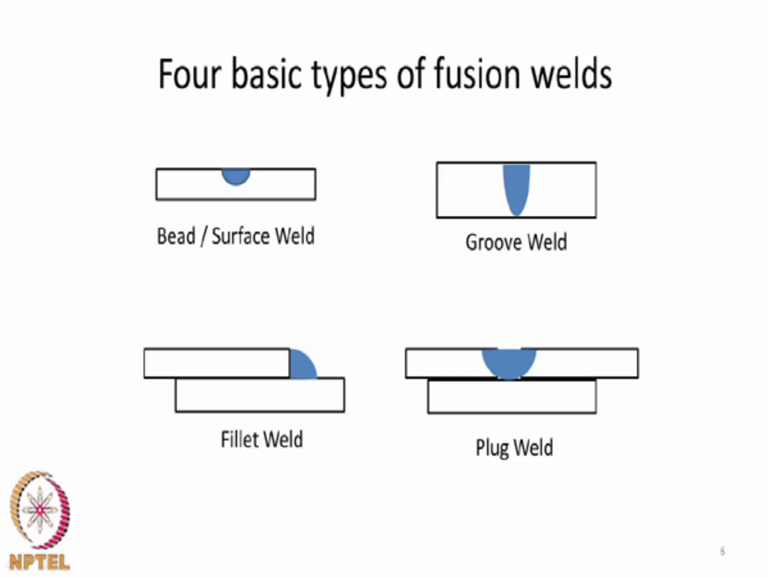

So, we will also make all this similar with some more joints, which can be understood by looking at the extent of the weld that is penetrated. So there are what are called as a bead or surface welds where a plate is welded by making the welding torch move along the surface. And these are generally used to join materials that are of low thickness and there is not much of preparation that is required to join materials in this fashion. For thicker materials, however, we will need what is called as a groove weld and we will talk about that in detail briefly.

A fillet weld is where we have them in the lap geometry and at the junction between the two plates, we have the joint been made using a filler. Plug weld is something like a spot weld where a locally the melt zone is made to join the two materials.

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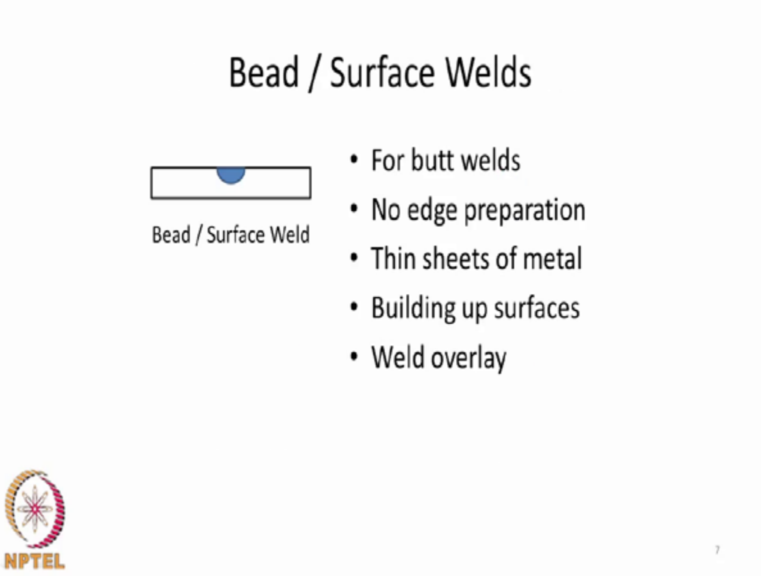

Little bit details about these; a bead or a surface weld is used very often for a butt welds; and the advantage of this geometry is that there is no edge preparation that is required; and this is used for thin sheets of metal. And this is also used for example, to build up surfaces. So if you want to repair a part, then you can remove some material by gauging or any other metal removal process and then the material can be build up at the same location again by making a bead on top of material.

We also can actually deposit different materials on top of objects that require a different property on the surface by using what is called as a weld overlay. So weld overlay is basically a process that is very similar to welding, however, the joining is not the objective of the process, but depositing a different material usually a corrosion resistance material or an abrasion resistance material is deposited, and these are generally done in a geometry that is called as surface weld.

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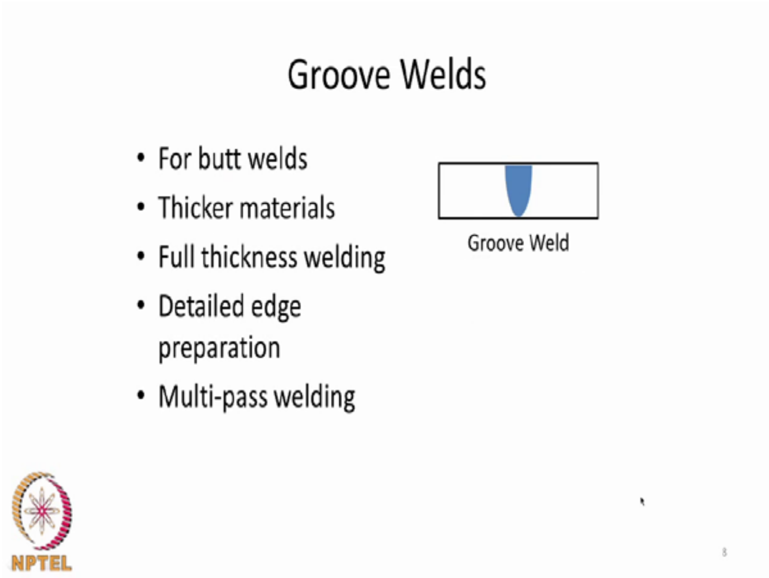

Groove welds are once that are used for large thickness joints. So these are also usually made in butt geometry and the large thickness also implies that we will have the weld penetrating to the entire thickness, and that would require a very detailed edge preparation. And very often the welding techniques may not be able to join the entire thickness in one go, so we may have to resort to what is called as a multi-pass welding.

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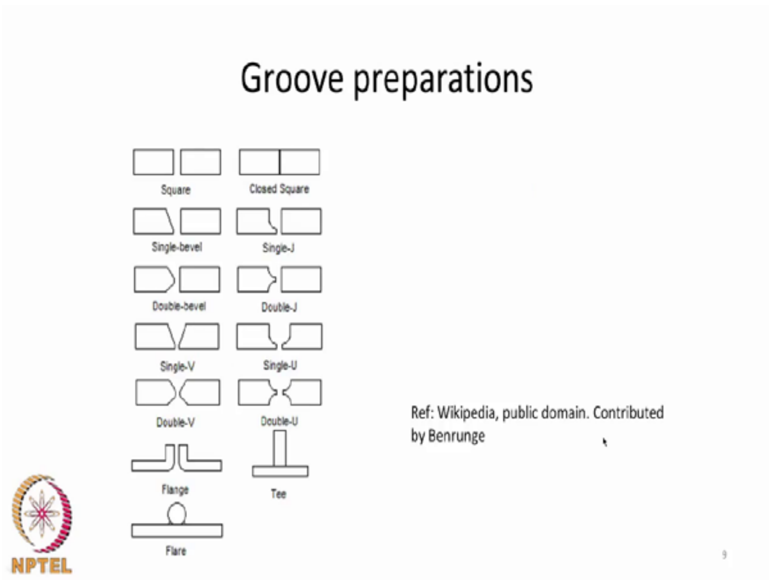

So how detailed can the joint preparation or edge preparation be in a groove weld is clear from this set of groove preparations. The image has been taken from a Wikipedia, but these joints are name are used in the literature quite commonly; so we have what are called square, closed square, single-bevel, single-J, double-bevel, double-J, single-V, single-U, double-V, double-U etcetera.

So we one can actually make a very detailed edge preparation, so that we can achieve a large thickness weld by making beats one after other, and the number of beads depends upon the thickness that we have to join. So, there are situations, for example, in nuclear industry where we may have to join a several tens of centimeters of a thickness plates and these could be joined for example, in several dozens or even hundreds of beads that are done one top of other.

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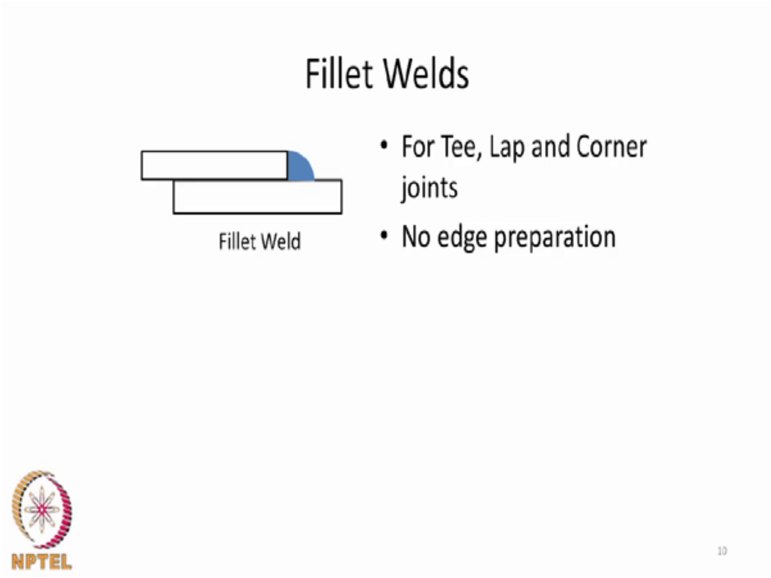

Fillet welds are `what are used to join materials when they are kept in lap geometry. And tee, lap and corner all three can be joined in this mode of fillets welds. The advantage of this particular way of joining is that there is no edge preparation; however, there is a requirement that you need to have filler.

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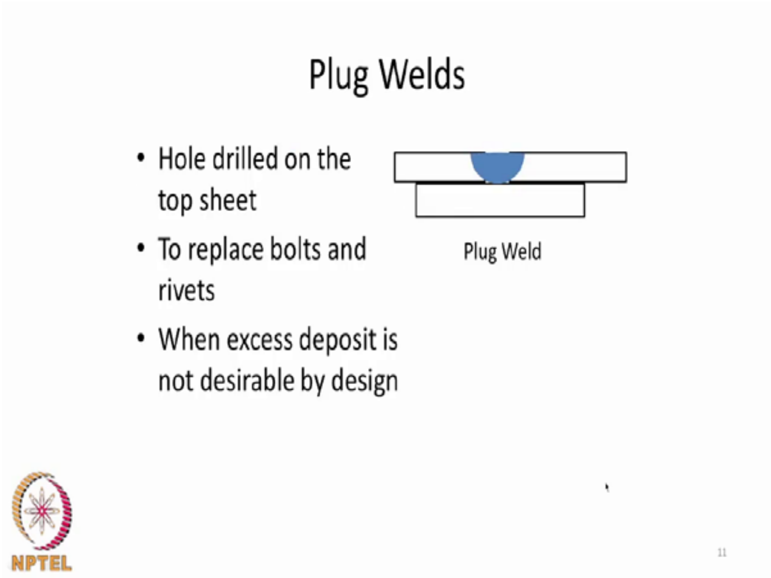

Plug welds are basically replacements for fastening process, fastening process be only a mechanical joint; if you want to make that fastening to be permanent in nature, then we would normally resort to what are called as a plug weld. So holes are drilled on the sheets that are on the top surface and then a weld bead is made on the top, so that then the hole is covered by the deposited material. These also are used when there is no design possibility to have an excess deposit and plug welds can be also called as spot welds.

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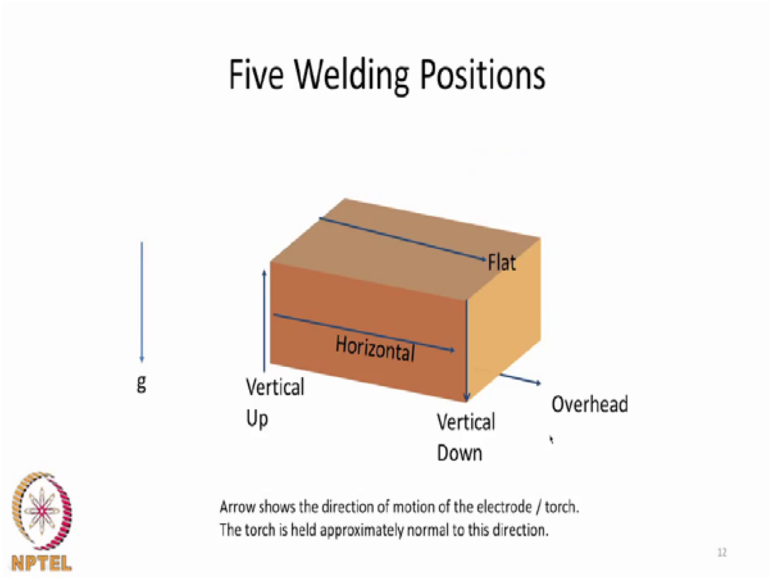

The welding itself can be done in different directions, and there are names that are commonly used in welding literature. So you must familiarize us with this name also. And here I have given you a schematic that shows the five different welding positions in which welding is done. Some welding positions are such that a certain welding processes cannot be used. I have shown on the left hand side, a vector show in the gravity direction downwards, which means that in this cube, the gravity is acting in the downward direction.

The five directions along which the torch can move are shown here. We have the a most common way of joining which is called as a flat geometry; in flat position, essentially the welding torch is kept almost vertically up and it is moved horizontally on a plane and this geometry is most common.

A horizontal geometry is where we have the torch moving horizontally, and the welding torch is held not in the direction of gravity, but at 90 degrees to it. Vertically up and vertically down will also require that the welding torch is held 90 degrees to the gravity direction, but it is moved vertically up or down as oppose to horizontal direction. Overhead welding is a different geometry it is where the torch is held exactly antiparallel to the gravity direction, and then it is moved along the horizontal direction, which means that the arc is going in the direction opposite to the gravity.

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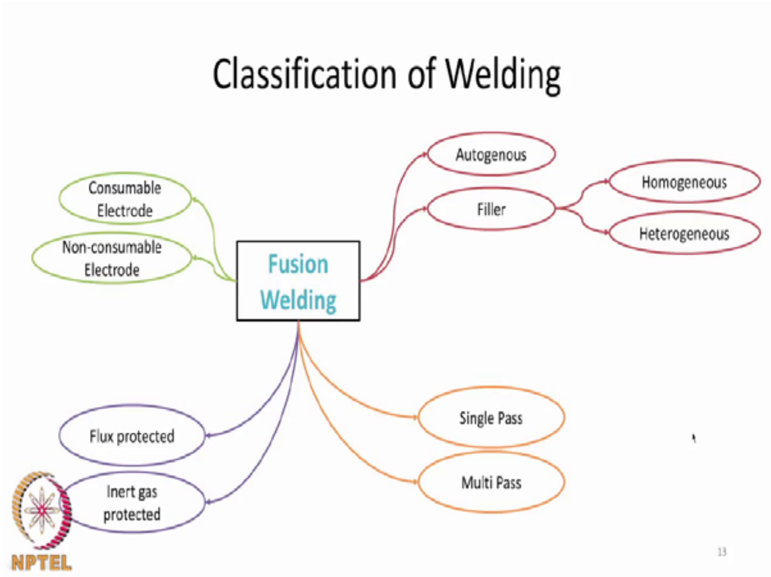

So, the welding processes which we have looked at till now fall under the broad category what is called as a fusion welding. And these fusion welding processes are also then classified in different, different terminologies, and we will make all these similar with the terminologies here. We will be able to classify them as consumable and non-consumable electrode to basically look at whether the electrode is used as filler or not. So we have processes such as TIG welding where it to be a non-consumable electrode welding; and then a process such as MIG welding would be a consumable electrode welding.

The welding can also be done without any filler at all in which case it is called as an autogenous welding. And if it is used with filler, you can say that it is a welding with filler. And this filler may match the material properties of the base metal, in which case, you can call it as a homogenous welding. And, in case the material that is used for the filler is different from the base material, so that the welding process is successfully completed without any weld cracking etcetera, then you would call that as a heterogeneous welding processes. So homogeneous and heterogeneous imply that there is filler that is used which is either same or different from the base material, and that is also one more way of classifying the fusion welding processes.

Fusion welding also means that the material that is being joined is going to be molten; and as you all know most of the metallic materials, when there in the liquid state are highly reactive and that would require that we have a protection for the liquid metal, so that it does not form oxides. If oxides are formed, they will enter the base metal during the solidification of the weld pool, and then cause defects and cracks later on. So it is important to protect the liquid metal during welding; and this can be done by either a flux or an inert gas. So, you could also classify fusion welding processes as flux protected welding process and inert gas protected welding process.

A fusion welding may not be successful for a high thickness joint in one pass, so you would also like to perhaps classify the fusion welding processes as single pass and multi-pass. Multi-pass actually would open up a more complications to understand the thermal process, because we would have multiple single passes that are laid on top of each other, and the residual heat would start playing a role with the welding efficiency that would be implied for the further process.

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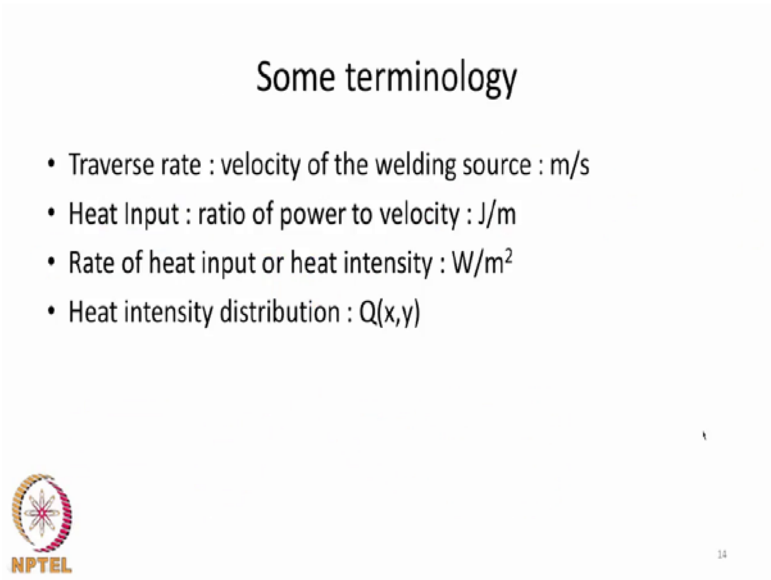

Some more terminology for us to make ourselves familiar, so we would be referring to what is called as a traverse rate; so what we mean by traverse rate is basically the velocity with which the welding torch or welding source is moved, and it would be usually the units same as velocity meters per second, but the unit that is used in welding community will be in millimeters per second, it would be usually hundreds of millimeters per second. And heat input is a specific term that is used; it should not be confused with the English meaning, which conveys that amount of heat that is given, but it is actually a ratio of the power that is being given by the welding source to the base material to the velocity at which the welding torch is moving.

So the power has units of joules per second and velocity has units of meters per second, so you would have heat input having the units of joules per unit length of the weld that is taking place. This also means that a welding process, which has a high-speed capability, would naturally be of a low heat input. And this may not be obvious from the word heat input when we apply two processes such as electron beam which are known to be low heat input processes. Rate of heat input or heat intensity is also one term that we will use; it is basically to show at what rate the heat will be arriving from the heat source to the base material, and it would be normally referred to in the units of a power per unit area watt per meter square.

And the area over which the rate of heat input is being applied should also be normally known so that we can integrate this particular quantity to know how much of heat has been deposited completely on the base metal over the duration when the welding is taking place. And how this heat is then distributed spatially on the surface of the base metal is also important and that is what we refer to as heat intensity distribution. Heat intensity distribution is often such that it is a maximum value at the center of the welding torch and goes down as you go away from the welding torch.

However, this will not be the only variations of heat intensity distribution, we can also have other variation that are possible as in for example, laser welding where a very detailed set of lenses could give you any distribution that you would wish. We will come to that shortly in a next lecture. So, these are the quantities that we will be referring to again and again during the course of this stock, so the technical meaning of these terms and the rough values of these quantities for a given welding process should come to as naturally as we go along this course.

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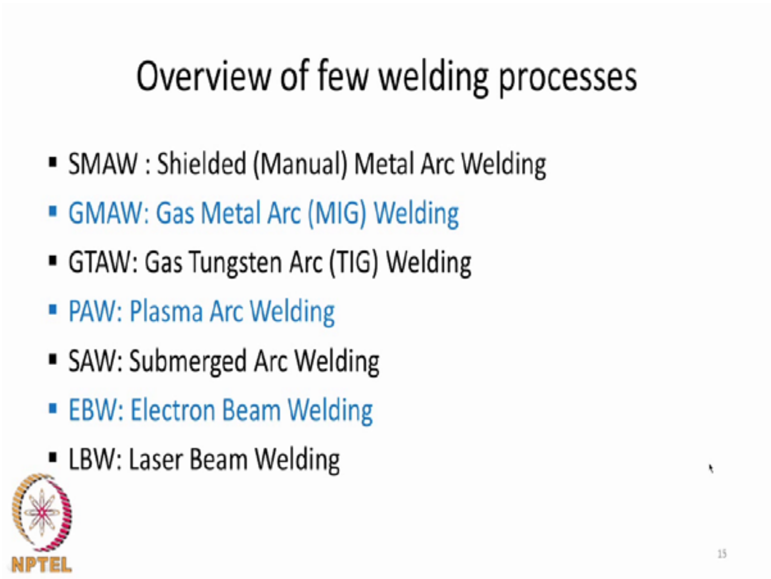

So, there is several welding process that we are going to look at for an overview in this first lecture. And I have listed some of them. This is not a compressive list of all the processes that are important in the industry, but it would give you a fairly large set of processes that would cover, what would what would be happening in the industry. So these are the processes we are going to look at shielded metal arc welding, gas metal arc welding, tungsten arc welding, plasma arc welding, submerged arc welding, electron beam welding and laser beam welding.

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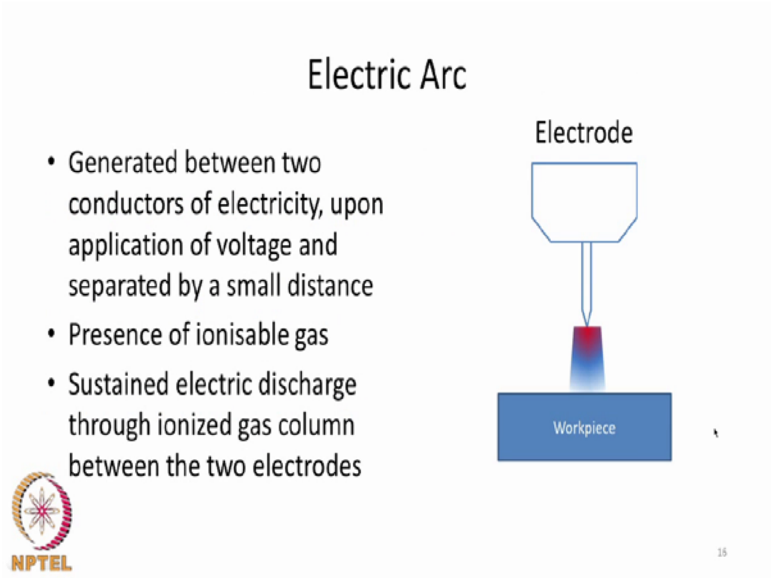

So, before we proceed the further with an over view of all these welding processes, it is important for us to look at how the electric arc is generated, and how it is sustained and then how that is playing a role as a heat sources. So, here is the detail we have the geometry on the right hand side in the schematic showing you that there is an electrode and what is coming out sharply below is the electrode, which is usually tungsten in the case of non-consumable electrode, and it is the same material as filler that is used as a wire.

And workpiece is shown at the bottom. Now it is a workpiece that has to be joined during this welding process and I am showing you between the electrode and workpiece what appears to be an electric arc. So there must be a polarity that must be applied for the electrode and workpiece and usually workpiece will be given a connection to the earthing and electrode will be then given a voltage either positive or negative has polarity would require.

And the both electrode and workpiece have to be conductors of electricity, so that upon application of voltage and a small gap that separates between the two then electric arc can be struck. And this arc should then be ionizing the gas that is present in between the electrode and the workpiece, which usually will be argon or helium as you may choose and the ionized gas would then start moving the energy from the electrode onto the workpiece.

So, it is important that the arc is stabilized so that the welding process can continue during the entire fabrication requirement. And sustained energy discharged from the electrode onto the workpiece is possible when we look at what constitutes the environment that surrounds the arc and we will look at that shortly.

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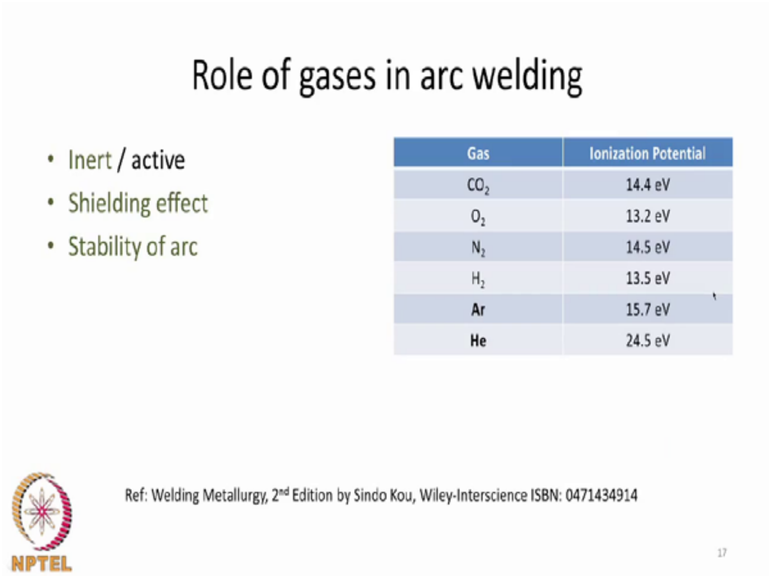

Gas	Ionization Potential
CO_2	14.4 eV
O_2	13.2 eV
N_2	14.5 eV
H_2	13.5 eV
Ar	15.7 eV
He	24.5 eV

So what kind of gases can be used to make the arc in an arc welding? So here I am just showing you some requirements for the gas, the gas generally for a given metal that you want to join could be a either inert or active; and usually we would choose the gas which is inert, because we do not want it to react with the base material and from compounds that are not desirable. However, there are situations where an active gas may also be applied. And the most important role of the gas is to shield the liquid metal from getting affected by the environment around and to give the stability of the arc.

And the kind of gases that are generally available in engineering environment are listed here; carbon dioxide, oxygen, nitrogen, hydrogen, argon and helium. And I have listed the parameter called as ionization potential on the right hand side in electron volts. So, what it implies is that this is the kind of energy that is required to ionize the gas, and that gives you a hint about how much of voltage is required to strike an arc and sustain it.

And you could see that argon and helium at the bottom are giving a bold, because they are the once there are commonly used in welding process. As you can see that argon have a lower ionization potential, and it is also having a slightly higher density which means that the shroud gas shroud will stay put near the arc without getting diffused away very fast, which makes argon as the gas of choice for use in welding processes.

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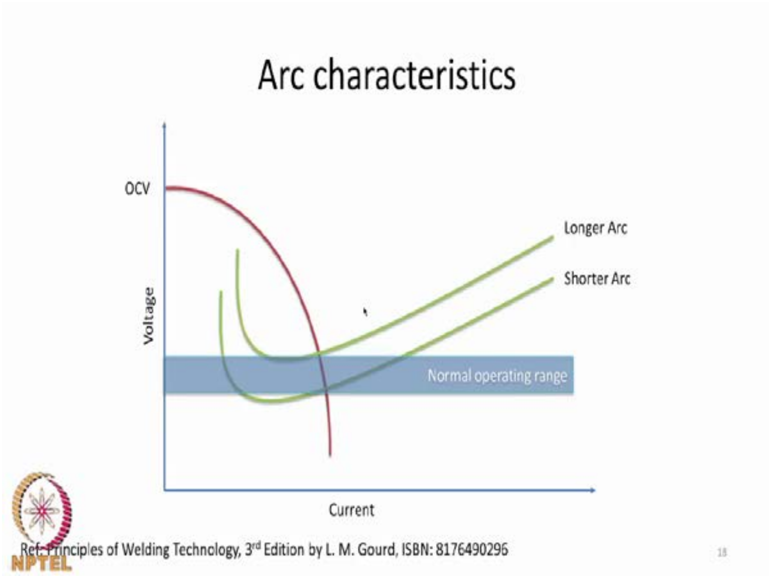

So, there are some characteristics of the arc that we need to be familiar with so that we can understand why the voltage and current condensations that are chosen for welding are like that. So we are seeing in this a plot, a red curve that is going from top to bottom, and this curve is also called as the drooping characteristic of the power source.

Essentially there is a voltage roughly between 60 and 80 volts that would be called as open circuit voltage that is available for the welding source. And the voltage current characteristic is such that it is drooping down that is going down as the current is increased. And how the arc will behave is given the roughly u shaped or a tick shaped curve that is shown in green color.

On the left hand side that is at low voltage and low current corner the arc is not stable; and therefore, those parameters should not be used for welding. So in the linear portion of this curve, we can start exploring the parameters for the welding purpose; and as you can see that for the same current, you would need a higher voltage to sustain arc over a longer length. It also means that during the welding process, if the arc length is varying because of any reason such as a manual operation or because of surface undulations on the sample surface it also means that the voltage at which we have to do the welding also will vary.

And the drooping characteristic of the power source as well as the arc characteristic intersect at points. So those are the combinations which are basically the appropriate voltage and current choices, so that the welding can take place. And I have highlighted the voltage ranges in blue background to showing is a normal operating range, which turns out to be between 15 and 30 volts for most of the arc welding sources, and the current values that would come out would the then between 100 and 300 amps.

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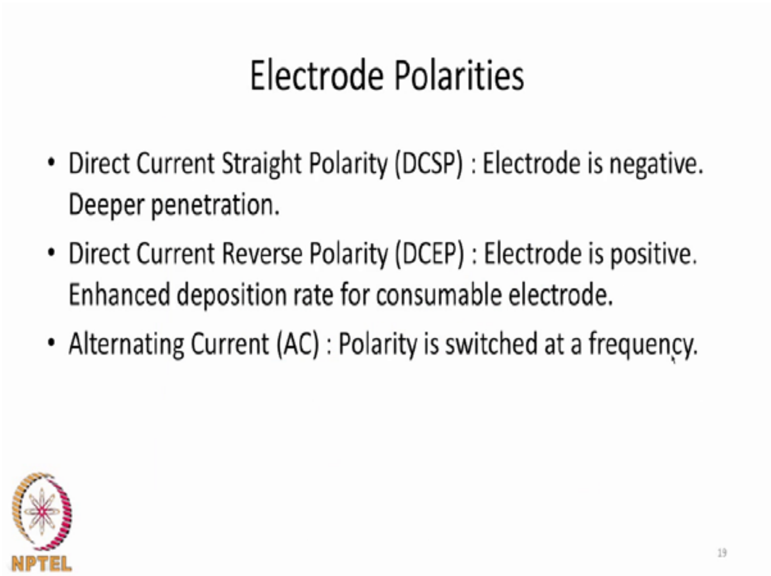

So, the electrode can then be given different polarity for the purpose of welding and we normally have a terminology that would also describe this, we call what is called as a direct current straight polarity - DCSP when the electrode is negatively charged. And this is used whenever deeper penetration is required. DCSP is also called as DCEN that is electrode negative.

There is a second type of polarity that is referred to as direct current reverse polarity DCEP electrode positive. And you also can use alternating current that is change the polarity from positive to negative at a particular frequency. So the electrode polarities are given in three different manners.

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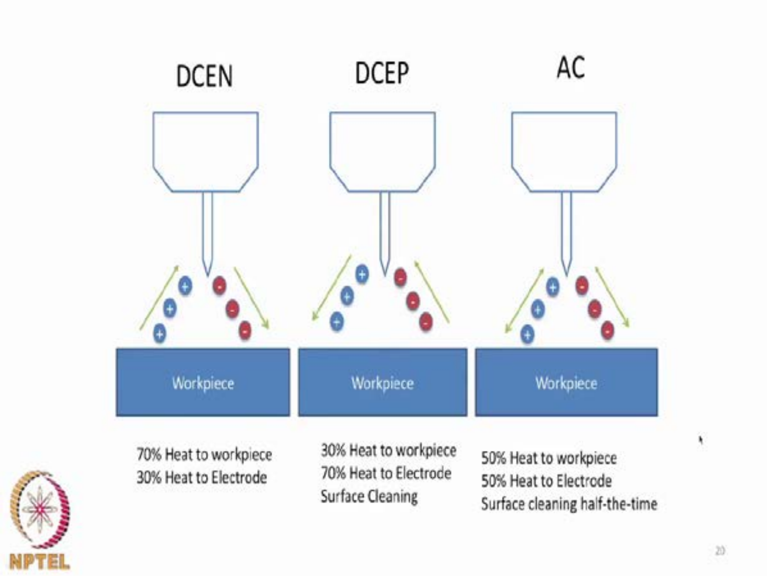

To understand how these polarities are to be chosen, we will go to a schematic on what happens when we change the polarities. So then the electrode negative polarity what happens is that because electrode is negative the negatively charged electrons are going away from the electrode into the workpiece. And these electrons are accelerated very high in the arc and they are then stopped by the workpiece, which converts the kinetic energy of the electrons into heat that will be generated in the workpiece which is basically the major source of energy release because of the arc on the surface of the workpiece.

And the positively charged ions, which basically are argon ions, when argon is the gas that is causing the arc; these argon ions are then moving in the opposite direction going towards the electrode in the case of DCEN. And you can see that there is a change in the direction when we go to the electrode positive geometry and what would happen in that situation are now analogues.

What happens when the electrode is positive is that the electrons, which are having high amount of kinetic energy, are then getting absorbed in the electrode, which means that the electrode is going to have more energy generated in its surface. And it may cause the electrode to heat up fast and may even melt, which means that this is not recommended polarity when you have a non consumable electrode welding process. However, for MIG welding where the electrode is to be also molten and deposited then it would be a recommended polarity.

And there is another reason why we would choose the electrode positive polarity, and that is evident from the direction in which the argon ions are going to travel. So, as you can see the positively charged ions they are rushing towards the workpiece, because the electrode is positively charged and workpiece is at neutral. And what this implies is that if the workpiece is going to be having a surface layer, which has a little bit of surface oxide then the large argon ions that are going to bombard the surface of the workpiece can break the oxide layer on the surface and expose the metallic surface for a smooth joining processes. So, this also implies that if you are going to join aluminum or stainless steel where the surface generally as an oxide layer thin oxide layer then DCEP polarity is suitable.

However, we normally have both of these alternating for these kinds of materials. So, we have AC where the positively charged argon ions as well as the electrons which are negatively charged are moving alternatively towards the electrode and towards the workpiece, which means that you would have the advantage of both the surface cleaning namely the dissociation of the surface oxide as well as enhanced energy release on the surface of the workpiece by the electrons that are coming with high kinetic energy and getting stopped. So often we have a choice of these three polarities and we make a judicious pick of the combination that is required for the particular material that is been joined.

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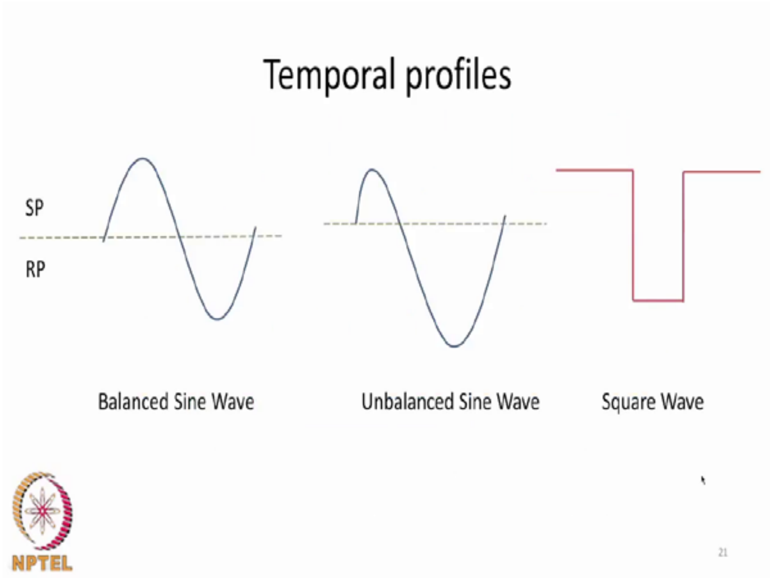

These values namely the voltage and current need not to be kept constant during the welding process. As you can see in the AC polarity, the voltage has to be going from positive to negative at a particular frequency. And you could then see that as usually a sine wave. You could also have a bias to that particular sine wave, so that it can be made as an unbalanced sine wave, and this also means that the electrode will be having different amount of times spent in the straight polarity and reverse polarity reigns. And this is tunable either going upwards or downwards, so that whichever polarity you desire most can be increased in the amount of duration so that the unbalanced sine wave can be made to work for the particular combination that you are interested.

We also can have a square wave that is the voltage can be kept constant at a particular value and then we changed sharply and suddenly to another value, and these variations can then be repeated at the particular frequency. So you could also have not only sine waves, but also square waves. Such temporal profiles of voltage would also imply that the current also will have similar temporal profiles. You may have currents that are changed from a high value to a low value at a particular frequency, when you employ for example, a square wave.

How these temporal profiles are useful in designing low heat input welding processes will be evident later on and we discuss further. So, we must understand that not only the polarity can be changed, but their temporal variations can also be changed, which means that the advances that are taking place in the welding source equipment can then be used to design a new welding processes by looking at all these combinations electronically and automatically configured.

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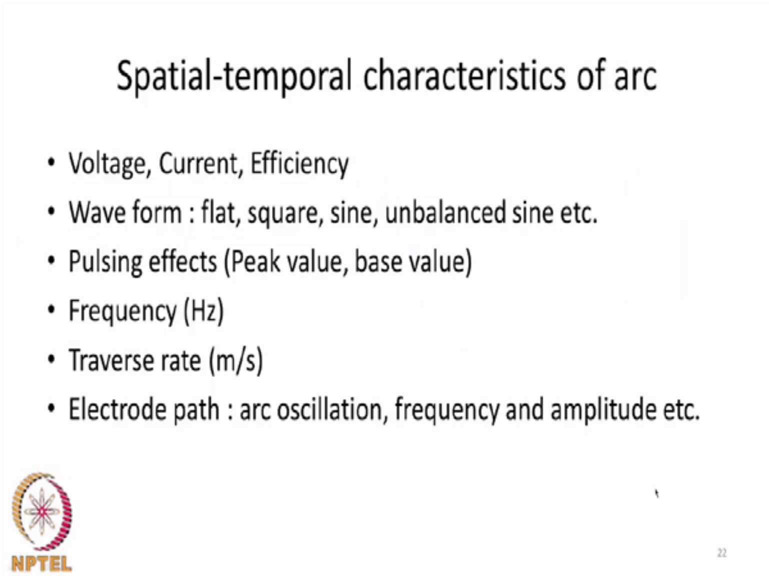

So, before we end the first part of this module, let me just also just summarize the different characteristics of an arc welding process. So we normally need to note down; what is a voltage, current and the efficiency of the heat transfer to the weld piece that will be taking place. And we also need to know what kind of a wave form was used, was it a flat, or a square wave, or a sine wave or unbalanced sine wave etcetera; and in that case then, what would be the frequency of that wave form etcetera.

And we also need to know whether there are any pulsing effects in the current; in case of a pulsing effect, what was the peak value, what was the base value, at what frequency is this switch over being made, and what is the duration of both the peak and pulse values? And the overall frequency of this process will then determine the characteristics of the arc welding process. And at what rate is this arc moving along the surface of the material that is being joined is also important, so we need to note down what would be the traverse rate at this welding process.

And the welding torch may not move in a linear path; and this has also implications. So, we may have what is called as a magnetic arc oscillation that may be placed in the welding setup. And in that case, then what would happen is that the arc is not going in a linear manner, it is going along a sine path. And what would be the frequency of such a path, what would be the amplitude as of such a path is also important in understanding how the welding process is going to take place.

So, as you can see that during the arc welding process, the numbers of parameters that can be changed and controlled are large; and all of these are very important. And how each of these will play a role in the thermal processes that take place during fusion welding using an arc welding process will then be discussed as part of this course.

We will take a short break, and then will come back to the second part of the talk.